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DEFORMATION PROCESSING OF TITANIUM AND ITS ALLOYS

By A. F. Gerds, D. E. Strohecker, T. G. Byrer, and F. W. Boulger

Prepared Under the Supervision of the
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ABSTRACT

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This report covers the state of the art of both primary and secondary fabrication methods for titanium and its alloys and is oriented toward the interests of the designer and the manufacturing engineer. Methods currently employed for primary fabrication of titanium include rolling, extrusion, forging, and drawing of tube, rod, and wire.

Secondary metalworking operations are those processes that produce finished parts from sheet, bar, or tubing using additional metalforming operations. The following secondary forming processes are discussed: brake bending, deep drawing, spinning and shear, drop hammer, trapped rubber, stretch, tube, roll, dimpling, joggling, and hot sizing. Equipment and tooling that are used for the various operations are discussed and illustrated wherever possible.

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report on practices used to deform titanium and its alloys into useful shapes is intended to provide information that may be of use to designers and fabricators. The recommendations are considered to be reliable guides for selecting conditions, tools, and equipment for specific operations. The causes for many of the common problems encountered are identified, and precautions for avoiding them are mentioned.

The report summarizes information collected from equipment manufacturers, technical publications, reports on Government contracts, and by interviews with engineers employed by major aircraft companies. A total of 121 references are included and most of them cover the period since 1957. Some of the most recent information was collected in connection with programs for the Federal Aviation Agency and Defense Metals Information Center. A detailed report that summarizes much of the prior data is contained in the two-volume TML Report, No. 42, which was issued in 1956 by the organization now known as the Defense Metals Information Center.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
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LIST OF ILLUSTRATIONS
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LIST OF TABLES
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DEFORMATION PROCESSING OF TITANIUM AND ITS ALLOYS

SUMMARY

One of the difficulties in the fabrication of titanium and its alloys is that much of the work has been done, until very recently, on equipment designed for fabricating stainless steel. This is especially important for operations such as rolling where the surface of the titanium must be conditioned more frequently, closer control of working temperature is required, smaller reductions during initial breakdown operations are needed, and fabrication must be done at the lowest practical temperature. Working pressures higher than those used for steel usually are developed.

Titanium alloys can generally be extruded by techniques similar to those used for steel. Glass lubricants and ram speeds of 200 to 400 inches per minute are used. These alloys can be forged in both open and closed dies with common forging hammers and presses. Parts as large as 5 feet in diameter and as heavy as 1500 pounds have been successfully forged.

Galling and seizing are the common problems in fabricating titanium and its alloys into bar, rod, and wire and also in the drawing of tubes.

The common secondary processing techniques are used to fabricate titanium and its alloys into finished parts. Important techniques that have been discussed include brake bending, deep drawing, spinning and shear forming, drop-hammer forming, trapped-rubber forming, stretch forming, tube forming and bending, roll forming, dimpling, joggling, and hot sizing. The relationships developed by Wood and his associates for many of these processes are cited. Other data available in the open literature have been summarized and referenced to present a rather comprehensive picture on the state of the art of these fabrication methods as related to titanium and its alloys.

INTRODUCTION

Since titanium was first used in the Douglas X-3 aircraft in 1948 (535 pounds), a vast amount of fabricating and processing technology has been developed. Today, titanium alloys can be worked almost as readily as many of the aluminum alloys and nickel-bearing steels with which it competes.

Much of this technical know-how has come from the aerospace industry where applications include cryogenic pressure vessels, rocket motor cases, nozzle exit cones, control mechanisms, etc. Ordnance applications for large pipe have also been extensive. In nonmilitary uses, titanium is firmly established in the chemical and petrochemical fields as well as in electroplating and anodizing industries. Additional applications appear to be forthcoming in the marine industry, food-processing equipment, heavy construction, and transportation.

The purpose of this report is to summarize the present status of titanium fabrication – both primary and secondary. Primary deformation processes are designed to reduce an ingot or billet to a standard mill product such as sheet or plate, bar, forging, and extruded or drawn rod, tube, or shape. Secondary metalworking operations are those processes designed to produce finished parts by additional forming of such primary shapes as sheet, bar, or tubing.

This report is based on information presented in a large number of technical publications and in reports on investigations sponsored by Government agencies. The source material is referenced so the reader can obtain more detailed knowledge by studying the pertinent publications. Additional information was collected by personal interviews with organizations currently concerned with fabricating titanium. Some of the collection activities were conducted as part of assignments on programs for the Defense Metals Information Center and for the Federal Aviation Agency.

TITANIUM ALLOYS

Titanium has about the same strength characteristics as the higher grade standard steels, but is over 40 per cent lighter. This strength-density advantage is shown graphically in Figure 1 and points up the potential for titanium in aerospace applications. The metal has two basic crystal structures, alpha and beta. By alloying, near-alpha and alpha-beta structures are obtained.

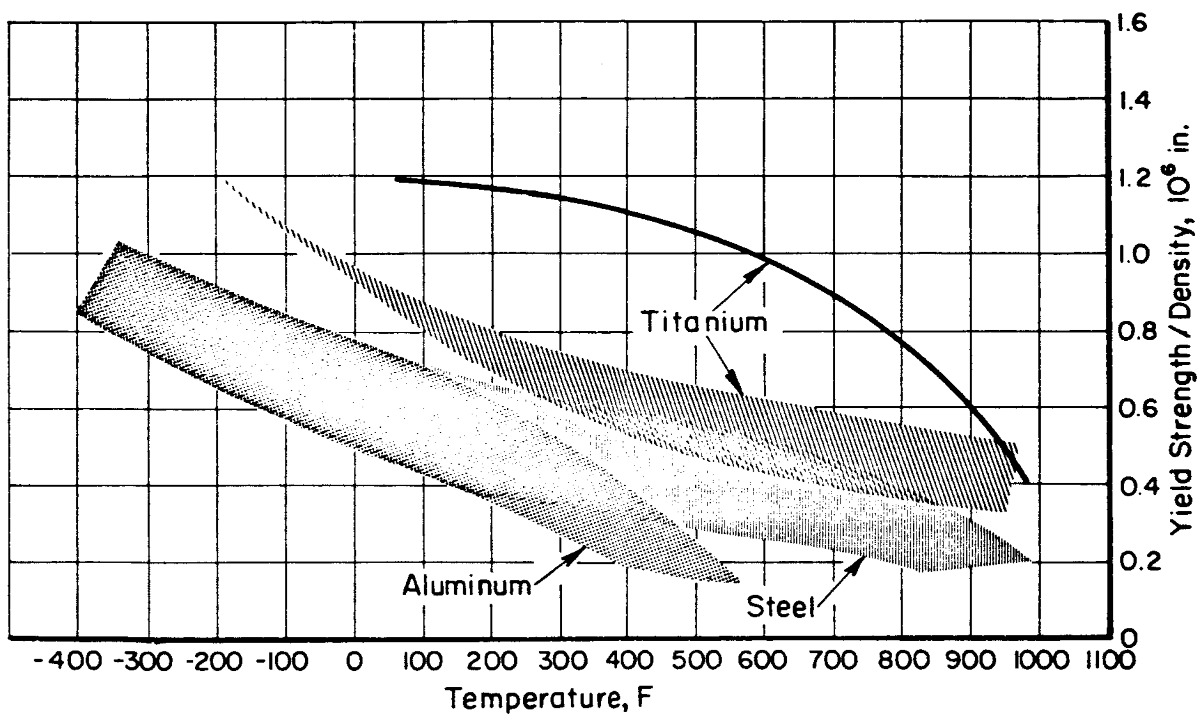


FIGURE 1. COMPARISON OF STRENGTH-TO-WEIGHT RATIOS FOR TITANIUM, STEEL, AND ALUMINUM (REF. 1)

Across the entire temperature range from below -400 F to 1000 F titanium maintains a margin of specific yield strength over most other metals. Upper curve is for aged beta alloy 13V-11Cr-3Al. Areas represent annealed titanium forgings, 4140 steel at various strengths, and aluminum alloys 2024-T81 and 6061-T6.

Alpha-phase titanium has a close packed, hexagonal structure at room temperature. Alloying with aluminum, zirconium, and tin produces alpha alloys that have good strength and ductility at cryogenic temperatures, high creep strength, and are easily welded. Generally speaking, these alloys have the highest strength and best oxidation resistance at 600 to 1000 F of all titanium alloys. They cannot be heat treated, however, which limits their strength at room and slightly elevated temperatures.

The beta structure is body-centered cubic. The principal beta alloy, Ti-13V-11Cr-3Al, is readily formed cold and can be heat treated to very high strength levels. The alloy is not thermally stable above 700 F and is the most sensitive to fabrication history of all titanium alloys. A new beta alloy Ti-12Mo-6Sn developed by Crucible (Ref. 2) promises better high-temperature stability for this alloy system.

The alpha-beta alloys commonly contain aluminum to promote alpha stability at higher temperatures and such beta stabilizers as vanadium, molybdenum, manganese, chromium, and iron. These alloys comprise the materials most commonly used in aerospace applications. They can be formed in the solution-treated condition and strengthened by precipitation hardening. The alpha-beta alloys are very workable but have poorer creep and temperature stability characteristics than the alpha alloys.

The characteristics of all commercially available titanium alloys are summarized in Table I (Ref. 3). Alloy specification numbers and producer's designations are included for reference. The mechanical properties reported are generally considered as nominal values at room temperature and specific producers should be contacted for determining design minimums and guaranteed properties.

ROLLING

One of the most extensive development programs ever conducted on a new material was the Department of Defense sheet rolling program for titanium, which was instituted in 1955 and continued in the early 1960's. In this program, which involved all of the major titanium producers, sheet-rolling procedures were developed for seven of the most important alloys, Ti-6Al-4V, Ti-8Mo-1Al-1V, Ti-2.5Al-16V, Ti-13V-11Cr-3Al, Ti-4Al-3Mo-1V, Ti-7Al-12Zr, and Ti-5Al-5Zr-5Sn. In addition, extensive design and property data were

TABLE I. SPECIFICATIONS, PROPERTIES, AND APPLICATIONS FOR WROUGHT TITANIUM AND TITANIUM ALLOYS (REF. 3)

Material (Nominal Composition)	Specifications AMS	Specifications Military	Specifications ASTM	Producers' Designations(a)	Mill Forms(b)	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Reduction of Area, per cent	Properties and Applications
Unalloyed				Ti-35A WC-25 RS-25	S, B, E, W, T	35,000	25,000	22	35	Special soft grade for uses where structural strength is less important than corrosion resistance; heat exchangers, explosive cladding of steel, vacuum tubes
Unalloyed		MIL-T-12117 Class 40	B-265-58T B-338-61T B-337-58T B-367-61T	RMI-30 HA-1940 WC-30	S, B, E, W, T	45,000	35,000	22	35	Valves, heat exchangers, dished heads, and similar uses where corrosion resistance is an important design consideration
Unalloyed	4902 4941 4951	MIL-T-9046C MIL-T-12117 Class 50	B-265-58T B-338-61T B-337-58T	RMI-40 RS-40 A-40 Ti-50A HA-1950 GOC-40 WC-40 OMC-105	S, B, E, W, T	65,000	50,000	28	50	Nonstructural aircraft and corrosion uses where ductility and formability are needed. Fusion weldable; processing equipment, fittings, heat exchangers, valve trim, marine uses
Unalloyed	4900A	MIL-T-9046C MIL-T-7993 Class II	B-265-58T B-338-61T B-337-58T	RMI-55 RS-55 A-55 Ti-65A GOC-55 WC-55	S, B, E, W, T	80,000	65,000	25	50	Properties and uses same as above except it has higher strength; used as rods and wire for welding other titanium alloys; anodizing racks; lining for chemical processing equipment
Unalloyed	4901B 4921A	MIL-T-9046C MIL-T-12117 Class 70 MIL-T-7993 Class I	B-265-58T B-338-61T B-337-58T	RMI-70 RS-70 A-70 Ti-75A HA-1970 GOC-70 WC-70	S, B, E, W, T	90,000	80,000	20	40	As above, but higher strength with some sacrifice in ductility and formability; aircraft nacelles, webs, stiffeners, angles, shrouds, fire walls, fasteners, engine rings, ammunition boxes, gun blast panels, shroud spacers, anodizing racks
						Alpha-Titanium Alloys				
0.15 Pd				Ti-Pd HA-8150 RMI-0.2% Pd	S, B, T	65,000	50,000	28	50	Chemical process equipment to withstand oxidizing and mildly reducing environments
5Al-2.5Sn(c)	4910 4926 4953	MIL-T-9046C MIL-T-9047C	B-265-58T B-338-61T B-367-61T	RMI-5Al-2.5Sn RS-110C A-110AT Ti-5Al-2.5Sn HA-5137 OMC-166-A	S, B, W, F, E	125,000	115,000	10	25	Forgings and welded sheet for creep resistance up to 900 F; aircraft engine compressor case housings, tail cones, shroud spacers, stiffeners, high strength fusion welded assemblies. Cryogenics tankage(c)
8Al-1Mo-1V(d)				Ti-8Al-1Mo-1V RMI-8Al-1Mo-1V HA-8116 WC-8-1-1 RS-135B	S, B	147,000	135,000	16		High-temperature jet-engine forging alloy; airframes; good creep properties at elevated temperatures; extends temperature range about 150 F over alloys like 6Al-4V
7Al-2Cb-1Ta				RS-115BL	S, B, F	125,000	115,000	17	35	Compressor blades, fire walls, tail cones, stiffeners, welded assemblies, marine plate, high strength forgings; has exceptional high temperature strength - about 200 F advantage in the 400 to 1000 F range, over 6Al-4V

TABLE I. (Continued)

Material (Nominal Composition)	Specifications AMS	Military	ASTM	Producers' Designations[a]	Mill Forms	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Reduction of Area, per cent	Properties and Applications
					Alpha-Titanium Alloys (Continued)					
8Al-2Cb-1Ta				RMI-721 WC-8-2-1	S, B, E, W, F	125,000	111,000	17	35	Same as 7Al-12Zr
7Al-12Zr				RMI-7Al-12Zr Ti-7Al-12Zr RS-120C	S, B, F	125,000	115,000	17	35	Excellent toughness and moderate strength; weld joint toughness comparable to base metal properties. Pressure vessel applications; jet engine forgings; exterior and interior pressure
5Al-5Sn-5Zr				Ti-5Al-5Sn-5Zr	S, B, F	120,000	110,000	10	20	Turbine engines and airframe applications requiring high creep strength
					Alpha-Beta-Titanium Alloys					
3Al-2.5V				RMI-3Al-2.5V	S, E, T	100,000	85,000	15		Highly weldable; particularly suitable for fabricating into welded and seamless tubing
3Al-5Cr	4927	MIL-T-9047C		RMI-3Al-5Cr	B, F	145,000	135,000	13	35	Aircraft forgings; fasteners
8Mn	4908A	MIL-T-9046C	B-265-58T	RMI-8Mn RS-110A C-110M Ti-8Mn WC-8Mn	S	130,000	120,000	15		For medium, high strength, sheet uses where good formability is needed; not used for fusion welded assemblies or above 650 F; longerons, bulkheads, channels, stressed skins, and frames
4Al-4Mn	4925A	MIL-T-9047C		RMI-4Al-4Mn RS-130 C-130AM HA-4145	B, W, F, E	145,000	133,000	15	40	High-strength airframe and engine forgings and fasteners where good weld ductility is not needed; industrial equipment requiring maximum strength with good corrosion and erosion resistance
4Al-3Mo-1V[d]	4912 4913			RMI-4Al-3Mo-1V RS-115 C-115AMoV Ti-4Al-3Mo-1V	S	133,000	123,000	11		Heat-treatable sheets with good formability in solution conditions; to get 155,000 psi yield strength, heat treat at 1650 F, 10-15 min, water quench, and age at 925 F for 6-12 hours
5Al-2.7Cr-1.25Fe[d]				RS-140 Ti-5Al-4FeCr	B, S	158,000	147,000	16	40	High-strength forgings and sheet parts; heat treatment increases tensile strength to 180,000 psi with corresponding increase in yield strength
6Al-4V[d]	4928 4911 4935	MIL-T-9046C MIL-T-9047C	B-338-61T B-367-61T	RMI-6Al-4V RS-120A C-120AV Ti-6Al-4V HA-6510 WC-6-4 OMC-164-B	S, B, E, W, F, T	145,000[f]	130,000	13	40	Medium high-strength aircraft and engine forgings; ordnance equipment; elevated-temperature strength and stability with good machinability; compressor wheels and blades, spacers, cryogenics[c] rocket cases
7Al-4Mo[d]				RMI-7Al-4Mo RS-135 C-135AMo Ti-7Al-4Mo HA-7146 WC-7-4	B, E, T	145,000	135,000	10	20	Heat-treatable forging alloy combines good creep resistance, stress stability, and high temperature strength; used in aircraft turbines for compressor wheels and blades, hubshafts, spacer rings, airframes
2.5Al-16V[d]				RMI-2.5Al-16V	B, S, W	175,000[e]	160,000	6		Airframe skins, webs, angles, shrouds, and fasteners; age hardened parts have good short time hot strength (yield strength about 100,000 psi up to 800 F); sheets are heat treatable with good formability in solution treated condition

TABLE I. (Continued)

Material (Nominal Composition)	Specifications AMS	Specifications Military	Specifications ASTM	Producers' Designations[a]	Mill Forms	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Reduction of Area, per cent	Properties and Applications
					Alpha-Beta-Titanium Alloys (Continued)					
6Al-6V-2Sn[d]		MIL-T-46035		Ti-6Al-6V-2Sn HA-5158 RMI-6Al-6V-2Sn WC-6-6-2 RS-140B	B, F, E, W	180,000[e]	170,000[e]	6	15	Good welding and fabricating characteristics; applications; ordnance, pressure vessels, rocket motor cases, airframes; forged and plate parts
1Al-8V-5Fe				RMI-185	B	220,000	210,000	10	20	High-strength fasteners for aircraft and missiles
					Beta-Titanium Alloys					
13V-11Cr-3Al[d]				RS-120B B-120VCA Ti-13V-11Cr-3Al RMI-13V-11Cr-3Al HW-13V-11Cr-3Al WC-13-11-3	S, B, W	125,000	120,000	10	25	Weldable, heat-treatable alloy for solid-propellant pressure casings; cold rolled and aged sheet provides tensile strengths in excess of 210,000 psi

(a) Producers' designations:
- RMI - Reactive Metals, Inc., Niles, Ohio.
- RS - Special Metals Div., Republic Steel Corp., Massillon, Ohio.
- A, B, and C - Crucible Steel Co. of America, Midland, Pa.
- Ti - Titanium Metals Corp. of America, New York.
- HA - Harvey Aluminum, Inc., Torrance, Calif.
- HW - Precision Metals Div., Hamilton Watch Co., Lancaster, Pa.
- WC - Wah Chang Corp., Albany, Oreg.
- OMC - Oregon Metallurgical Corp., Albany, Oreg.
- GOC - G. O. Carlson, Inc., Thorndale, Pa.

(b) S - sheets, strip, plates
- B - bars and billets
- E - extrusions
- F - forgings
- T - tubes.
- W - wire.

(c) For cryogenics applications, best and most uniform properties are obtained by holding interstitial impurities (O, Fe) to low values. "L" and "ELI" have been used as designations for such controlled analysis material

(d) Indicates response to heat treatment. (Guaranteed heat-treat capabilities of alloys responding to heat treatment available from producers.)

(e) Age hardened.

(f) Sheets from Reactive Metals, 180,000.

obtained and evaluations made of potential applications for these sheet materials in the aircraft industry.

Detailed results of the various programs are available in the individual reports from the contractors (Refs. 4-9). Various compilations of data were also published by Titanium Metallurgical Laboratory (Ref. 10), now known as the Defense Metals Information Center. Several additional studies were sponsored by the Air Force (Refs. 11-13) after the conclusion of some of the initial programs. As a result, considerable technical know-how has been generated on rolled titanium products in the few short years that titanium alloys have been in existence.

CLASSIFICATION OF ROLLING PROCESSES

The rolling operation combines both compressive and tensile forces to reduce the cross section of plastic metal or to change its shape, or both. This combination of rolling forces deforms the metal symmetrically about a neutral plane, parallel to the surface, distorting the grain structure. Cylindrical rolls produce flat products — grooved rolls produce rounds, squares, and structural shapes. The major uses of titanium to date from the standpoint of rolled products have been for sheet, strip, and plate. Thus, most of the information available on the primary processing of titanium is related to the production of these forms.

The terms hot rolling and cold rolling as used in this report denote processing above or below the recrystallization temperature, respectively. Little or no strain hardening occurs in hot rolling, considerable work hardening occurs in cold rolling. Rolling develops directional mechanical properties and distorted grain structures.

ROLLING EQUIPMENT

Detailed information on the design and operation of steel-mill rolling equipment is available elsewhere (Ref. 14) so that only a brief discussion of equipment and rolling nomenclature is provided here as a basis for the process descriptions provided in the report.

Figure 2 shows the most common mill designs used in rolling. The reversing two-high and three-high mills are commonly used for breakdown and semifinishing operations in the fabrication of both flat products and shapes. Single-strand two-high mill are reversible so that the workpiece can be deformed while traveling in either direction.

Heavy pieces and long lengths can be handled conveniently on this type mill for fabrication of slabs, blooms, plates, billets, rounds, and partially formed sections.

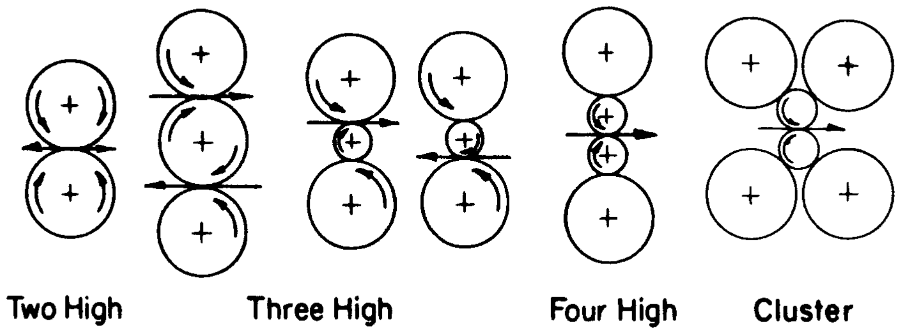


FIGURE 2. TYPICAL ROLLING-MILL DESIGNS

The three-high mill does not require any drive reversal as the direction of rolling depends upon whether the piece is traveling above or below the center roll. This mill is generally used for products other than plate or sheet.

For rolling of narrow-width material where thickness control is not critical the two-high and three-high rolling mills described above are adequate. For rolling of wide material, particularly wide plate, then a four-high mill is used to provide better roll rigidity and closer thickness control. The four-high mill may be used for producing both hot- and cold-rolled plate and sheet. Several of these mills are used in tandem for continuous rolling of sheet.

The cluster mill is used for rolling very thin sheet or strip where very close thickness control must be maintained.

FABRICATION OF TITANIUM-ROLLED PRODUCTS

Much of the rolling of titanium has been done on equipment designed and used for fabricating stainless steel. With the advent of greater titanium production, some of the producers are now installing equipment that is especially designed for fabricating and processing titanium. In many ways, the rolling procedures for titanium are very similar to steel. A number of important differences exist, however, such as the need for frequent surface conditioning of titanium during processing, closer control of working temperatures, smaller reductions per pass in initial breakdown operations, and the fabrication of titanium at as low a temperature as possible commensurate with equipment capabilities. Working pressures are also higher for titanium than for steel.

Ingot Breakdown. The ingots are prepared for fabrication by machining off some of the skin in large lathes. The practice varies considerably in that some producers prefer to remove most of the skin after slabbing. The main purpose of scalping is to remove the rough exterior that might result in defects in the mill products. Also the exterior skin often is segregated because of volatile material condensing on the sides of the mold above the ingot.

After application of a protective coating, the ingot is heated and press forged. Crucible's studies (Ref. 11) showed that such products as Markal CRT, Du Pont J-400, and Crucible's No. 50 reduced surface contamination, and minimized surface conditioning. These materials also exhibited lubricating properties by reducing roll-pressure requirements.

After conditioning, the forged billet is reheated, bloomed on a blooming mill or two-high reversing mill, and fabricated into sheet bars. These sheet bars measuring 1/2 to 2 inches in thickness are then cross rolled to 0.125 to 0.150-inch-thick sheet. Extensive surface conditioning precedes subsequent finishing operations.

Sheet Rolling. Unalloyed titanium generally is hot rolled and cold finished to sheet in continuous bands. Most alloy grades generally are hot finished by pack rolling in hand-sheet mills between steel sheets. Hand-sheet rolling has been a common practice since it permits cross rolling to be incorporated into the rolling schedule for the purpose of equalizing the longitudinal and transverse properties. Also, the market for alloy sheet has not been large enough to warrant continuous strip processing even though procedures have been developed (Ref. 13).

The typical pack or sandwich design used for rolling alloy grades is shown in Figure 3 (Ref. 15). A parting agent such as lime and Al_2O_3 is put between the sheets to prevent sticking. The sandwich is then welded together to protect the contents from contamination.

In addition to the protection afforded the sheet material during rolling, other advantages of the procedure include good control of sheet thickness, minimizing of crown, and improvement of sheet surfaces. Of possibly greater importance is the ability to roll wide

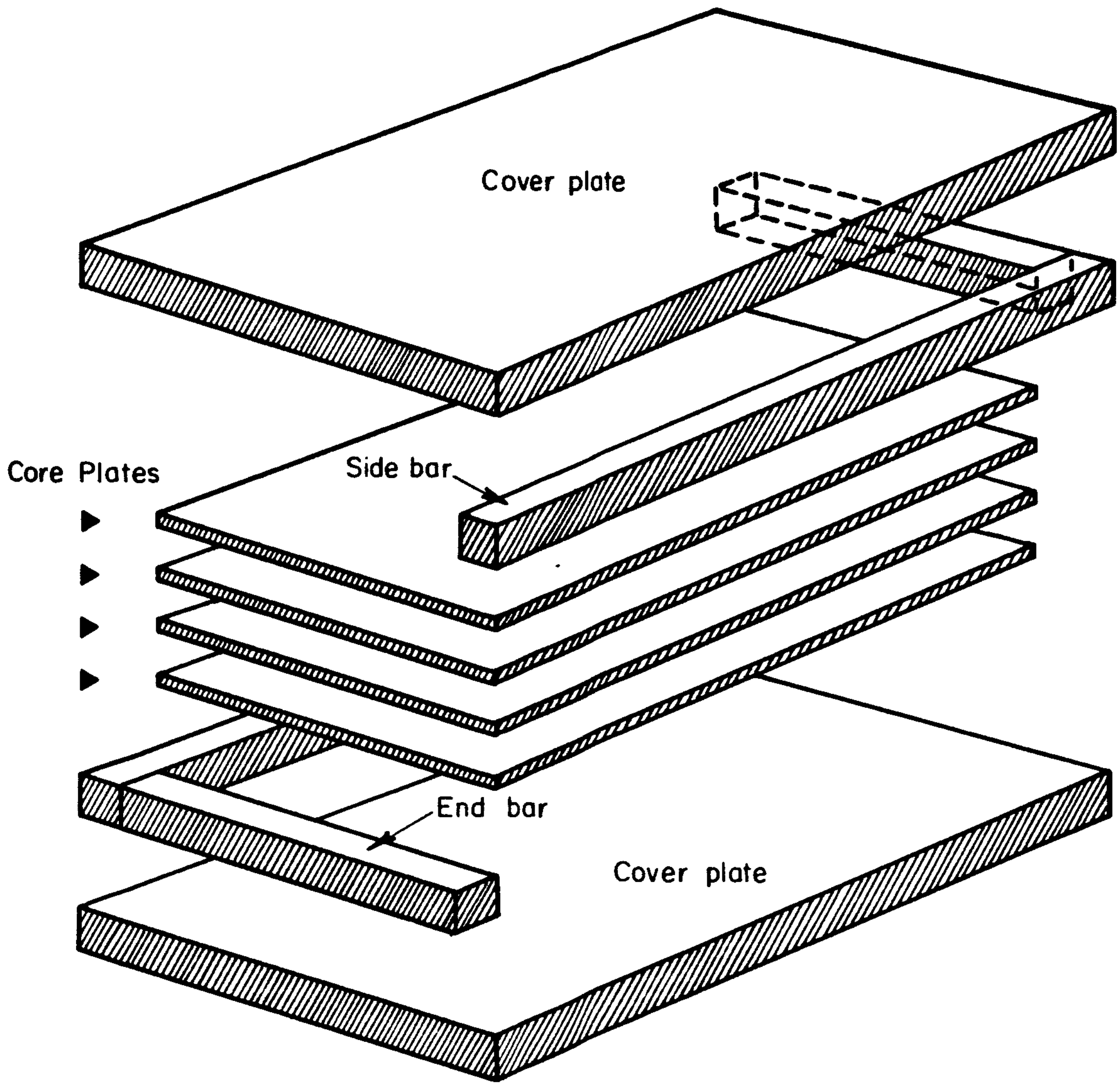


FIGURE 3. SCHEMATIC OF SANDWICH ASSEMBLY USED FOR ROLLING TITANIUM ALLOYS (REF. 15)

sheet since the sandwich thickness permits rolling to be done on plate mills that are wider than sheet-rolling mills.

After rolling, the sheet is sheared out of the sandwich, heat treated, trimmed, surface ground, and pickled.

Working temperatures used in rolling various titanium-alloy-sheet materials are listed below:

	Recommended Working Temperatures, F		
Alloy	Initial Breakdown	Intermediate	Finish
Ti-8Al-1Mo-1V	2050	1880-1890	1800
Ti-5Al-5Sn-5Zr	2050-2150	1800-1890	1750
Ti-7Al-12Zr	2050-2150	1800-1890	1750
Ti-2.5Al-16V	1900	1850	1300(a)
Ti-4Al-3Mo-1V	1900	1675	1675(a)
Ti-6Al-4V	1900	1800	1625
Ti-3Al-13V-11Cr	2050-2150	1900	1900(a)

(a) Commonly finished cold to improve surface finish and sheet tolerances.

POST-ROLLING TREATMENTS

After rolling, all subsequent processing is dependent upon the specification requirements. The most common practice after final annealing or heat treatment is to surface grind and pickle in a HNO_3-HF bath (Ref. 16). Creep flattening is generally used if flatness requirements are stringent. Roller-leveling techniques have also been developed (Ref. 17). Precision surface grinding can be performed if required (Ref. 18).

MECHANICAL PROPERTIES OF TITANIUM-ROLLED PRODUCTS

A more complete compilation of mechanical properties is available elsewhere (Ref. 19). Detailed information on specific properties is available from the titanium producers. Table II contains a brief summary of typical properties of commercial titanium alloys in sheet, plate, or bar form (Ref. 19).

TABLE II. MECHANICAL PROPERTIES OF TITANIUM ALLOYS (REF. 19)

				Typical Mechanical Properties			
Alloy	Condition	Form[a]	Test Temperature, F	Ultimate Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Modulus of Elasticity, 10^6 psi
99.5 Ti	Annealed	S	80	38	27	30	14.9
			600	20	10	50	12.1
99.0 Ti	Annealed	S	-321	175	--	--	--
			80	90	75	20	15.1
			600	43	27	28	12.5
98.9 Ti	Annealed	S	80	100	85	17	15.5
			600	47	30	25	12.6
Ti-5Al-2.5Sn	Annealed	S	80	125	117	18	16.0
			600	82	65	19	13.4
			1000	75	56	18	--
	Annealed	b	80	115	110	20	--
	Annealed	p[b]	80	136	130	13 long. 4 trans.	--
Ti-5Al-2.5Sn (low O)	Annealed	S	-423	229	206	15	--
			80	110	95	20	16.0
			600	78	60	20	13.4
Ti-5Al-5Sn-5Zr	Annealed	S	80	125	120	18	16.0
			600	94	74	20	14.2
			1000	84	67	21	--

TABLE II. (Continued)

Alloy	Condition	Form[a]	Test Temperature, F	Typical Mechanical Properties: Ultimate Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Modulus of Elasticity, 10^6 psi
Ti-7Al-12Zr	Annealed[c]	S	80	135	130	15	16.0
			600	109	86	21	14.3
			1000	93	75	23	--
	Annealed[d]	b	80	135	130	15	--
			600	109	86	21	--
Ti-7Al-2Cb-1Ta	Annealed	b	80	126	120	17	17.7
			600	100	81	25	15.1
		p[e]	80	123	114	13	--
Ti-8Al-1Mo-1V	Annealed	S	80	160	150	18	18.5
	Annealed		1000	85	70	20	--
	Duplex annealed		80	145	138	15	18.0
	Triplex annealed		80	150	142	13	--
Ti-8Mn	Annealed	S	80	137	125	15	16.4
			600	98	75	13	14.4
			800	80	59	15	--
Ti-2Fe-2Cr-2Mo	Solution heat treated and aged	b	80	179	171	13	--
			600	136	112	16	--
Ti-2.5Al-16V	Solution heat treated and aged	S	80	180	165	6	15.0
			600	155	140	8	13.5
			800	140	125	10	--

TABLE II. (Continued)

Alloy	Condition	Form(a)	Test Temperature, F	Typical Mechanical Properties: Ultimate Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Modulus of Elasticity, 10^6 psi
Ti-3Al-2.5V	Annealed	S	80	100	85	20	15.5
			600	70	50	25	13.0
Ti-4Al-4Mn	Solution heat treated and aged	b	80	162	143	10	--
			600	125	100	11	--
Ti-4Al-3Mo-1V	Solution heat treated and aged	S	80	195	167	6	--
			600	152	120	7	--
			800	145	115	8	--
Ti-5Al-1.25Fe-2.75Cr	Solution heat treated and aged	b	80	190	175	6	17.6
			600	144	117	10	16.2
Ti-5Al-1.5Fe-1.4Cr-1.2Mo	Solution heat treated and aged	b	80	195	184	9	17.0
			600	150	125	14	14.6
Ti-6Al-4V	Annealed	S, b	80	138	128	12	16.5
			600	105	95	11	13.5
			800	90	78	18	--
		P(b)	80	132	115	11 long. - 8 trans.	--
	Solution heat treated and aged	S	80	170	155	8	--
			600	130	105	7	--
			800	130	100	8	--

TABLE II. (Continued)

Alloy	Condition	Form(a)	Test Temperature, F	Typical Mechanical Properties: Ultimate Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Modulus of Elasticity, 10^6 psi
Ti-6Al-4V (low O)	Annealed	S	-320	220	205	13	--
			80	135	127	15	16.5
			600	105	95	12	13.5
Ti-6Al-6V-2Sn-1(Fe, Cu)	Solution heat treated and aged	b	80	190	180	10	16.5
			600	150	132	15	14.5
Ti-7Al-4Mo	Solution heat treated and aged	b	80	185	175	10	16.9
			600	150	123	12	15.0
Ti-1Al-8V-5Fe	Solution heat treated and aged	b	80	221	215	10	16.5
			600	140	123	12	14.5
			800	120	100	30	--
Ti-3Al-13V-11Cr	Annealed	S	80	135	130	16	14.2
			800	115	100	18	--
		P(b)	80	132	129	18 long. - 8 trans.	--
	Solution heat treated and aged	S	80	185	175	8	14.8
			600	175	145	8	13.8
			800	160	120	12	--
	Cold rolled and aged	S	80	260	245	4	--

(a) S = sheet; b = bar; P = plate.
(b) 2-inch plate thickness.
(c) 1600 F annealing temperature.
(d) 1380 F annealing temperature.
(e) 1-inch plate thickness.

SIZE AND TOLERANCE LIMITATIONS FOR TITANIUM-ROLLED PRODUCTS

The proper designation as "sheet, strip, or plate" is dependent upon the linear-dimensional relationships of the three products. In the titanium industry, the distinction between the three is generally defined as follows:

Product	Dimensions, inches Width	Thickness
Plate	>10 and >5T	>0.1875
Sheet	>24	<0.1875
Strip	<24	<0.1875

Plate. Plate is available in unalloyed or alloy titanium in widths up to a maximum of 150 inches. Lengths and thicknesses at this maximum depend on ingot size and product yield. Lengths of 320 inches and thicknesses of 6 inches have been produced (Ref. 20).

The more common plate sizes produced to date are listed below:

Thickness, inch	Plate Sizes Available Today, inches
0.1875 to 0.50	48 x 150
0.500 to 1.00	48 x 300
1.00 and up	76 x 300

The thickness and flatness tolerances on rolled plate currently being produced is given in Table III (Ref. 21).

Sheet, Strip, and Foil. A summary of available sheet sizes is given in Table IV. Generally speaking, any of the sheet sizes can be slit into strip of any desired width.

Rolled Rod and Bar. Rod and bar are available in rounds, squares, and rectangles having cross-sectional areas ranging from 16 in.^{2} down to 0.25 in.^{2} (Ref. 21). Lengths up to 30 feet can be produced – usually lengths of 16 to 20 feet are produced.

TABLE III. TYPICAL THICKNESS AND FLATNESS TOLERANCES OF CURRENT TITANIUM PLATE (REF. 21)

Plate Thickness, inches	Thickness Tolerance: Width	Thickness Tolerance: Thickness Overage, inch	Width, inches	Flatness Tolerance, inch in 15 feet
0.1875 to 0.375	Maximum available	0.050	Up to 48	~0.75
0.375 to 1.00	Ditto	0.060	Up to 48	~0.50
			48 to 76	~0.62
1.00 to 2.00	"	0.070	Up to 48	0.5 to 0.2[a]
			48 to 76	0.6 to 0.3[a]

(a) Flatness increases with increasing thickness and decreases with increasing plate size.

TABLE IV. COMMERCIAL AVAILABILITY OF TITANIUM SHEET AND FOIL (REF. 21)

Thickness, inch	Maximum Width, inches	Maximum Length, inches	Remarks[a]
Up to 0.008	24	Coil	Unalloyed grade foil
	8	Coil	Alloy grade foil
0.008-0.012	26	Coil	Alloy grades
0.010	48	Coil	Unalloyed grades
0.012-0.016	30	Coil	(b)
0.016-0.020	36	96-144	(b)
0.020-0.032	36	120	(b)
	48	96	(b)
0.032-0.060	36	144	(b)
	48	120	(b)
0.060-0.187	48	48	(b)

(a) Tolerances meet AMS 2242 specifications.
(b) Thinner sheets in greater widths are generally available in unalloyed grades than alloyed grades.

Rolled shapes have not been fabricated in titanium, but could be produced on existing bar-mill facilities if sufficient quantities of a given shape made the process economical.

ANISOTROPY IN TITANIUM ALLOYS

Metals characterized by directional variations in properties are said to be anisotropic. Anisotropy, which can have either beneficial or undesirable effects in certain applications, develops during plastic working of materials with hexagonal close-packed crystal structures. In such metals, crystallographic textures develop during deformation because only a limited number of slip systems are available. Consequently properties such as ductility, strength, and elastic moduli may vary in the same piece of material depending on the direction in which they are measured.

The anisotropy that results from this texturing may be exhibited in the plane of the sheet-planar anisotropy, or in a direction 90 degrees to the plane of the sheet-normal anisotropy. In titanium alloys the problem of planar or mechanical anisotropy often manifests itself in differences in longitudinal and transverse tensile properties. This condition was noted early in the titanium-sheet-rolling programs when rolling was done nearly all in one direction after initial breakdown from the ingot. After cross-rolling practices were adopted, planar anisotropy was greatly reduced in the alpha alloys and all but eliminated in the alpha-beta alloys where the body-centered cubic structure of beta phase is present. The beta alloy is isotropic by virtue of its body-centered cubic structure.

The possible importance of normal anisotropy was not recognized until recently. For example, an alpha-titanium sheet may show very little planar anisotropy and yet flow strengths in the thickness direction, 90 degrees to the plane of the sheet, may be as much as 80 per cent greater. Under conditions of uniaxial tension, this factor may not be of importance. In biaxial tension, however, such as is encountered in rocket-motor cases, for example, this high flow strength in the thickness direction means exceptional resistance to thinning – an important factor in rocket-case design.

Therefore, the strength of sheet to be used in a balanced biaxial stress application may be increased by increasing its strength in the thickness direction. This, hopefully, can be done by developing the proper crystallographic texture in the sheet, or "texture hardening" as defined by Backofen et al. (Ref. 22), and discussed in detail by

Whiteley (Ref. 23). Lower strengths in the thickness direction tend to improve performance in deep drawing.

The application of texture hardening to titanium has been investigated by Larsen (Ref. 24), McHargue et al. (Ref. 25), and most recently by Hatch (Ref. 26). The latter's studies involved Ti-4Al-0.25O (oxygen added to provide adequate room-temperature strength), Ti-5Al-2.5Sn, and Ti-6Al-4V alloys. The results showed that the Ti-4Al alloy had the greatest potential for texture hardening followed by the Ti-5Al-2.5Sn and Ti-6Al-4V alloys. A review of deformation mechanisms in titanium had indicated that a preferred orientation for texture hardening would place the (0001) pole normal to the sheet plane (Ref. 25). This was confirmed in these studies for the Ti-4Al alloy. This alloy is under development by TMCA for tubing applications.

In summary, planar or mechanical anisotropy may be a problem particularly in alpha-titanium alloys unless processing conditions are controlled to reduce directionality. However, normal anisotropy may be used to an advantage when present studies in texture hardening are completed.

EXTRUSION

INTRODUCTION

Titanium-alloy extrusions have two specific aerospace applications – aircraft-engine parts and airframe shapes. Aircraft-engine manufacturers employ massive shapes that are subsequently machined all over to form a finished part. Extrusions were first used with the advent of the gas turbine for such parts as nonrotating spacers, rings, and flanges of uniform and relatively simple cross section. The extrusions are formed and flash welded into circular shapes to produce these parts. More recent jet-engine uses include blades, disks, and spacers, as shown in Figure 4 (Ref. 27).

The use of titanium extrusions in airframe applications has been very limited because the state of the art up to now is not adequate to produce extrusions with surface finish and dimensional tolerances equal to aluminum. Recent studies, however, show promise for producing thin-section shapes by extruding and warm drawing.

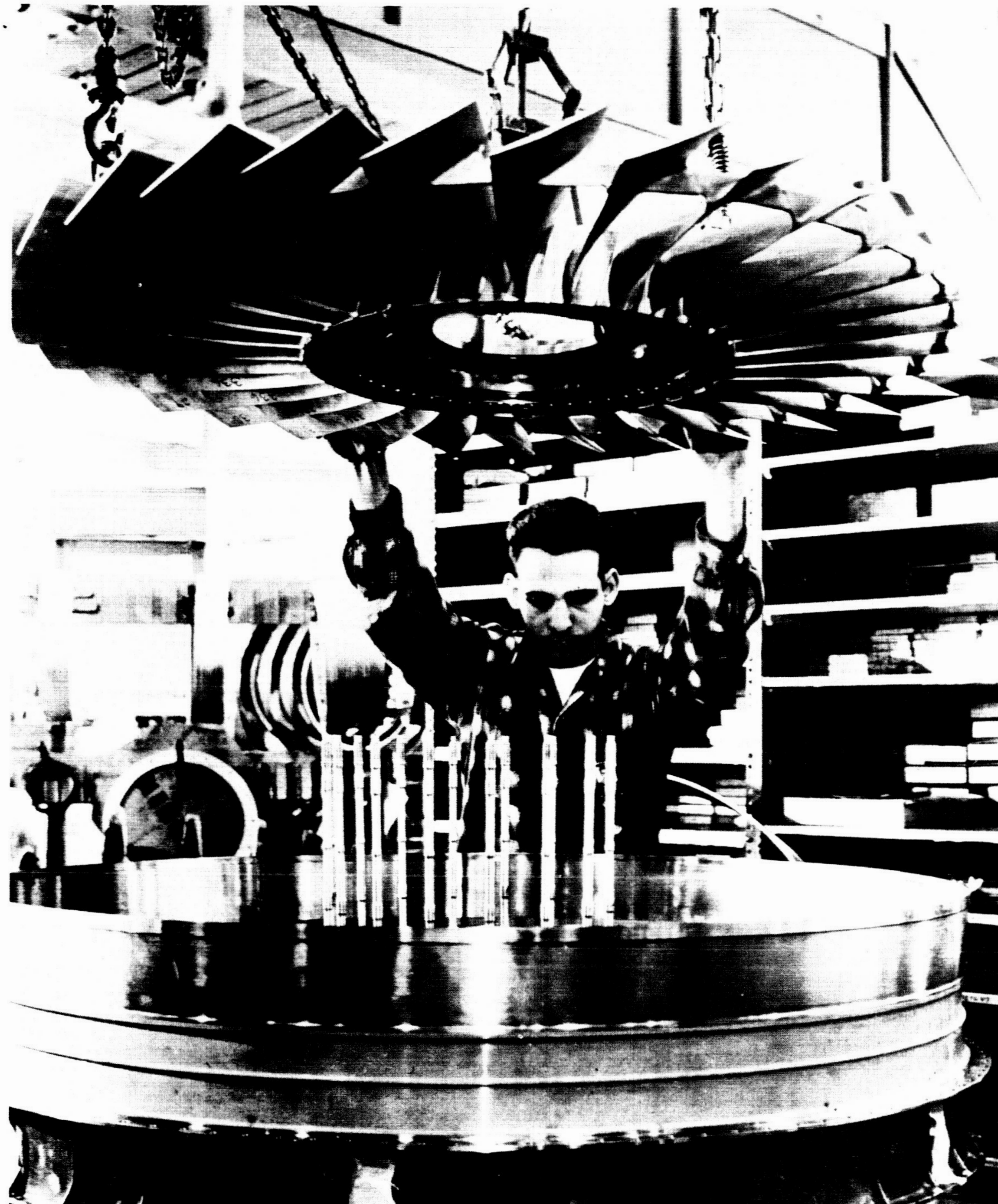


FIGURE 4. COMPRESSOR SECTION OF JET AIRCRAFT ENGINE WITH BLADES, DISKS, AND SPACERS PRODUCED FROM Ti-6Al-4V ALLOY (REF. 27)

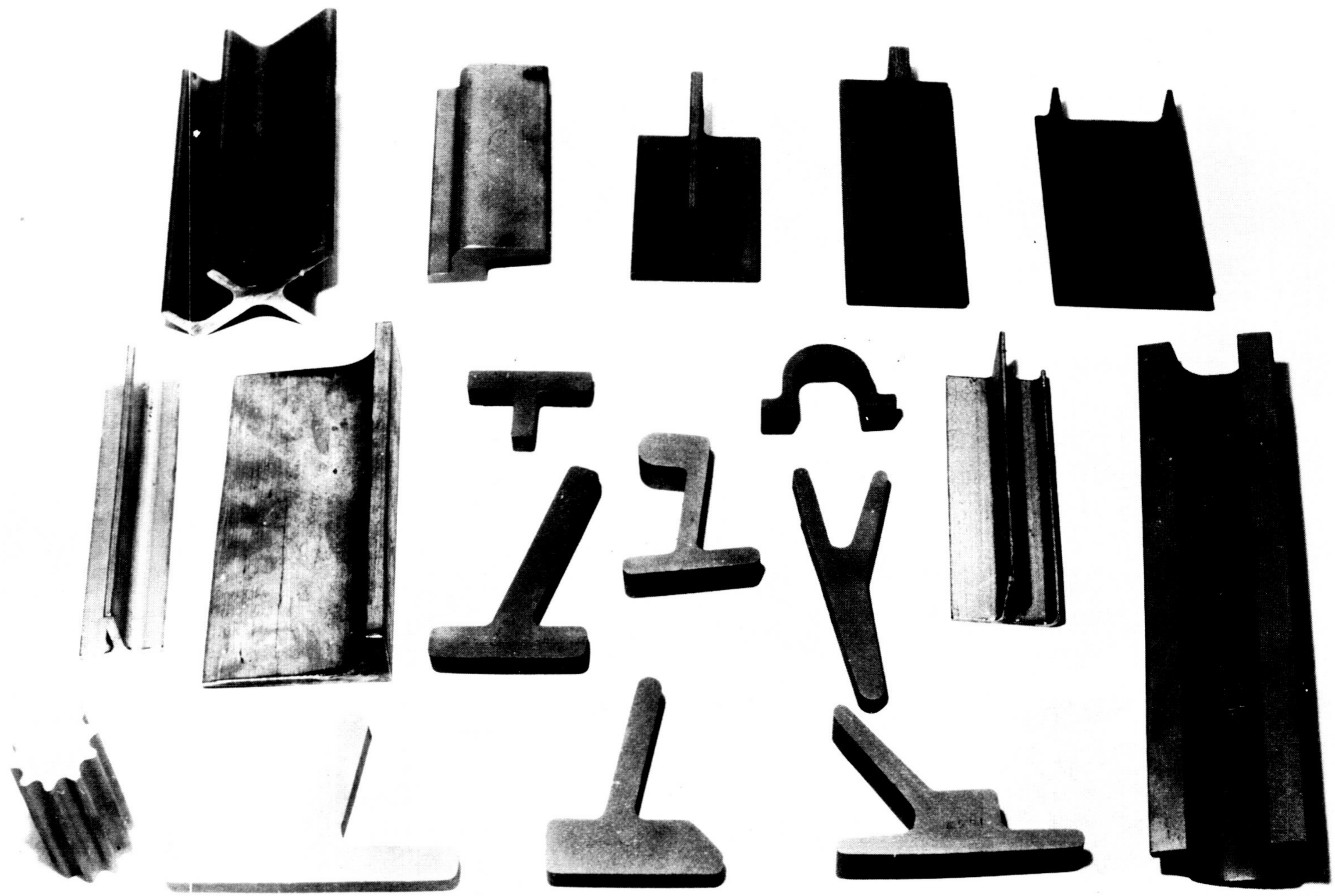


FIGURE 5. SECTIONS OF TYPICAL TITANIUM-ALLOY STRUCTURAL SHAPES EXTRUDED BY HARVEY ALUMINUM COMPANY (REF. 28)

Large-diameter titanium and titanium-alloy-extruded tubing has represented a large portion of the titanium market over the past few years. Applications have been primarily in ordnance, and in the commercial chemical-processing industry.

Generally speaking, the techniques for titanium extrusion are very similar to steel-extrusion practices. Some typical shapes (Ref. 28) that have been produced are shown in Figure 5.

CLASSIFICATION OF EXTRUSION PROCESSES

In the extrusion process, the billet is forced under compressive stress to flow through the opening of a die to form a continuous product of smaller and uniform cross-sectional area. The process can be used to produce rounds, shapes, tubes, hollow shapes, or cups.

<u>Conventional Extrusion</u>. The most common method of extrusion is referred to as "direct" extrusion. In this technique, the

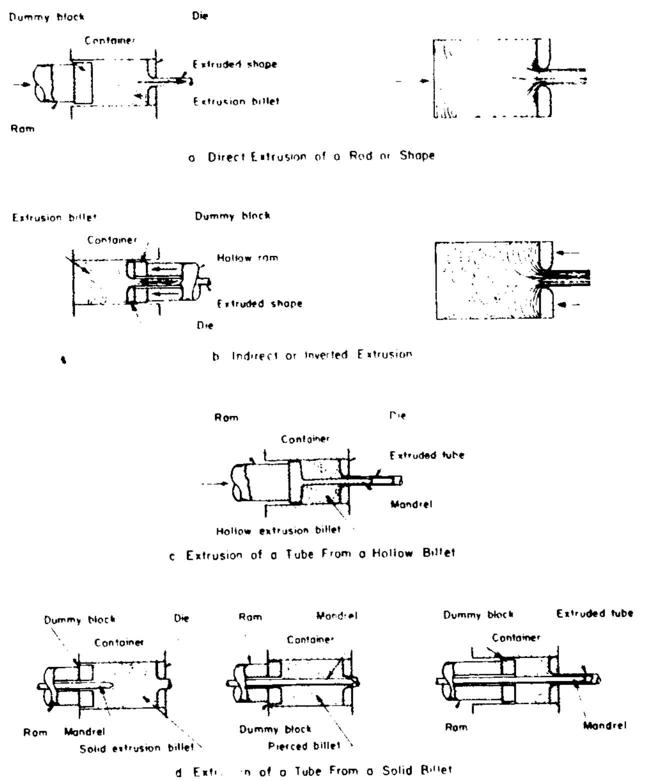


FIGURE 6. DIAGRAMMATIC REPRESENTATION OF DIFFERENT TYPES OF EXTRUSION PROCESSES (REF. 29)

ram moves through the container to force the billet material through a stationary die. The ram, billet, and extrusion all move in the same direction. In the "indirect" or "inverted" method of extrusion, a hollow ram and die move against a stationary billet causing the billet material to flow in an opposite direction through the die and ram. These processes are shown schematically in Figure 6 (Ref. 29). (Also included in Figure 6 are diagrams illustrating methods for tube extrusion.)

The indirect process requires lower pressures for extrusion since friction between the container and the billet is largely eliminated. The actual use of the process, however, is not widespread because of various physical limitations inherent in the operation.

Hydrostatic Extrusion. In conventional extrusion, significant contributions to the pressure required to extrude are (1) friction between the billet and the tools and (2) redundant work caused by nonuniform metal flow during extrusion. In hydrostatic extrusion, the effects of these factors can be minimized, thus permitting significant reductions in extrusion pressures.

The hydrostatic-extrusion process, shown in Figure 7, uses a pressurized fluid to force the billet through the die. Container-billet friction is eliminated and billet-die friction is reduced by improved lubrication resulting from the pressurized fluid. Since the die is enclosed in the pressure system, small-angle conical dies can be used without the need of massive support rings required in conventional extrusion. With small-angle conical dies, less redundant work (more uniform deformation) is obtained compared with flatter die designs.

Most of the research on this experimental process has been done at room temperature although temperatures as high as 850 F have been tried. In recent studies by Fiorentino (Ref. 30), Ti-6Al-4V alloy was extruded to a 1-inch-diameter rod at an extrusion ratio of 4:1 (75 per cent reduction). This was done at room temperature. A "T" section (1 x 3/4 x 1/4 inch thick) was extruded from the same alloy at 500 F and a ratio of 2.5:1 (60 per cent reduction).

This process shows considerable promise as a technique for working hard, brittle materials, particularly when the product is extruded against a fluid back pressure. The process may also be applicable for extruding materials which tend to be hot short.

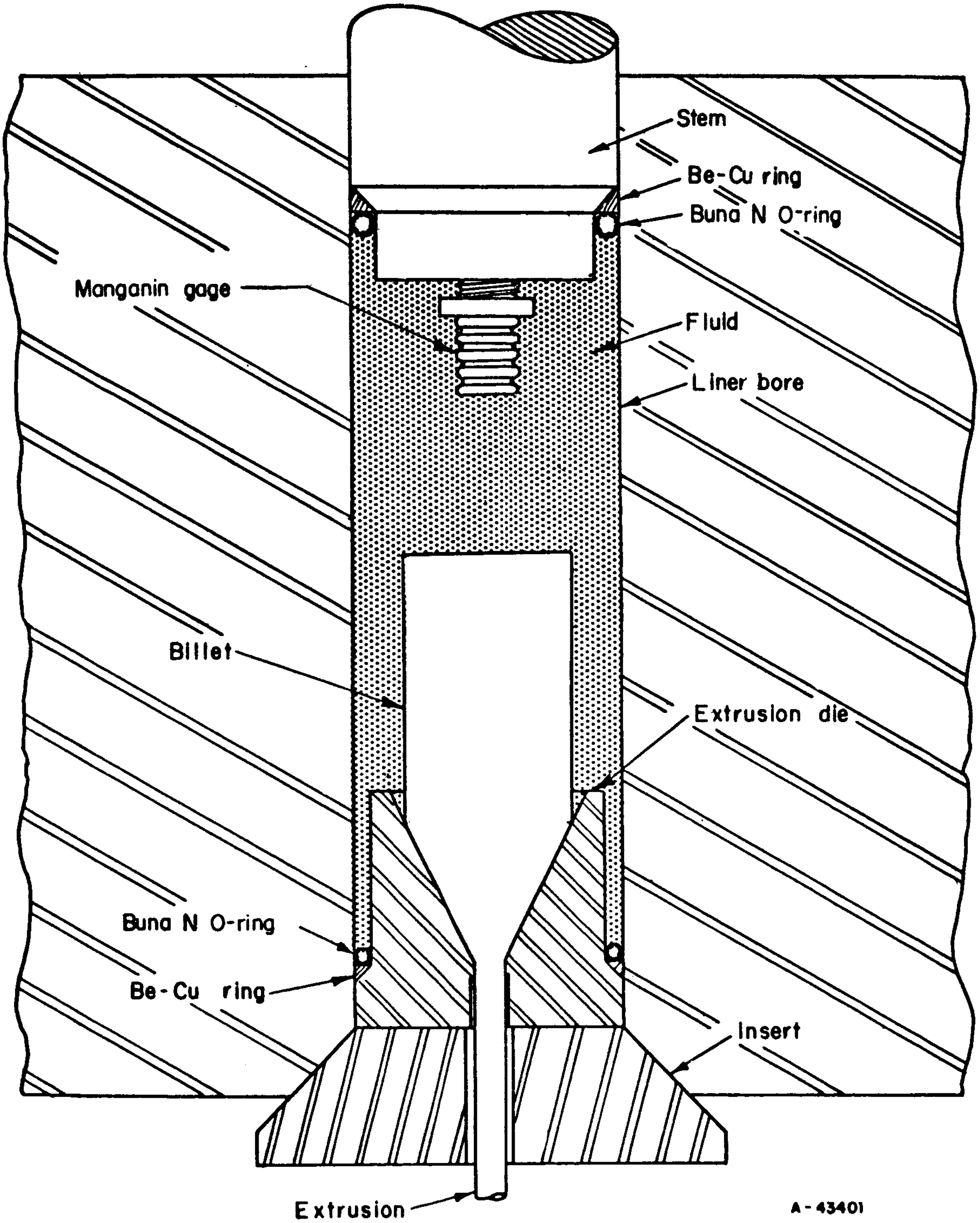


FIGURE 7. PRINCIPLES OF THE HYDROSTATIC-EXTRUSION PROCESS (REF. 30)

The application of force to the billet by a ram is actuated hydraulically or mechanically. Hydraulic presses are driven directly by high-pressure oil pumps or by hydropneumatic accumulators. Mechanical presses utilize the energy of electrically driven fly wheels. Idealized diagrams indicating the time-energy profiles characteristic of different types of presses, including the more recent pneumatic-mechanical types, are shown in Figure 8 (Ref. 31). From this diagram it can be seen that the major difference between the various types of presses is in the time interval in which the energy is delivered to the ram and, in turn, the workpiece.

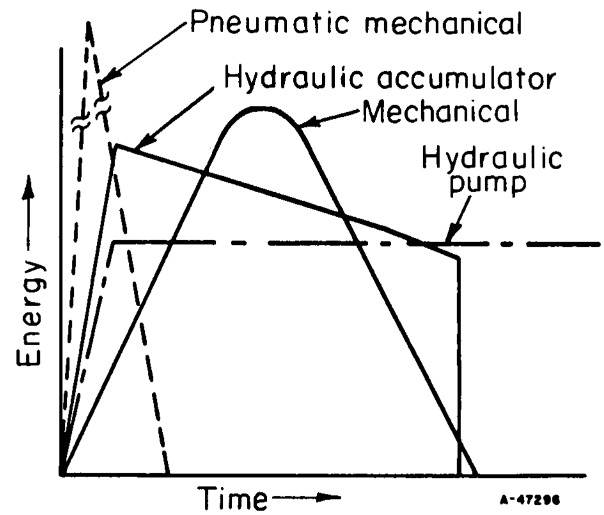


FIGURE 8. TYPICAL ENERGY-TIME CHARTS FOR VARIOUS TYPES OF PRESSES USED FOR EXTRUSION OPERATIONS (REF. 31)

Horizontal Presses. Horizontal presses are ordinarily used for hot-extrusion operations and are available with capacities up to 14,000 tons. The largest presses of this kind were built as a result of the U. S. Air Force heavy-press program. Presently in the United States there are nine of these heavy presses, ranging in capacity from 8,000 to 14,000 tons. The largest press equipped for titanium extrusion has a capacity of 12,000 tons.

The selection between pump-driven or accumulator-driven presses is primarily governed by the press capacity and the material being extruded. On the basis of press capacity only, the choice is one of economics. Direct-drive pumping systems are usually more economical for comparatively small presses (Ref. 32), and accumulators are used only where high ram speeds are necessary. For large presses of high capacity, e.g., 4000 tons or more, the economics generally favor accumulators whether high speeds are required or not. Thus, all of the heavy presses are driven by accumulator systems even though the ram-speed capabilities range from about 50 inches per minute to over 700 inches per minute.

When materials are taken into consideration, then the ram-speed requirement becomes a deciding factor in press selection. High ram speeds are required in high-temperature extrusion where there is a problem of heat transfer from the billet to the tools. This problem becomes increasingly critical with increasing billet temperatures. Accumulator-driven presses are used for commercial extrusion of titanium.

Vertical Presses. Vertical presses are preferred for producing small-diameter, thin-wall tubes. The design simplifies the solution to problems of alignment of tooling and securing fast production rates. The maximum capacities of such presses usually range from 650 to 2400 tons. The larger presses are also used for cold extrusion and operations resembling hot forging.

High-Energy-Rate Machines. Pneumatic-mechanical machines, powered by compressed gases, have also been used for extrusion (Ref. 33). The capacity of such equipment, controlled by the kinetic energy of the moving piston and ram, ranges up to 1.5 million foot-pounds. Striking velocities range up to 3600 inches per second. The high speed permits deformation under essentially adiabatic conditions and minimizes the time available for heat loss from the billet to the tooling.

However, the use of high-impacting speeds has an adverse effect on tool life and results in unusually high exit speeds. Sometimes the extrusion product is ruptured by the inertial force. A number of approaches have been tried, with limited success, for slowing down the extrusion product of high-energy-rate machines.

Extrusion Tooling. Tool steels used for extruding steel and nickel alloys are also used for titanium. The tool materials used for hot extrusion are available elsewhere (Ref. 34).

EXTRUSION PRACTICES FOR TITANIUM

The hot-extrusion process is employed for the production of long titanium sections. Some cold extrusion of titanium has been done (Ref. 35), but commercial applications of the process are not known.

Most extruders use the Sejournet glass process for titanium, using procedures similar to those developed for extruding steel. The high reactivity of titanium necessitates special care in heating to protect billet surfaces from contamination. Also important is the selection of proper glass compositions to prevent reaction between titanium and the glass.

The major differences in processing techniques used by titanium extruders center around such variables as lubrication, billet heating, die material and design, and extrusion speed.

Extrusion Lubricants. Lubrication of tool surfaces for extruding titanium, as with other metals that require high working temperatures, is essential to reduce friction between the billet and tools and to minimize tool wear. Because of the severe galling characteristics of titanium, lubrication is particularly important.

Ineffective lubrication not only causes titanium pickup on the die, but also excessive die wear with an accompanying loss of dimensional tolerance. Either of these conditions can produce deep scoring and tearing of the extruded surface.

Predominantly, two basic types of lubricants are used for extruding titanium: (1) greases containing solid-film lubricants such as graphite and (2) glass. Metallic copper coatings are also used by some extruders in conjunction with grease lubricants.

Grease. Most commercial hot-working lubricants are essentially a mixture of grease or oil and graphite. Other solid additives such as molybdenum disulfide, mica, talc, soapstone, and asphalt are also used in conjunction with graphite. Powdered-aluminum metal has been employed as an additive to grease lubricants. The more common greases are made up of various oils and a gelling agent - usually a soap of calcium, lithium, aluminum, or sodium, or a nonsoap derivative of bentonite clay.

Commercial grease mixtures offer little or no thermal protection to the die. Thus, die wear with the common die steels, most desirable from a cost viewpoint, limits their use.

Recent studies at TRW Inc. (formerly Thompson Ramo Wooldridge) (Ref. 36) have demonstrated that a mixture of magnesium metaborate and graphite in water shows considerable promise as an extrusion lubricant at temperatures as high as 3500 F. 4340 steel "T" sections were extruded at 1800 F. Mo-0.5Ti "T" sections were extruded at 3500 F. Surface finishes were good in both instances.

Glass. The use of glass as an extrusion lubricant, as in the Ugine-Sejournet hot-extrusion process, was originally developed by the Comptoir Industriel d'Etirage et Profilage de Metaux, Paris, France, for extruding ferrous materials. As glasses were found that could be employed at lower temperatures (1600 to 1900 F), the process was adopted for titanium and its alloys.

The practices employed by the American licensees of the glass process for extruding titanium are essentially identical. Billets are transferred from the heating furnace to the charging table of the extrusion press. As a billet rolls into position in front of the container, it passes over a sheet of glass fiber or a layer of glass powder that fuses to the billet surface. In addition, a fibrous glass pad is placed in front of the die, providing a reservoir of glass at the die face during extrusion.

For tubes, either a fibrous glass sock is placed over the mandrel or powdered glass is sprinkled on the inside surface of the hollow billet.

Besides providing effective lubrication, glass serves as an insulator to protect the tools from contact with the hot billet during extrusion. Excessive overheating of tools does not occur, tool life is increased, and die costs are reduced.

Billet Heating. It is necessary to maintain titanium billets as nearly scale-free as possible during heating. With grease lubricants, only a thin film separates the billet from the tools so a heavy oxide scale would be detrimental to effective lubrication and cause excessive tool wear. Under conditions of streamline metal flow, where the surface of the billet becomes the surface of the extrusion, excessive scale would also have an adverse effect on surface finish.

Since the lubricant film separating the billet and tools is thicker with glass, particularly at the die face, the primary effect of scale is to produce a poor surface finish rather than to cause tool wear. Many glasses in the molten state will react with the oxide scale, thereby altering the glass's thermal properties and viscosity, and rendering it unsuitable.

Babcock and Wilcox has employed various means for heating billets – salt bath, induction, and argon-atmosphere furnaces. Best results have been obtained in the muffle furnace under an argon atmosphere, the method currently employed. Cleaner billet surfaces (scale-free with no residual salt film) are achieved without sacrificing accurate and uniform billet temperature.

The use of low-frequency induction heating in an inert atmosphere also has been successful. This method offers flexibility, rapid heating, high efficiency, and is easily adapted for automatic operation. Scale formation is very slight because of the rapid heating rate and the use of inert atmospheres minimizes further oxidation.

Precise temperature control of induction heating was somewhat difficult to achieve in the past, but induction furnaces are now being built as either single or multistage units with preheat and high-heat coils that can be operated on a heat-and-soak cycle. Temperature control has been markedly improved, resulting in more uniform billet heating.

Die Design. Two basic types of metal flow occur during extrusion of titanium with lubrication:

(1) Parallel metal flow in which the surface skin of the billet becomes the surface skin of the extrusion

(2) Shear metal flow in which the surface skin of the billet penetrates into the mass of the billet and creates a stagnant zone of metal at the die shoulder, which is retained in the container as discard.

Shear flow is undesirable because it prevents effective lubrication of the die and can cause interior laminations and surface defects in the extruded product.

Modified flat-faced dies having a dish shape (re-entrant angle and radiused die entry) are satisfactory for extruding most simple structural shapes using grease lubricants.

In the glass-extrusion process, the die must be designed not only to produce parallel metal flow, but also to provide a reservoir of glass on the die face. The general design employed by companies licensed for the process is a flat-faced design with a radiused die opening. The combination of the glass pad on the die and uniform metal flow produces a conical entry into the die opening.

A study by Republic Aviation Corporation (Ref. 37) has shown that a 0.015-inch alumina coating on the die face is important in extruding thin-section shapes. The coating acts as a thermal barrier and prevents softening and die work.

Extrusion Speed. Titanium is now extruded on presses originally installed for aluminum, brass, or steel. Several companies have direct-drive presses with maximum ram speeds around 40 to 80 in./min. Others have accumulator-drive presses capable of maximum ram speeds of 300 to 700 in./min. Thus, extrusion speed (exit rate of extruded section) has varied in commercial practice from several hundred to several thousand in./min.

High extrusion speeds are preferred whether grease or glass is used as the lubricant. As grease lubricants offer little protection from the high extrusion temperatures, the hot billet should be in contact with the die for as short a time as possible. Contact with the container should also be brief in order to minimize cooling of the billet. Otherwise, serious variations in the structure and properties from front to back of the extrusions may occur.

The actual ram speed attainable during extrusion varies with alloy composition, extrusion temperature, and extrusion ratio, but is usually in the range of 200 to 300 in./min.

With glass acting as an insulator between billet and tools, these problems are not severe. However, the basic principle of glass lubrication - glass in a state of incipient fusion flowing continuously from a reservoir - requires high extrusion speeds. With low speeds the reservoir may be depleted before completion of the extrusion stroke, since the melting rate of the glass is a function of time.

Therefore, companies that use the glass process also employ high-speed presses. For example, the maximum ram speeds used by Babcock and Wilcox and Allegheny-Ludlum for titanium are in the range of 200 to 400 in./min.

Post-Extrusion Processing. The methods of processing after extrusion have differed considerably among various companies, mainly because of the differences in specifications between extrusions produced with glass and those produced with grease.

Straightening and detwisting are almost universal requirements for structural shapes, whether they be for airframes, engines, or any other application. Hydraulic torsional stretchers are usually employed, although some companies use roll- or punch-straightening machines.

Commercially pure titanium can be straightened either cold or hot with little difficulty, according to most extruders. Commercial alloys, however, are extremely difficult to cold straighten because of their high yield strengths and, particularly, because of springback. It has usually been necessary to straighten at temperatures of about 700 to 1000 F.

Before further processing, the glass adhering to the surface of shapes extruded by the glass process must be removed by quenching the hot extrusions, pickling, or shot blasting. Therefore, reheating is generally necessary before straightening and detwisting.

Although the major demand is for extrusions having ultimate strengths greater than 150,000 psi, heat treatment of long extruded shapes has been limited to annealing thus far. A problem not yet solved is the elimination of distortion and surface contamination during solution treating and quenching.

The annealing treatment employed by most extruders consists of heating for various lengths of time at temperatures of 1200 to 1400 F (depending on the alloy) followed by air cooling. Contaminated surface scale is removed by vapor blasting and pickling.

PROCEDURES FOR EXTRUDING THIN-SECTION SHAPES

The development of extrusion techniques for producing thin-section titanium alloys to aluminum airframe specifications has made considerable headway in recent years. Extrusion studies just concluded by Republic Aviation (Ref. 37) have demonstrated the ability to produce an RB-70 "T" section to desired specification by combining extrusion and warm drawing. Alloys investigated were Ti-6Al-4V, Ti-7Al-4Mo, and Ti-4Al-3Mo-1V. Figure 9 shows the extrusion technique that was used. Segmented dies sprayed with a 0.015-inch coating of alumina proved to be an important step in process development.

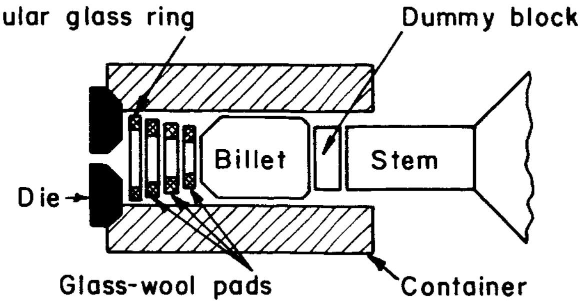


FIGURE 9. CROSS SECTION OF EXTRUSION PRESS SHOWING TECHNIQUES USED FOR PRODUCING THIN-SECTION SHAPES (REF. 37)

Note the granular glass ring and glass-wool pads that provide lubrication.

Extrusions having a 3/32-inch section thickness were warm drawn in 20-foot lengths to 0.080-inch thickness. Thickness tolerance of ±0.005 inch were met. Flange- and leg-length tolerances of ±0.005 inch could be met only by edge machining. Straightness requirements of 0.010 inch per foot of length; 1/2 degree per foot, 3-degree maximum twist, and ±1/2-degree angle were all realized. Surface finish of the extruded sections was 80 microinch rms, which was below the 100 microinch rms specification.

These same tolerance requirements were met with 0.043-inch-thick "T" sections that were warm drawn in five passes from 0.065-inch-thick extruded sections. Surface finishes of 115 microinch rms were achieved, however, just above the specified limits.

Subsequent studies along these same lines were made on the Ti-13V-11Cr-3Al alloy (Ref. 38). Eight full-length (15 to 30 foot) extrusions were made in 1/8-, 3/32-, and 1/16-inch cross-section thicknesses (extrusion ratios of 30, 50, and 80:1, respectively). Severe die wash was encountered and the alloy was sensitive to attack by the glass lubricants used on other titanium alloys. Thus, considerable research remains to develop extrusion techniques for this alloy.

All of the aforementioned programs have just been concluded and no thin-section titanium-alloy extrusions have been produced on a commercial basis. A new Air Force program is under way at Nuclear Metals (Ref. 39) to further develop the extrusion warm-drawing process developed by Republic Aviation.

DESIGN LIMITS AND TOLERANCES

Airframe manufacturers desire extruded titanium structural shapes of a quality comparable with aluminum extrusions with regard to surface and dimensional-tolerance specifications. Their major need is for shapes having minimum section thicknesses in the range of 0.040 to 0.125 inch. The greatest airframe demand would probably be for simple "alphabetic" shapes that would fit in a circumscribing circle 5-1/2 inches in diameter, in lengths up to 25 feet, and with minimum section thicknesses of about 0.040 inch; and an ultimate strength level of about 170,000 psi. Minimum radii, nonuniform section-thickness ratios, and surface and tolerance specifications desired are similar to the specifications for aluminum.

Currently titanium alloy extrusions of requisite quality for airframes are not commercially available. Table V contains typical standard manufacturing limitations and tolerances for steel and titanium as reported by Harvey Aluminum Company (Ref. 21).

The largest extrusion press equipped for hot extrusion of titanium in the United States is the 12,000-ton press operated by Curtiss-Wright Corporation, Buffalo, New York. Curtiss-Wright has extruded a variety of large titanium shapes on this press and is a major supplier (along with Harvey Aluminum) of titanium and titanium-alloy pipe. Curtiss-Wright has extruded such pipe up to 20 inches in diameter with wall thicknesses of 0.1 to 1.25 inches.

The product capabilities of extruding a particular material are peculiar to the press size in question, the metallurgical and mechanical properties of the material, and the overall economics involved in the process.

Increasing the cross-sectional area of the extruded part means a greater envelope, more weight per foot, and more machining. Decreasing the billet diameter means less pounds extruded per push and hence higher costs (the costs per push for operating the press remains the same).

Thus, a list of sizes of titanium and steel extrusions that are economical and competitive was established at Curtiss-Wright (Ref. 40) for the 12,000-ton press. The list is presented on page 36.

TABLE V. STANDARD MANUFACTURING LIMITATIONS AND TOLERANCES FOR TITANIUM AND STEEL EXTRUSION (REF. 21)

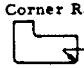
Manufacturing Limitations

Size Limitations

	Titanium	Steel
Circumscribing Circle Diameter: the diameter of the smallest circle that will completely enclose the cross section of the shape	7-in. maximum	7-in. maximum
Cross Sectional Area:	0.50-sq. in. minimum	0.50-sq. in. minimum
Finished Cutting Length:	20-ft maximum	17-ft maximum
Finished Weight Per Piece:	180-lb. maximum	300-lb. maximum

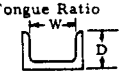
Dimensional Limitations

		Titanium	Steel
Section Thickness:		0.150-in. minimum	0.150-in. minimum
Corner Radii:		0.093-in. standard 0.062-in. minimum	0.093-in. standard 0.062-in. minimum
Fillet Radii:	Included angle (α) less than 70 deg	0.375-in. standard 0.250-in. minimum	0.375-in. standard 0.250-in. minimum
	Included angle (α) greater than 70 deg	0.250-in. standard 0.188-in. minimum	0.250-in. standard 0.188-in. minimum


Corner

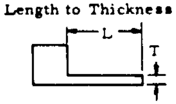
Design Proportions

Tongue Ratio



Tongue width (W) should be equal to or greater than tongue depth (D) $\frac{W}{D} = \frac{1}{1}$

Leg Length to Thickness Ratio:



Leg length (L) should not exceed 14 times the leg thickness (T) $\frac{L}{T} = \frac{14}{1}$

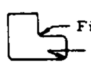
Tolerances

Cross-Sectional Tolerances

Dimensions:

Specified Dimension, inches	Tolerance, inches
Up thru 1.999	±.030
2.000 thru 2.999	±.040
3.000 and up	±.050

Corner and Fillet Radii:

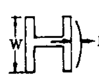


Radii	Tolerance
Corner	±0.025 in.
Fillet	±0.062 in.

Angles

Specified Leg Thickness (T)	Angular Tolerance (α)
Less than 0.250 in.	± 2 deg
0.250 in. and over	± 1-1/2 deg

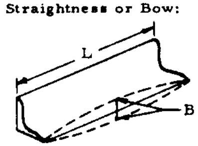
Transverse Flatness:



Allowable deviation (D) from flat:
0.010 in. per inch of width (W)
0.010 in. minimum on dimensions less than 1 in.
D = 0.010 in. x W (inches),
0.010 in. minimum

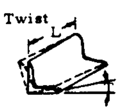
Longitudinal Tolerances

Straightness or Bow:



Maximum allowable bow (B) in inches: 0.025 inch per foot of length (L)
B = 0.025-in. x L (ft)

Twist



Maximum allowable twist (T) in degrees:
1 deg per foot of length (L);
5 deg maximum = 1 deg x L (ft).
5 deg maximum

Length:

Tolerance in cutting length = ±1/4 in. -0.00 in.

Surface Finish

Roughness:
Maximum roughness = 250 rms (this value is used as a guide only since rms standards are established primarily for machined surfaces and may not be directly applicable in all respects to extruded surfaces)

Local Defects:
Local defects, such as gouges, dents, handling marks, and linelaps, may extend a maximum of 0.015 in. below the minimum dimensional tolerance

Diameter, inches		Minimum Area, sq in.			Minimum Thickness, inch		
Container	Circumscribing Circle	Carbon Steel	Stainless Steel	Titanium	Carbon Steel	Stainless Steel	Titanium
14	6 to 8	4	5	5	0.090	0.150	0.250
16	8 to 10-3/4	5	6	6	0.125	0.250	0.312
20	10-3/4 to 12-1/2	14	18	28	0.125	0.312	0.375
26	12-1/2 to 16-1/2	31	40	106	0.250	0.438	0.562
28	16-1/2 to 20-1/2	50	--	--	0.312	0.500	0.750

FORGING

INTRODUCTION

Titanium parts as large as 5 feet in diameter and as heavy as 1500 pounds have been forged in production quantities. Applications include rocket motor cases (Ti-6Al-4V), motor-case end closures (Ti-13V-11Cr-3Al), helicopter rotor hubs (Ti-6Al-4V), pressure vessels, and a variety of aircraft structural components. Figures 10 and 11 show some of the intricate designs that have been fabricated in titanium alloys (Ref. 41).

CLASSIFICATION OF FORGING PROCESSES

The general term "forging" covers a variety of processes for producing metallic parts by plastic deformation in presses, hammers, or forging machines. The primary force in forging is compressive, but bending, twisting, indenting, or extrusion forces may also be employed. The most common types of forging operations are summarized in Table VI (Ref. 42). The principles employed in some of these forging operations are shown in Figure 12 (Ref. 42).

Forgings are often classified as having been made in either open flat dies or in closed impression dies. The differences between the two methods are characterized as follows:

Open-Die Forging	Closed-Die Forging
(1) Highly localized forces employed	(1) Forces exerted on all surfaces of the workpiece
(2) Ingots or billets deformed to relatively simple shapes	(2) Produces complex shapes with close dimensional control
(3) Commonly used for initial breakdown operation	

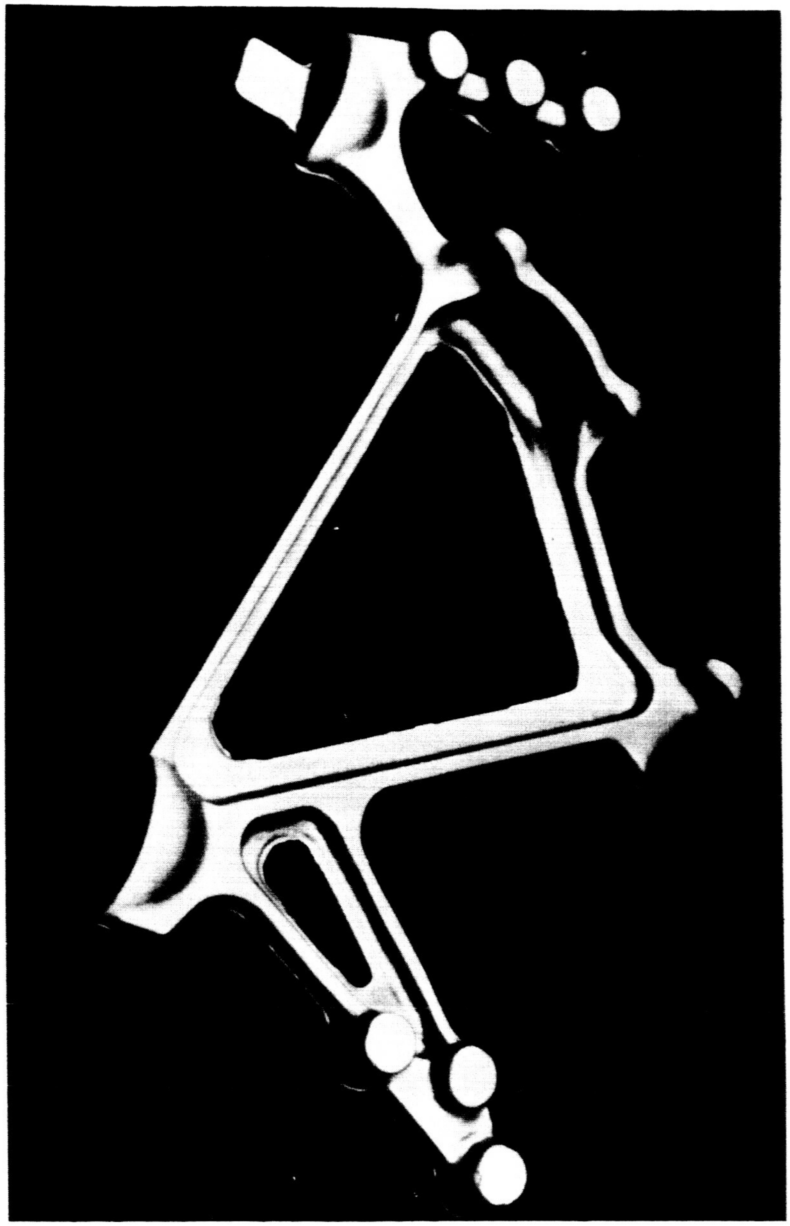
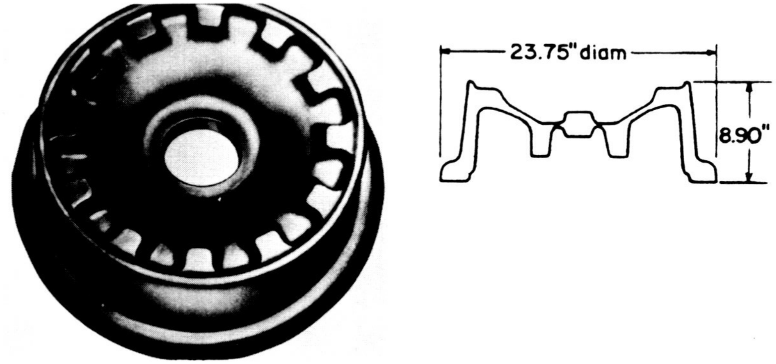


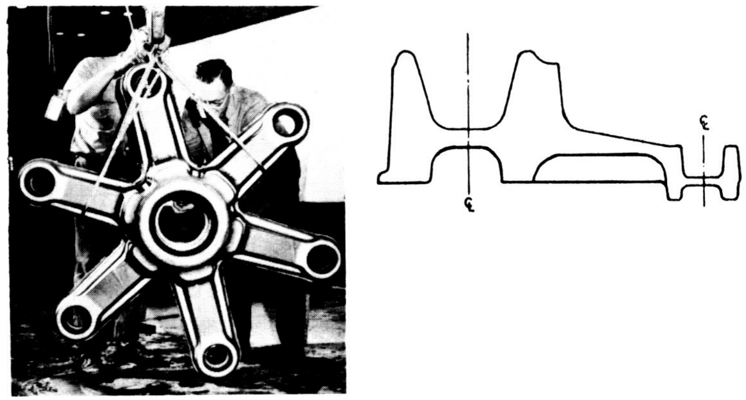
FIGURE 10. FORGED TI-6Al-4V ALLOY JET-ENGINE SUPPORT (REF. 41)

Heat Treatment	1300 F (2 hr), air cooled
Ultimate Tensile Strength, 1000 psi	135.2-155.8
Yield Strength, 1000 psi	127.2-148.3
Elongation, per cent	14-18
Reduction in Area, per cent	36.6-43.0



a. Aircraft Wheel

Heat Treatment	1750 F (1 hr), water quenched + 1300 F (4 hr), air cooled
Weight, lb	775
Ultimate Tensile Strength, 1000 psi	138.6-152.8
Yield Strength, 1000 psi	125.2-141.4
Elongation, per cent in 4 dimension	10-16
Reduction in Area, per cent	25.3-41.9



b. Helicopter Roter Hub

FIGURE 11. COMPLEX FORGED TITANIUM SHAPES (REF. 41)

Ti-6Al-4V Alloy.

TABLE VI. DESCRIPTION OF AND MACHINERY USED FOR SEVERAL COMMON TYPES OF FORGING OPERATIONS (REF. 42)

Type of Forging	Method of Operation	Commonly Used Machinery
Upsetting	Compression in the longitudinal axis of the work	Single-action and counterblow hammers Upsetting machines Hydraulic, air, and mechanical presses High-energy-rate machines
Drawing out	Stretch out of the work by a series of upsets along the length of the workpiece	Single-action hammers Hydraulic and air presses
Die forging	Compression in a closed, impression die	Single-action and counterblow hammers Hydraulic and mechanical presses High-energy-rate machines Impacters
Ring rolling	Radial compression on a ring shape to increase diameter	Ring-rolling mills Hammers and presses with supported mandrel
Swaging	Circumferential compression to lengthen a workpiece	Swaging machine Single-action hammers Air and hydraulic presses
Core forging	Displacing metal with a punch to fill a die cavity	Multiple-ram presses
Extrusion forging	Forcing a metal into a die opening by restricting flow in other directions	Hydraulic and mechanical presses Multiple-ram presses High-energy-rate machines
Back extrusion	Forging with a punch and forcing metal to flow opposite to the punch direction	Single-action and counterblow hammers Hydraulic and mechanical presses Multiple-ram presses High-energy-rate machines

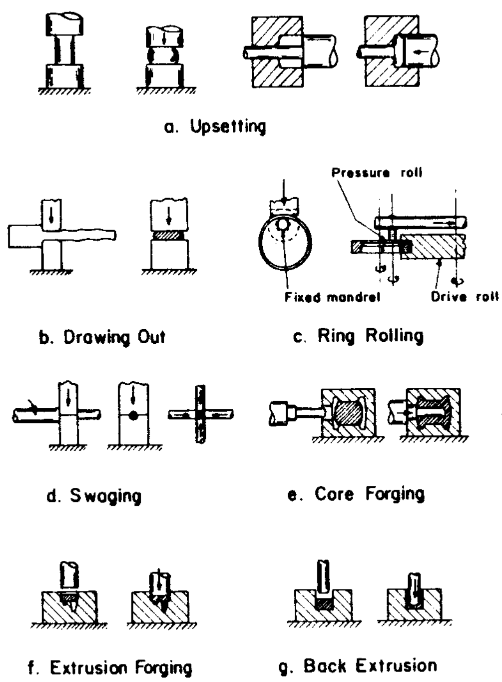


FIGURE 12. PRINCIPLES OF SEVERAL TYPES OF FORGING OPERATIONS (REF. 42)

The forces required for forging depend on (1) properties of the workpiece and (2) frictional forces between the die and the workpiece. Therefore, such operations as upsetting, drawing out, swaging, and ring rolling require relatively small tool forces since there is limited metal confinement and frictional forces are not high. Conversely, high forging pressures are required in extrusion forging, core forging, or die forging where metal confinement is much greater.

FORGING EQUIPMENT

Forging equipment can be described on the basis of the types of shape changes that can be produced and on the deformation rate that can be obtained. Metallurgically, the latter is most important. Although equipment types differ mechanically, they all accomplish the forging operation by either steady or repeated applications of force. Equipment manufacturers are the best source of information for detailed equipment capabilities.

Hammers, forging machines, and presses represent the three types of equipment used in forging. Detailed equipment capabilities are available elsewhere (Refs. 31,42). Only brief descriptions of each will be presented here.

Hammers (Ref. 31). A simple drop hammer depends on gravity for its force, with the falling hammer or ram being controlled by vertical guides. Except for machines assisted by pressurized air or steam behind the ram (sometimes termed double acting), drop hammers are rated according to the weight of the falling ram. Production sizes of single-action drop hammers range from 500 pounds to a 50,000-pound steam hammer. Ram or striking velocities of hammers are usually of the order of 12 to 20 feet per second. During the forging operation, the ram strikes the workpiece rapidly and repeatedly to shape the metal in a stepwise fashion. Dies attached to the ram and anvil may be flat or contain cavities suitable for producing closed-die forgings.

Counterblow hammers were developed to avoid the necessity for the heavy bases characteristic of single-action drop hammers. They employ two opposed rams moving along the same axis, usually horizontally, to deliver a sharp blow to stock placed between them. The rams are driven by steam pressure at velocities about 50 per cent faster than normal drop-hammer speeds. The ratings of counterblow hammers are based on the weights and combined striking velocities of the opposed steam-driven rams. Therefore, the counterblow principle increases the energy available for hammer forging without necessarily requiring a heavier ram.

Upsetters or Forging Machines (Ref. 31). Mechanically powered, double-acting, horizontal machines are used for mass production of parts ranging from 1/2-inch bolts to 12-inch flanged pipe. Forging machines are rated by the size of the stock they will handle in normal upsetting operations. A typical machine designed for 5-inch rounds will have a 15-inch stroke and operate at about 30 rpm or strokes per minute.

Forging machines are often called headers or upsetters because they are commonly used for enlarging the ends of bars. Upsetters are widely employed for both hot- and cold-forging operations.

Simple forgings like rivets can be made in one operation on an upsetter or heading machine; multiple operations, usually three or four, are more common. Multiple operations are conducted sequentially, with die blocks containing several cavities, by moving the stock from one impression to another after each stroke. Forging machines can be fed with rods or with blanks cut to length. They will produce parts with short shanks, with pierced holes, or long parts with forged ends.

Presses (Ref. 31). Since presses deliver a push rather than a sharp blow they produce less-severe shock loads on the dies or tools. Both hydraulic and mechanically actuated presses are used for forging.

Ram speeds are low compared with hammers, up to about 0.15 feet per second.

The pressure exerted by hydraulic presses is supplied by large pistons driven by high-pressure hydraulic or hydropneumatic systems. The direct-drive type is pressurized by oil or water supplied by high-pressure pumps. The hydropneumatic presses are operated by fluid supplied from accumulators that are pressurized by high-pressure pumps. Larger presses are of this type.

The direct-drive type of press is capable of maintaining the maximum pressure at all stages of the forging cycle. With a hydropneumatic system, the accumulator pressure may drop enough to lower the capacity of the press as the ram advances.

Hydraulic presses are made in a wide variety of sizes. Production forging presses ordinarily range in capacity from 200 to 15,000 tons; the two largest presses in this country are rated at 50,000 tons.

Some hydraulic forging presses have more than one movable ram. In double-acting presses the rams move coaxially. In many specialized applications, multiple-rams operating in different directions offer advantages over drop hammers or single-acting presses.

Mechanically driven, vertical presses are used to produce a wide range of small- and medium-sized forgings. Power, supplied by a motor-driven rotating fly wheel, is usually transferred to the ram by cranks, cams, or eccentrics. They are made in capacities up to 6000 tons for forging in impression dies. Since fast-acting presses normally have comparatively little space between the ram and anvil, they are best suited to forging shallow profiles. In many mechanical presses, the force exerted on the work decreases toward the end of the stroke. This can be a disadvantage compared with hydraulic presses. Ram speeds usually range from 0.10 to 0.35 feet per second. The ram speeds on mechanical presses are ordinarily a little higher at the start and lower at the end of the stroke than those typical of hydraulic presses.

A recent development in special metal-forming equipment has been the high-energy rate machines such as the Dynapak. This machine is powered by compressed gases and develops ram speeds in the order of 75 feet per second. Relatively small parts have been forged on this equipment to very close tolerances.

With titanium, either hammers or presses may be used, with hammers being preferred for forgings containing thin sections. With the high-strength beta alloy, hammers are not generally used since the high-working-pressure requirement limits the amount of deformation obtainable with each hammer blow.

FORGING OF TITANIUM ALLOYS

Initial breakdown forging of titanium-alloy ingots is usually done at temperatures above the beta transus because the body-centered cubic structure is more ductile, and forging-pressure requirements are generally lower. Final forging is usually done at temperatures below the beta transus to prevent excessive beta-grain growth and attendant low ductility. In general, a 50 per cent forging reduction should be made below the beta transus to ensure optimum properties in the forged piece. Forging characteristics of titanium alloys are presented in Table VII (Ref. 41).

Variations in strain rate have little influence on the forgeability of alpha and alpha-beta alloys; both alloy types are readily forgeable in either presses or hammers. The B120VCA beta alloy also exhibits good forgeability in both presses and hammers when forged above 1400 F. However, when forged just below 1400 F, the alpha phase begins to precipitate, and the alloy is more susceptible to cracking, particularly in drop hammers. For reasons of mechanical-property control, this alloy is frequently forged in the lower temperature range, but the reductions are small; hence, the reduced forgeability does not present a major problem.

The marked effect of temperature on the forging pressure of Ti-6Al-4V is characteristic of titanium alloys in general. Figure 13 (Ref. 42) shows how the forging pressure for each of the three types of titanium alloys increases more rapidly with decreasing temperature than does that of low-alloy steels. Thus, in ordinary die-forging operations, cooling of the workpiece has a more critical effect on raising forging pressures of titanium than of steels.

Since titanium alloys exhibit rapidly increasing strengths with increasing strain rate, more energy is required for hammer forging than for press forging at comparable temperatures. The B120VCA alloy at 1450 F, for example, requires nearly 50 per cent more energy at a typical hammer velocity of 200 in./sec than at a typical press at velocity of 1.5 in./sec. For equal reductions, the energy required for forging B120VCA at hammer velocities at 1450 F is nearly four times that for AISI 4340 at 2300 F.

ALLOY CHARACTERISTICS IN FORGING

Alpha-Beta Alloys. The principal feature of the alpha-beta alloys is their ability to be heat treated to high-strength levels. These alloys have been the most widely used of all titanium alloys. Both the 6-4 and 6-6-2 alloys have excellent forgeability.

The general influence of forging temperature on the room-temperature mechanical properties of alpha-beta alloys is illustrated in Figure 14 (Ref. 42). When forged above the beta transus, the alloys exhibit coarse beta grains with attendant low ductility and widely varying strength properties. Improved ductility and more uniform strength properties are obtained when the alloys are forged below the beta transus.

TABLE VII. FORGING CHARACTERISTICS OF TITANIUM ALLOYS (REF. 41)

Alloy	Type	Alpha Transus, ±25 F	Beta Transus, ±25 F	Die Forging Range, F	Required Pressure[a], 1000 psi	Resistance to Cracking
Commercially pure	Alpha	1660	1760	1550-1700	65-75	--
Ti-5Al-2.5Sn	Alpha	1735	1900	1775-1850	75-85	Fair to good
Ti-8Al-1Mo-1V	Alpha-Beta	1700	1900	1775-1850	75-85	Fair
Ti-5Al-5Sn-5Zr	Alpha	1715	1815	1700-1800	75-85	Poor
Ti-7Al-12Zr	Alpha	1710	1825	1700-1800	75-85	Fair to good
IMI-679	Alpha-Beta	--	1750	1650-1725	75-85	Fair to good
Ti-6Al-4V	Alpha-Beta	--	1820	1650-1800	75-85	Good
Ti-6Al-4V ELI[b]	Alpha-Beta	--	1820	1650-1800	75-85	Good
Ti-6Al-6V-2Sn	Alpha-Beta	--	1735	1575-1675	65-75	Excellent
Ti-7Al-4Mo	Alpha-Beta	--	1840	1680-1825	75-85	Fair to good
Ti-4Al-4Mn	Alpha-Beta	--	1700	1500-1650	65-75	Good
Ti-13V-11Cr-3Al	Beta	--	1325	1600-1800	85-100	Excellent

(a) For forging in hydraulic press.
(b) Extra low interstitial.

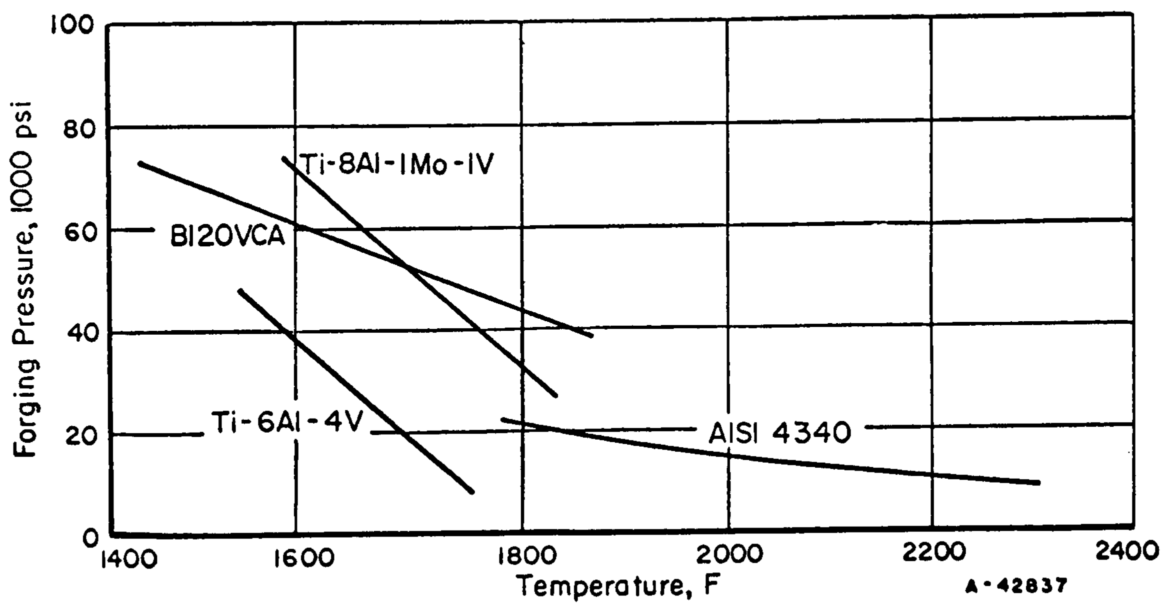


FIGURE 13. COMPARATIVE INFLUENCE OF TEMPERATURE ON THE FORGING PRESSURE OF TITANIUM ALLOYS AND LOW-ALLOY STEELS (REF. 42)

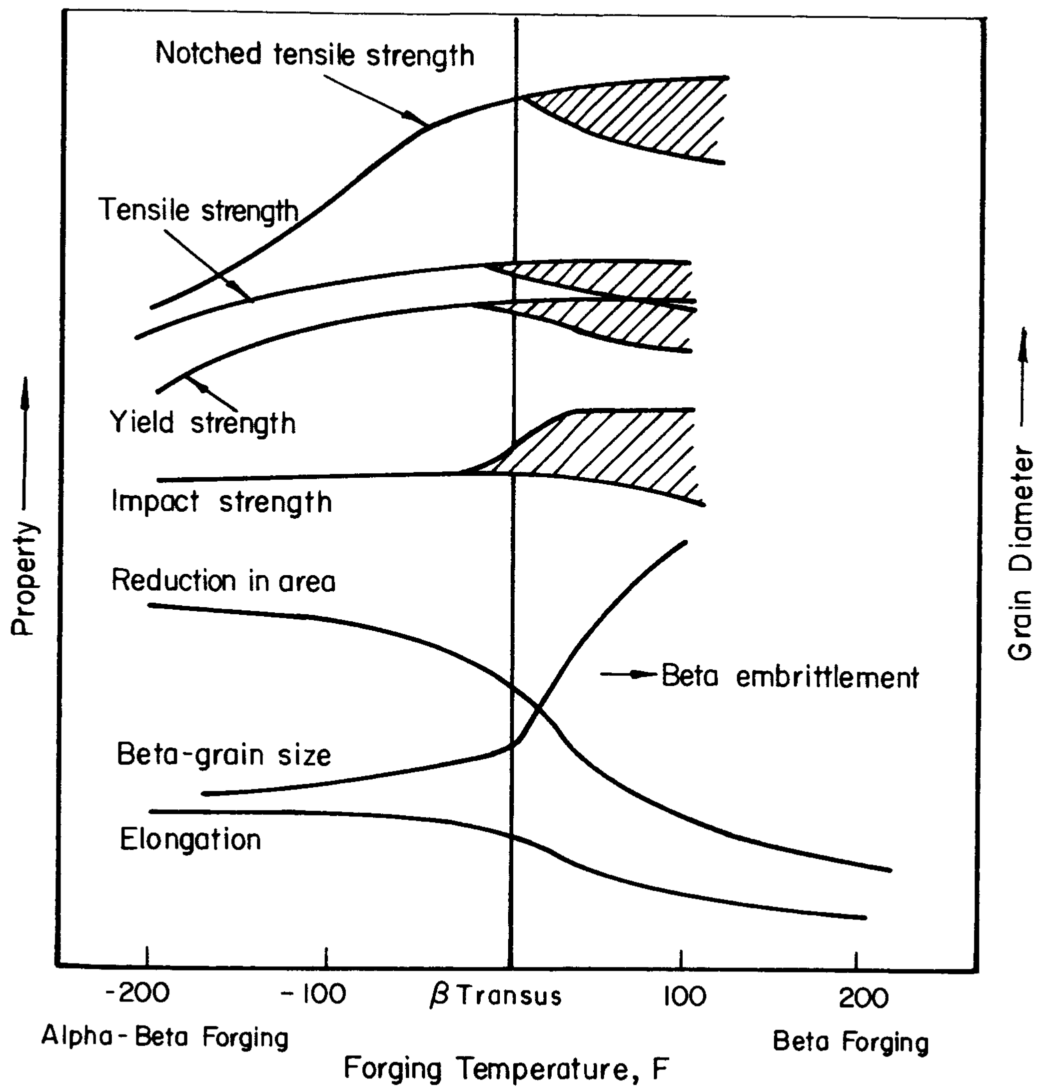


FIGURE 14. GENERALIZED INFLUENCE OF FORGING TEMPERATURE ON BETA-GRAIN SIZE AND ROOM-TEMPERATURE MECHANICAL PROPERTIES OF FORGED ALPHA-BETA ALLOYS (REF. 42)

Shaded areas indicate erratic behavior of beta-forged alloys.

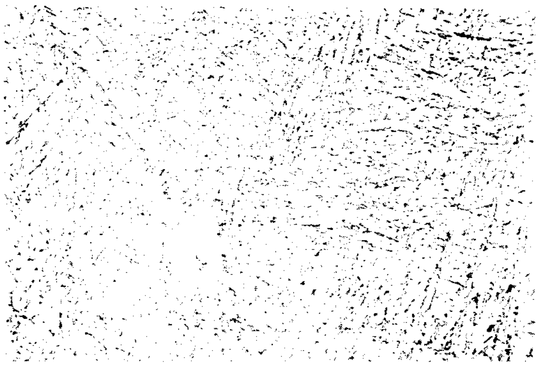
This behavior is related to the physical characteristics of two-phase alloys. On heating above the beta transus, alpha-beta alloys transform completely to the beta phase. On cooling from the beta region, the beta decays or transforms partially to alpha, which takes on the classical acicular shape normal to such systems. If the beta-to-alpha transformation occurs during deformation, the alpha separating from the beta takes on an equiaxed grain structure (primary alpha). This is because the alpha repeatedly recrystallizes and undergoes grain growth at the expense of the transforming beta. However, if deformation is completed before the beta transforms to an equilibrium amount of alpha, the remaining beta transforms to the acicular alpha structure. Figure 15 (Ref. 42) illustrates the various typical structures obtained by forging at temperatures above and below the beta transus.

The relative amount of equiaxed alpha in the microstructure has an important influence on the ductility and notch sensitivity of alpha-beta alloys. Reduction in area increases with increasing percentages of equiaxed alpha; but the notch sensitivity (notched/unnotched-tensile-strength ratio) decreases. The best combination of properties is obtained when the structure contains about 20 to 30 per cent equiaxed alpha (Figure 15b). To achieve this structure, it is necessary to forge at temperatures about 100 F below the beta transus.

Thus, with material that has a prior beta structure it is important that a sufficient amount of work be done 100 F below the beta transus to obtain the desired microstructure. At least a 50 per cent reduction at this temperature is reportedly required to restore optimum room-temperature ductility in beta-embrittled Ti-6Al-6V-2Sn alloy.

<u>Alpha Alloys</u>. Alpha-titanium-alloy forgings are used when both good weldability and good elevated-temperature stability are required. Alpha alloys are not heat treatable.

As the name implies, all-alpha alloys are those that contain alpha-stabilizing elements and are essentially all alpha at room temperature. When heated, they retain the same structure until about 1750 F (alpha transus) where beta begins to form. The alloys transform completely to beta at about 1950 F (beta transus). Like the alpha-beta alloys, the alpha alloys are generally forged in this alpha-beta range because forgeability is good and optimum room-temperature ductility is obtained. Forging below the alpha transus is usually complicated by shallow surface rupturing and increased

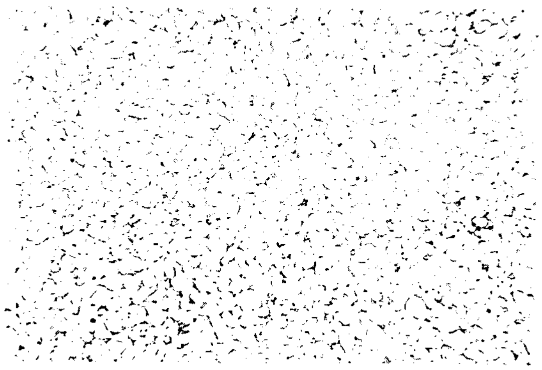


500X N32240

a. Forging Completed Above Beta Transus (Acicular Alpha)

500X N41095

b. Forging Completed About 100 F Below Beta Transus (About 30 Per Cent Equiaxed Alpha)



500X N32241

c. Forging Completed About 200 F Below Beta Transus (About 80 Per Cent Equiaxed Alpha)

FIGURE 15. TYPICAL MICROSTRUCTURES OF ALPHA-BETA ALLOYS FORGED AT TEMPERATURES ABOVE AND BELOW THE BETA TRANSUS (REF. 42)

Structures shown are for the Ti-6Al-4V alloy.

forging-pressure requirements. Forging above the beta transus causes beta embrittlement, but to a lesser extent than in the case of alpha-beta alloys.

Beta Alloys. At the present time, there is only one all-beta forging alloy in commercial production, namely, Ti-13V-11Cr-3Al. A great deal of attention has centered around this alloy because it is capable of tensile strengths of over 200,000 psi. Particularly attractive to the consumer is the fact that the alloy can be forged, machined in the soft condition, and then aged to yield strengths of over 180,000 psi.

Compared with the other titanium alloys, the all-beta alloy is the most sensitive to fabrication history. The general influence of forging temperature on the room-temperature mechanical properties of the Ti-13V-11Cr-3Al beta alloy (B120VCA) is illustrated in Figure 16 (Ref. 42). Characteristic of other single-phase-alloy systems, the beta-titanium alloy exhibits decreasing ductility with increasing grain size, and increasing strength with increasing amounts of cold work. Although the alloy recrystallizes at about 1400 F, cold work is retained after forging at temperature as high as 1600 F. When cold work is retained, precipitation of the alpha phase occurs more rapidly and evenly during subsequent aging. This shortens the aging time needed to achieve a given strength level with good ductility. After forging at temperatures above about 1600 F, longer aging times are required, and the alpha precipitate concentrates at the grain boundaries, causing low ductility.

The beta alloy has a potential yield-strength capability exceeding 200,000 psi. However, at these higher strengths, the alloy is quite brittle and exhibits elongation values consistently below 5 per cent. For this reason, most investigations have concentrated on achieving a yield-strength level of about 180,000 psi, where higher elongation values may be expected. Even at this strength level, careful control of forging temperatures and reductions is important for controlling aging response and, hence, mechanical properties.

PROCESS CONTROLS IN FORGING TITANIUM ALLOYS

There are a number of factors that make titanium alloys more difficult to forge than steels. The metallurgical behavior of the alloys not only imposes certain controls and limitations on the forging operation but influences all of the steps in manufacturing forged parts. Particular care is necessary throughout the processing cycle to avoid

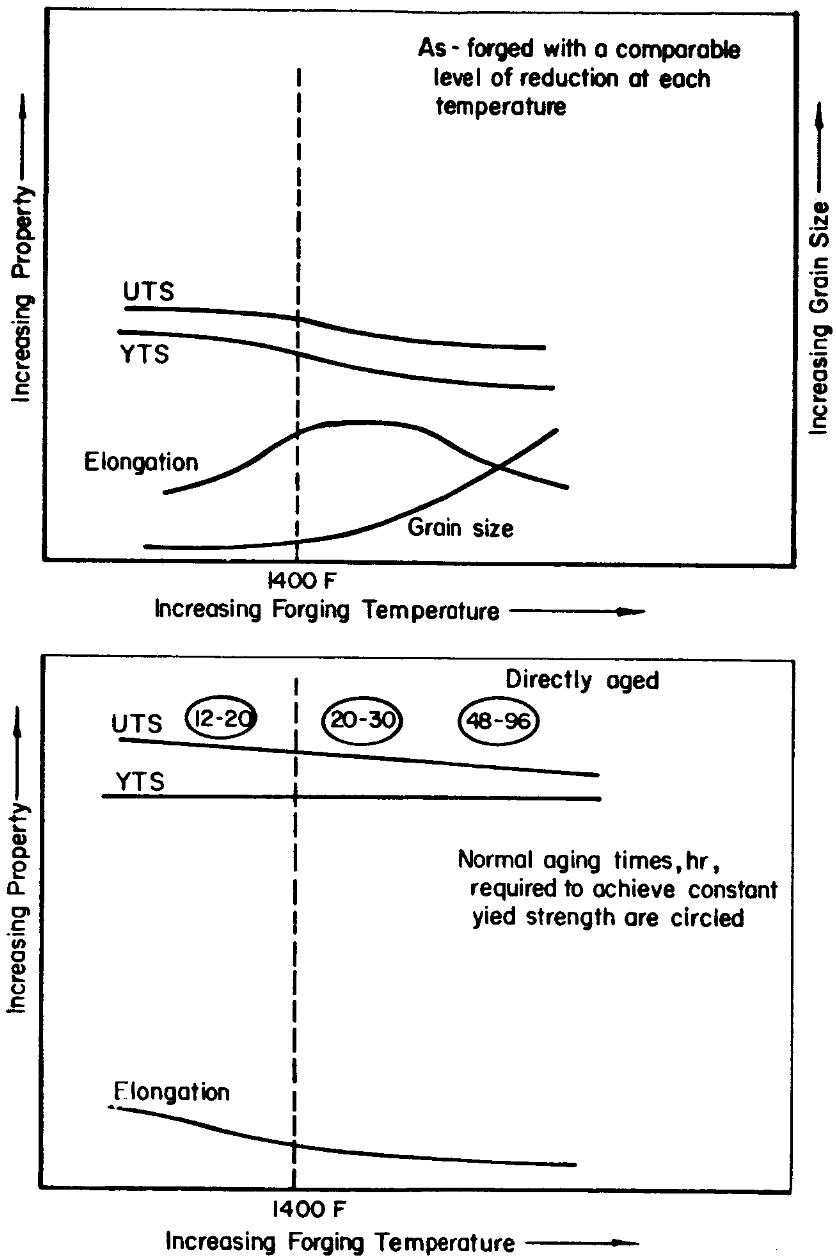


FIGURE 16. GENERALIZED INFLUENCE OF FORGING TEMPERATURE ON ROOM-TEMPERATURE MECHANICAL PROPERTIES OF B120VCA BETA ALLOY IN THE AS-FORGED AND AGED CONDITIONS (REF. 42)

Typical effect of forging temperature on grain size shown for as-forged condition.

contamination by oxygen, nitrogen, carbon, and/or hydrogen, which can severely impair the properties and overall quality of a forged part.

Composition Sensitivity. The forging behavior and mechanical properties of individual titanium alloys are not very sensitive to variations in metallic alloying elements. However, both of these factors are influenced significantly by variations in interstitial elements (e.g., oxygen, nitrogen, and carbon). An increase from 0.1 to 0.2 per cent oxygen, for example, will raise the beta transus of the Ti-6Al-4V alloy as much as 75 F and increase the strength level by as much as 15 per cent. The influence of oxygen content on mechanical properties is illustrated below for two forging alloys:

Alloy	Typical Tensile Strength, psi, at Indicated Oxygen Levels		
	0.10%	0.15%	0.20%
Ti-6Al-4V (annealed)	135,000	147,000	155,000
Ti-13V-11Cr-3Al (aged)	190,000	205,000	214,000

Increased carbon and nitrogen contents cause similar but less noticeable changes in strength.

Heating. At temperatures above about 1000 F, oxygen and nitrogen react with titanium to form an adherent surface scale and a hard, alpha-rich subsurface layer. The subsurface layer is brittle even at forging temperatures and can cause rupturing during forging. The alpha alloys are particularly sensitive to this, and forgings of these alloys sometimes require frequent in-process grinding operations. When the beta alloy is forged above about 1800 F, it exhibits the same characteristics.

When hydrogen is absorbed at forging temperatures, it diffuses inward, raising the hydrogen content of the entire forging. In extreme cases, this can lead to hydrogen embrittlement. Thus, when titanium alloys are heated for forging in conventional oil- or gas-fired furnaces, slightly oxidizing atmospheres are preferred to minimize hydrogen pickup. However, direct impingement of flame on the metal should be avoided. A muffle-type furnace with baffles is preferred.

Extreme care must be taken in using protective atmosphere furnaces. Their use is sometimes necessary for parts having extremely thin sections that require multiple heating operations. However, water vapor may be present with this type of atmosphere and could cause severe hydrogen pickup. Preheating and "gettering" of the protective gases would reduce the moisture problem.

Stock is usually preheated to about 1300 F and then heated to the forging temperature and forged as quickly as possible. Preheating avoids thermal-stress cracking as a result of too rapid heating while minimizing the time the metal is at forging temperature. By minimizing the time at forging temperature, surface contamination and grain growth are avoided.

Removal of Contaminants and Defects. The hard, alpha-rich subsurface layer produced by heating titanium in air is difficult to machine. Depending on heating times, the layer ordinarily ranges in thickness from 0.005 to 0.025 inch. Pickling forgings in hydrofluoric acid (2 to 3 per cent aqueous solution) will remove the layer at a rate of about 0.001 inch per minute. To minimize hydrogen contamination from the acid bath, the solution is usually modified with about 20 to 30 per cent nitric acid. This retards the metal removal rate by about 50 per cent.

The heavy scales formed at temperatures above 1000 F may require a double treatment to effect removal. Descaling in a molten salt bath (molten sodium hydroxide and sodium hydride, nitrate or chloride) precedes the acid pickling process above.

Surface defects are always removed by machining or grinding since exposed cracks or defects in titanium will not heat during forging. A torch should never be used on titanium. Care must be taken in cold grinding to prevent localized overheating which can cause grinding cracks. If considerable conditioning is required, the billet or forging should be ground while still hot (600 to 1200 F) or reheated before grinding.

Equipment Cleanliness. While forging titanium, care should be taken to prevent contact with steel scale. A "thermite" type reaction can occur, which can ruin a forging die. Apparently, the titanium reduces iron oxide in an exothermic reaction set off by the conditions of pressure and high temperature. This reaction is known in forge shops as "firing". Furnace hearths and the forging equipment may be sources for steel scale and should be cleaned thoroughly before using for heating titanium.

Lubrication. The adherent scale formed on titanium billets during heating is abrasive and causes dies to wear at rates considerably faster than for comparable steel forgings. The use of glass-type billet coatings for titanium alloys has reduced die wear to about the same level as for stainless steels. The glass-type coatings provide a two-fold advantage of reducing oxidation and providing lubrication. Other common die lubricants are colloidal graphite and the soot from partially burned kerosene. Those lubricants are often applied by spraying, especially for parts forged in intricate die cavities. Swabs are used for simple shapes like disks and blades.

CLASSIFICATION OF STEEL- AND TITANIUM-DIE FORGINGS BY SHAPE AND DESIGN TOLERANCES

Configurations of titanium forgings can be classified broadly as follows: (1) rib-and-web structural shapes, (2) forged rings, and (3) disk shapes. Certain of these general shapes lend themselves to higher degrees of dimensional precision than do others during forging.

The ASM Committee on Forgings has developed a series of "commercial tolerances for steel forgings", classified into four distinct tolerance groups: (1) blocker type, (2) conventional, (3) close tolerance, and (4) precision. These are listed below for comparison with present-day titanium forging tolerances, which are listed later on in this section.

Blocker-Type Designs. Blocker-tolerance forgings are usually produced from one set of dies and conform to the general shape of the final part. Adequate machining stock is present so that surface defects may be removed. The design usually allows for adequate metal flow so that the resulting metallurgical properties are comparable with those found in forgings of conventional design. In blocker-type designs, very little attention is paid to die wear, die shift, fillet radii, draft angles, die closure, and tolerances described by the ASM Committee.

Conventional-Tolerance Designs. The ASM Committee's description of commercial tolerances applies to the conventional design. Some of the forging companies offer closer tolerances than these in order to reduce metal requirements. In these instances, the general design remains conventional, but machining allowances and die-closure tolerances are reduced to effect a weight saving.

Typical conventional tolerances are:

Length	±0.05 inch per foot
Thickness	+0.06 inch/-0.03 inch
Die wear	0.06 inch
Draft	5 to 7 degrees
Machine cleanup	0.03 to 0.19 inch

Close-Tolerance Designs. Compared with conventional designs, close-tolerance forging designs require greater dimensional accuracy and less draft. Less machining cleanup is allowed and, in some cases, localized "as forged" surfaces are specified. Additional tooling is usually required for forging, but the parts are forged in conventional equipment and conventional tooling.

Typical close tolerances are:

Length	±0.03 inch per foot
Thickness	+0.02 inch/-0.01 inch
Die wear	0.03 inch
Draft	1 to 3 degrees
Machine cleanup	0 to 0.06 inch

Precision-Tolerance Designs. Precision forgings are those that require both special tooling and forging equipment. This type of forging usually combines very close tolerances with small fillets and radii, no draft, and little or no machining allowances. The special equipment usually consists of low-rate presses or specially developed impacters. The complex tooling required might consist of split dies, segmented dies, or dies that can be heated to temperatures approaching the forging temperature. Even preliminary tooling must have a high degree of accuracy so that the volume of stock in the forging does not vary from part to part. To achieve this accuracy, complex additional tooling is usually required.

Typical precision tolerances include:

Length	±0.02 inch per foot
Thickness	±0.01 inch
Die wear	0.01 inch
Draft	0 to 0.5 degree
Machine cleanup	0 to 0.03 inch

Present-day design tolerances for forging titanium alloys are provided in Table VIII (Ref. 41). The blocker type of design is

TABLE VIII. DESIGN ALLOWANCES AND TOLERANCES FOR TITANIUM FORGINGS (REF. 41)

Type of Forging:	Blocker			Conventional			Close		Precision(d)
	Large(a)	Medium(b)	Small(c)	Large(a)	Medium(b)	Small(c)	Medium(b)	Small(c)	Small
Design Criteria									
Minimum Draft Angle, deg	5-7	5	5	5	5	3-5	3-5	3	0-1
Minimum Web Thickness, in.	0.75-1.00	0.62-0.75	0.62	0.62-0.75	0.50-0.62	0.25-0.38	0.25-0.31	0.20	0.15
Minimum Rib Width, in.	0.88-1.25	0.75-1.00	0.62-0.75	0.62-0.75	0.50-0.62	0.31-0.50	0.25-0.38	0.19-0.25	0.09
Minimum Corner Radius, in.	0.44	0.38	0.31-0.38	0.31	0.25-0.31	0.16-0.25	0.12-0.19	0.12	0.06
Minimum Fillet Radius, in.	1.00-2.00	1.00-2.00	0.88-1.50	1.00-1.50	0.88-1.00	0.75-0.88	0.38	0.25	0.12-0.19
Tolerances									
Thickness, in.	+0.38 -0.03	+0.25 -0.03	+0.25 -0.03	+0.25 -0.03	+0.12 -0.03	+0.09 -0.03	+0.06 -0.03	+0.04 -0.01	+0.02 -0.01
Length and Width, in./ft	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.03	±0.02
Straightness Within, in.	0.25	0.25	0.19	0.19	0.09	0.06	0.03	0.03	0.02
Maximum Machining Allowance, in.	0.38	0.31	0.25	0.25	0.12	0.09	0.03	0.03	0.03

(a) Large - larger than 400 $in.^2$
(b) Medium - 100 to 400 $in.^2$
(c) Small - less than 100 $in.^2$
(d) Values shown for precision forgings are estimated as reasonable values once techniques are fully established for producing this type.

frequently used for prototypes and small-quantity production runs. The conventional design is preferred to the blocker type for relatively large production quantities. Close-tolerance titanium forgings are limited to designs in the medium-size range. At present, precision forgings are in the development stage.

A general idea of the types of forging shapes commonly produced in titanium and their availability in the several categories of dimension tolerances is shown in Table IX.

TABLE IX. AVAILABILITY OF SPECIFIC TOLERANCES FOR EACH OF SEVERAL FORGING SHAPES IN TITANIUM ALLOYS (REF. 43)

Forged Shape	Type Forging Classified by Dimensional Tolerance			
	Blocker(a)	Conventional	Close(b)	Precision(c)
Disks	A	A	L	U
Cones	A	A	L	U
Hemispheres	A	A	L	U
Cylinders	A	A	L	U
Blades	A	A	A	L
Airframe (fittings)	A	A	A	LS
Airframe (rib and web)	A	A	L	U
Rings	A	A	L	U

(a) A - readily available.
(b) L - limited availability.
(c) LS - limited availability — small parts only
U - virtually unavailable.

THE EFFECTS OF DESIGN AND FABRICATION ON FORGING COST

It is apparent that forging costs will increase as dimensional tolerances are tightened. An Air Force-sponsored program on the producibility and costs of precision titanium forgings supports this promise (Ref. 44). The results of the program indicated that the costs of producing a final forged part of precision design were about 3 to 5 times those of a conventional forging. Precision forging in its present stage of development is not a practical approach to reducing costs, especially for short production runs. However, when unit costs, such as material and machining costs, are high in relation to the final tooling costs, then precision forging is applicable for large-quantity orders. Figure 17 (Ref. 44) summarizes such a comparison for a particular aircraft part for different alloys made to conventional and precision tolerances. For the titanium alloy, economic advantages could be realized from using precision forgings if 575 or more

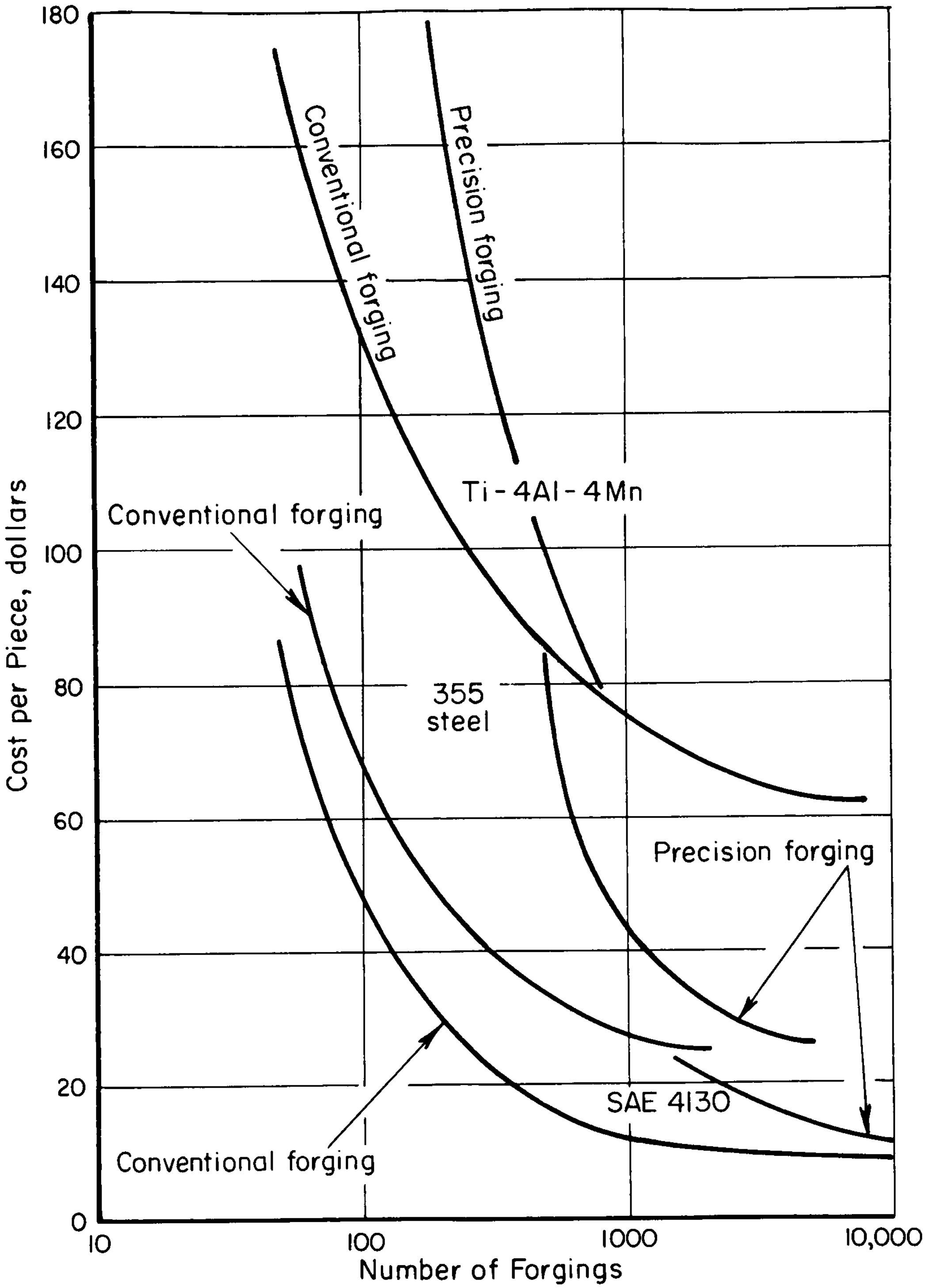


FIGURE 17. MANUFACTURING COST PER PIECE FOR AIRCRAFT FORWARD HANDLE-FITTING-PRECISION VS CONVENTIONAL FORGING DESIGNS (REF. 44)

identical parts were needed. This was true because the cost of billet material is high and the forgings were relatively expensive to machine. Conversely, steel forgings made to conventional tolerances were more economical for the lot sizes of interest.

It is impossible to make precise comparisons of costs of forging titanium and steel without knowing the specific part configuration and the lot size, but a few generalizations can be made. In the first place, titanium alloys cost more than steel. Furthermore, the forging of titanium alloys usually requires special practices as indicated in previous sections of this report.

Since production rates on titanium forgings are often as low as 60 per cent of those for steel, labor costs for titanium are almost half again those for forging similar parts in steel. Because forging loads are higher for titanium than for steel, heavier equipment or more operations may be required. A fair estimate is that the costs resulting from these additional equipment requirements would be about 1.25 times those for forging steel.

Die costs are usually an important part of the final per-piece price of a forging. The costs of forging dies for titanium and steel are comparable; however, depending on the design, the life of dies used for forging titanium may be only one-half that of dies for steel forging. Die life for titanium and stainless steels are about equal, however.

Rejections of finished parts are now less than 10 per cent – similar to steel. Rejections of forged aluminum parts are normally 6 to 9 per cent.

Scrap losses remain a major factor in the cost of titanium forgings. This is due to the high raw-material cost as well as the fact that scrap is not recoverable. Titanium chips have no resale market – bulk material is sold to scrap dealers for 4 cents per pound.

Scrap losses have been significantly reduced in the forging of large parts. Typical processing losses on parts forged to conventional tolerances are listed below:

Weight of Forged Part, lb	Scrap Loss, per cent, $\frac{\text{Input Weight-Final Weight}}{\text{Input Weight}} \times 100$
Up to 200	35 - 40
200 - 500	30
500 - 1100	20

DRAWING AND TUBE REDUCING

INTRODUCTION

Drawing is a cold-working process that reduces the cross section of a long workpiece by pulling it through a die. Semifinished shapes are cold drawn into rod, wire, and tubular products for a variety of applications. Drawing is capable of producing better finishes, closer tolerances, and thinner sections than hot-working processes. A variety of titanium alloys are drawn into rod and wire, for fasteners and weld-filler wire, from hot-rolled bar and rod. In addition to the materials listed in Table I as available in wire form, some are made particularly for fasteners. This is the case for the Ti-7Al-12Zr and the Ti-1Al-8V-5Fe alloys. For applications where a tensile strength of 200,000 psi is specified, fasteners made from the Ti-4Al-4Mo-4V alloy have been supplied (Ref. 45).

Unalloyed titanium tubing is available in a number of sizes, primarily for applications in the chemical industry. Alloy tubing is being evaluated for possible application in the hydraulic lines of supersonic transport planes. Tubular products are currently available, commercially, in the Ti-3Al-2.5V and Ti-0.15Pd alloys from Superior Tube (Ref. 46) and perhaps from other companies. Seamless tubes have been produced experimentally by Wolverine Tube (Ref. 47) and by Harvey Aluminum Company (Ref. 21) from the Ti-6Al-4V composition. A number of industrial organizations are capable of producing cold-drawn titanium products when there is a demand.

PROCESSING

In general, the equipment developed for producing bar, wire, and tubular steel products is used for cold drawing titanium. Since information on procedures and equipment is readily available (Ref. 14) and voluminous, it is inadvisable to present details here.

Diamond or tungsten-carbide dies are used for cold drawing titanium and its alloys depending on the size of the product. Hardened steel dies can be used for small-lot production. Standard die designs, with included angles of about 25 degrees are usually employed. Products to be cold drawn are pointed, so they will enter the die far enough to be gripped, by machining filing or swaging.

Galling and seizing are common problems in drawing titanium-rich materials. A wide variety of lubricants and coatings has been used to alleviate or prevent trouble of that kind. Graphite, copper powder, lead oxide, soaps, molybdenum disulfide dispersions in a lacquer carrier, and various proprietary materials have been used with different degrees of success. Dry-film lubricants suspended in lacquers do not appear to be satisfactory. The lacquer breaks down at the temperatures reached at normal speeds and the reductions must be kept below 15 per cent, in area, per pass. Pretreating titanium and its alloys in a fluoride-phosphate bath to develop a chemical-conversion coating is recommended. It can be used with conventional lubricants; graphited greases are usually satisfactory. The coating can be removed quite easily by pickling. Individual companies have developed other proprietary lubricants and lubricant systems.

Like other metals, titanium and its alloys are annealed when necessary between successive drawing operations. Vacuum annealing is necessary for small-diameter wire and desirable in thin-walled tubing. Other products are generally annealed in an oxidizing atmosphere and then pickled. Welding wire is sometimes shaved after drawing to remove surface defects.

Drawbenches, which take a single draft, are used for the larger products. Hydraulic and mechanical benches operate at speeds ranging from 10 to about 150 feet per minute. They can produce lengths up to 100 feet, which are later cut to the dimensions ordered. Benches are used for drawing bars larger than 1/2 inch in diameter and for extruded shapes. They are also used for drawing seamless tubes as shown schematically in Figure 18.

Individual bull blocks are used for drawing rod from 1/2 to 1 inch in diameter. A block is a drum, ordinarily driven by an individual motor, that pulls the rod or wire through the die and produces a coil. The blocks, which may be either vertical or horizontal, range from 24 to 34 inches in diameter for rod and rotate at 10 to 25 rpm. Blocks can be assembled into a frame or machine for continuous drawing of wire through a series of dies. Such equipment utilizes smaller

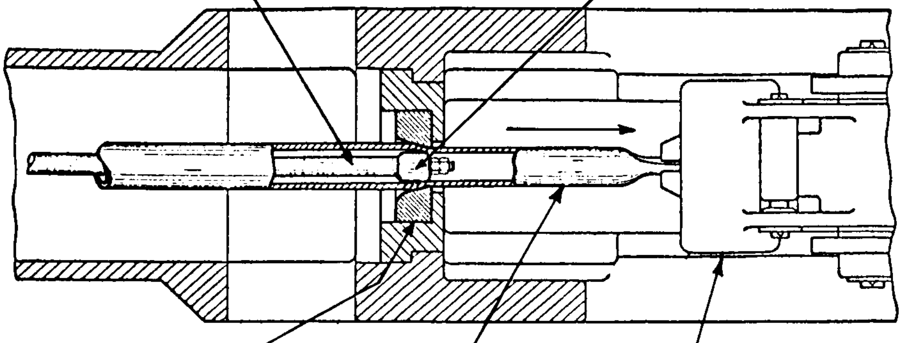


FIGURE 18. DIAGRAMMATIC VIEW OF DRAWBENCH SHOWING SEAMLESS TUBE IN THE PROCESS OF DRAWING (REF. 48)

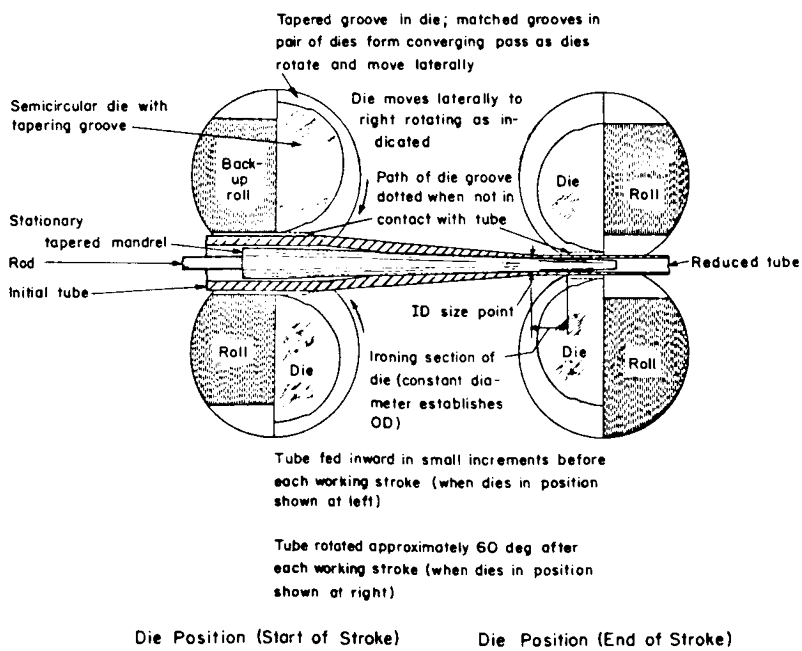


FIGURE 19. VERTICAL SECTION THROUGH TUBE-REDUCER PASS SHOWING DIES AT START AND END OF STROKE (REF. 14)

blocks, down to 6 inches in diameter, for fine wire. Usually the drawing speed increases as wire diameter decreases.

"Turks head" machines use rolls instead of dies to produce four-sided sections from rod or wire. Squares, rectangles, and keystones can be obtained by pulling the stock through four hard rolls mounted at right angles to each other in a fixture. The "turks head" fixture can be used with either a drawbench or a bull block.

Some tubing is made by seam welding bright-annealed, roll-formed sheet and drawing it to the size desired. Seamless titanium tubing is usually made from extruded shells. It can be drawn over a mandrel by the technique indicated in Figure 18 or produced by the tube-reducing process illustrated by Figure 19.

A tube reducer decreases the diameter and wall thickness of tubing, simultaneously, by a swaging action. The workpiece is compressed between two semicircular rolls, with matching tapered grooves, and a stationary tapered mandrel aligned at the centerline of the pass. The tube is rotated about 60 degrees between each reciprocating motion of the rolls to avoid the formation of fins and to insure concentricity. Large reductions per pass are possible because the forces are mainly compressive and the deformation occurs incrementally in small steps. These characteristics permit reductions up to about 85 per cent in area, per pass, more than twice those feasible in drawing. Incremental working also results in smaller residual stresses. Compared with drawing, the heavier reductions help to compensate for the much lower rate (maximum of 3-1/2 ft/min) of tube travel. Tube reducing also eliminates some of the intermediate cutting, annealing, pickling, and pointing operations needed in drawing. On the other hand, drawing is more suitable for small-lot production because dies are relatively cheap and are easier to change.

PRODUCTS

<u>Bar, Rod, and Wire</u>. Cold-drawn titanium is produced in sizes ranging from 0.3125 to 3.5 inches in diameter. The larger bars are commonly shipped in 15 to 20-foot lengths and smaller rods may be obtained in lengths up to 50 feet. Titanium-rod and wire products are used primarily for fasteners and welding wire. Wire is ordinarily available in sizes from 0.009 to 0.3125 inch in diameter in coils 300 to 500 feet long. Longer continuous lengths can be procured in finer sizes. Commercially pure titanium is available in a wider variety of sizes and smaller diameters than alloy stock.

The normal tolerances for cold-finished wire, covered by specification AMS 22410, are as follows:

Diameter, inch	Tolerance (±), inch
0.008 - 0.012	0.0003
0.012 - 0.033	0.00075
0.033 - 0.044	0.0008
0.044 - 0.3125	0.001

Tubing. For several years, unalloyed-titanium tubing has produced commercially in a variety of sizes, and the processing techniques are well established. The situation is different for titanium alloys. Superior Tube has announced the commercial availability of Ti-3Al-2.5V and Ti-0.15Pd alloy tubing in all sizes now sold in the unalloyed grade. The sizes over 3-1/2-inch diameter are hot extruded and then machined to achieve the necessary tolerances. Smaller tubing is drawn from extruded tube shells or welded tubes. The tube reducing process is used for all alloy titanium tubing and for heavy-walled unalloyed tubes. Seamless tubes have been produced in experimental quantities from the Ti-6Al-4V alloy by Harvey Aluminum and Wolverine Tube. Work is in progress at Titanium Metals Corporation of America to develop procedures for producing textured tubing from the Ti-4Al-0.250 alloy by the weld-and-draw process.

Good quality seamless tubing is readily available in unalloyed grades of titanium in sizes ranging from 0.25 to 2-1/2-inch OD. The wall thicknesses available range from 0.012 inch to 0.25 inch depending on the diameter. Very small sizes are produced with outside diameters as small as 0.010 inch and wall thicknesses of 0.002 inch. Tolerances for titanium tubing meet ASTM Specification B-338-61T.

Although Ti-6Al-4V tubing is not a commercial product the feasibility of producing it has been demonstrated. The following tabulation of some experimental tubing indicates the future industrial capabilities.

Producer	Tube Size, inch: Outside Diameter	Tube Size, inch: Wall Thickness
Wolverine Tube	1	0.083
Harvey Aluminum	1	0.050
Wolverine Tube	5/8	0.030
Harvey Aluminum	1/2	0.030
Harvey Aluminum	1 x 1 square	0.050

Shapes. Hot-extruded titanium shapes do not ordinarily meet the dimensions and tolerances desired for aerospace components. However, those characteristics can be improved to levels closely approaching those met by aluminum alloys by cold drawing titanium extrusions at 900 F.

The benefits of warm drawing hot-extruded structural shapes were investigated in a development program conducted by Republic Aviation Corporation (Ref. 38). The studies were made on 20-foot-long "T" extrusions. Warm drawing reduced the thicknesses of the flange and leg of the section from 0.094 and 0.065 inch to 0.080 and 0.043 inch, respectively, in one pass. Aircraft quality requirements on thickness, straightness, and twist tolerances were met. On the other hand, the ends of the flange and the leg had to be machined to meet dimensional tolerances. Warm drawing improved the surface finish of the structural shapes. Surface finishes were 80 microinch rms on the thicker section but slightly above the desired limit of 100 rms on the thinner section. The study represents a significant advance in the art of producing thin extruded shapes of titanium. Research of this kind is continuing at Nuclear Metals under subcontract from Republic Aviation (Ref. 39).

SECONDARY DEFORMATION PROCESSES

The primary products resulting from rolling, extrusion, and forging are converted to more useful shapes by secondary processes. Most of the conventional deformation processes used for this purpose have been applied successfully to titanium and its alloys. Descriptions of such forming operations, and the limits imposed by the characteristics of the materials, are presented in this section of the report.

General data on the relative formability of annealed titanium alloys for six sheet-forming operations at room and elevated temperatures are given in Table X. It can be seen that the all-beta alloy (Ti-13V-11Cr-3Al) is relatively easy to form and that the Ti-6Al-4V and the Ti-5Al-2.5Sn alloys are generally near the bottom of the list for most forming operations. The formability of the various alloys will be discussed in more detail under the specific forming operations.

TABLE X. RELATIVE FORMABILITY OF ANNEALED TITANIUM ALLOYS FOR SIX SHEET-FORMING OPERATIONS AT ROOM AND ELEVATED TEMPERATURES (REF. 49)

Brake Press (Minimum Bend Radius), room temperature	Drop Hammer (Maximum Stretch), 850 to 950 F	Hydropress (Trapped Rubber) Stretch (Maximum), 600 to 700 F	Hydropress (Trapped Rubber) Shrink (Maximum), 600 to 700 F	Joggle (Runout/Joggle-Depth Ratio) Room Temperature	Joggle (Runout/Joggle-Depth Ratio) 600 to 700 F	Stretch Wrap (Maximum), room temperature	Skin Stretch (Maximum), 850 to 950 F
3Al-13V-11Cr (1.5t)	3Al-13V-11Cr (16%)	3Al-13V-11Cr (10%)	3Al-13V-11Cr (6%)	3Al-13V-11Cr (1.25)	3Al-13V-11Cr (1)	8Mn (8%)	8Mn (18%)
8Mn (3T)	8Mn (16%)	8Mn (7.5%)	8Mn (5%)	8Mn (4)	8Mn (3)	5Al-2.5Sn (8%)	6Al-4V (17%)
5Al-2.5Sn (3.5T)	5Al-2.5Sn (13%)	6Al-4V (5%)	6Al-4V (4%)	5Al-2.5Sn (4)	6Al-4V (3)	3Al-13V-11Cr (5.5%)	3Al-13V-11Cr (13.5%)
8Al-2Cb-1Ta (4T)	6Al-4V (13%)	5Al-2.5Sn (<5%)	5Al-2.5Sn (3%)	6Al-4V (4.5)	5Al-2.5Sn (4.5)	6Al-4V (3.5%)	5Al-2.5Sn (12.5%)
4Al-3Mo-1V[(a)] (4.5T)							
2.5Al-16V[(a)] (4.5T)							
6Al-4V (4.5T)							
5Al-2.8Cr-1.2Fe (6.2T)							

Note: Alloys are listed in order of forming ease, the most formable alloy being at the top of the list. Numbers in parentheses following alloy designations are laboratory test values for the indexes of formability shown in parentheses at the top of each list. Laboratory index values shown should be relaxed at least 25 per cent when designing for production.

(a) Solution-treated condition.

BLANK PREPARATION

Introduction. The preparation of a blank for metal forming may be as simple an operation as cutting a tube to the length desired or cutting a shape that closely resembles the shape of the final sheet-metal part. The size of the blank depends on whether the parts are formed to final dimensions or are to be trimmed after forming. Since the practices suitable for preparing blanks for different types of metal-forming operations bear many similarities they are summarized in this section. Some precautions that may not be necessary for other materials are important in processing titanium.

In thicknesses up to 0.125 inch, titanium and its alloys can be cut to shape by techniques used for 1/2-hard stainless steel. Thicker sheet is usually sawed. Flame cutting, however, is not considered a suitable process because it impairs the properties of titanium (Ref. 50).

Shearing. Titanium-alloy sheet has been sheared to size on a production basis in thicknesses up to 0.140 inch (Ref. 21). Thicker sheet can be sheared if precautions are taken to avoid slipping during shearing. Heavy hold-down pressures, which may not be available on standard shearing equipment, are required to prevent slipping. The equipment should be checked for capabilities in shearing titanium before being used for the production of parts.

Suitably smooth surfaces may be difficult to obtain on sheared titanium parts especially in thicker sheet. Irregularities 0.01 to 0.02 inch deep have been noted on edges of sheared titanium parts. This condition is generally the result of insufficient stiffness in the shear blades. The substitution of a thicker blade sometimes remedies this condition. Edge cracking in titanium sheet above 0.080 inch has been a problem (Ref. 21). If the cracks are not too deep (0.015 inch maximum) they can be removed by grinding and polishing. Small cracks in a trim area, which will be removed after the part is formed, should not cause any difficulty. When shearing causes cracks in a critical section of the part, an alternative method of blank preparation such as band sawing should be considered.

Conventional power shears (square shears) with blade clearances and relief angles normal for shearing stainless steel can be used for shearing titanium. A power shear rated at 50 per cent greater capacity than that required for the same thickness of low-alloy steel should be used for titanium (Ref. 21). The cutters must be in a sharp condition and free of nicks to prevent edge cracking. Blades made from W2 steel are considered satisfactory.

Blanking. Blanking is normally performed on a punch press to produce a blank with the desired shape in one operation. Concentric shapes in titanium have been produced by this method in thicknesses up to 1/8 inch and irregular-shaped blanks up to 0.050 inch (Ref. 21). Dies made to a tolerance of ±0.004 inch can be used for titanium blanking in thicknesses up to 0.050 inch, while a decrease in tolerance to ±0.001 inch is necessary for thicknesses up to 0.125 inch. Elevated-temperature blanking may minimize edge cracking in thicker sheet titanium.

Dies for blanking titanium should be rigid and guide pins should be used to insure proper alignment. This requirement becomes more pronounced as the thickness of the material is increased. Insufficient stiffness in the tooling causes die failure and edge cracking in the blanks. The cutting edge of the tools must be sharp and free of irregularities. Standard die clearances for steel blanking dies can be used for titanium blanking, but the shear angle should be larger.

Band Sawing. Band sawing is used for cutting titanium blanks in thicknesses above 0.125 inch (Ref. 21). It eliminates edge cracking but has the disadvantage of creating a burr that must be removed from the blank.

The saws used on titanium should be of rigid construction and have ample horsepower to maintain a constant speed during cutting. The equipment should provide automatic positive feeding, band tensioning, and a positive flow of the coolant. The blades with the pitch and width recommended by the manufacturer should be used for best results. Normally, high-speed steel saw bands will maintain sharpness and give the most consistent results.

Slitting. Slitting is used for preparing long, narrow, thin blanks or for cutting circles. Where contour changes are not too sharp slitting may also be used for irregularly shaped blanks. Since the process is generally limited to 0.025-inch titanium, the cut edge is generally smooth and free of shear cracks.

Conventional slitting equipment suitable for stainless steel and the drawbench type of equipment have been used successfully on titanium (Ref. 21). For best results the equipment must be of rigid construction and the tooling maintained in a sharp condition.

Routing. Routing is a process that uses a milling cutter that is moved by hand to cut a stack of sheets to the desired contour. The router follows a template with the desired pattern. Although routing has been used successfully for preparing blanks from aluminum, the force required to hand feed a router in cutting titanium makes the process impractical for this application. The development of automatic feed systems for routing could result in considerable time saving in the preparation of irregularly shaped titanium blanks.

Nibbling. Nibbling is a slow process usually restricted to the preparation of a small number of blanks. It can be used to produce irregularly shaped blanks, but the edges must be smoothed by filing or belt grinding before the parts can be formed. Short tool life and high maintenance costs are normally associated with this type of blank preparation. It also has the same limitations as shearing regarding the thickness of material that can be cut.

Edge Conditioning. Titanium blanks must be deburred before forming, regardless of the cutting method used, to minimize damage to the forming tools. The edges of the blank in the region that will be deformed should be polished to remove stress raisers that would lower the formability of the material. Scratches from deburring or polishing the blank edges should be parallel to the surface of the sheet; scratches across the edge are more detrimental to formability. Cracks in the edge of sheared blanks are also undesirable. Edge cracks less than 0.005 inch deep and parallel to the surface of the material or in areas that will be removed by trimming after forming generally do not cause any difficulty in forming.

Sharp edges should be removed from the blank to prevent damage to the forming tools. The edges of blanked holes and cutouts as well as pilot holes should be deburred on both sides. The edges of holes in blanks that are to be formed by stretching should also be polished.

Deburring and polishing can be done by draw filing or belt grinding on blanks up to 0.040 inch thick. The direction of cutting should be parallel to the sheet surface. For thicker sheet materials a machining operation such as milling should be considered.

Methods of Sheet Layout for Titanium. Economy of material is a factor to consider in layouts on titanium sheets of standard mill size. This becomes very important when using a material that may cost from 6 to 10 times as much as the same area of aluminum. Only noncontaminating inks and pencils should be used for layouts. Marking materials that are not inert to titanium may cause surface defects on the sheet. Scribes or vibrating tools that will leave defects on the surface of the material will reduce formability and may make the parts structurally unacceptable. The cutting sequence should be arranged so that straight-line shearing can be used to reduce the size of each sheet handled for final edge contouring. This takes some planning to assure that the maximum number of parts can be cut from each sheet with a minimum of scrap.

When making the layout sufficient additional material should be included in the outline to permit removal of shear cracks and other stress raisers. Titanium thicknesses up to 0.070 inch should have a cleanup allowance that will permit the elimination of any evidence of surface defects. Shop practice for thicker sheet materials generally requires a cleanup allowance on each edge equal to the thickness of the material. The layouts should include additional material for those operations that require it. As an example, stretch forming requires additional material for the grip area.

Surface Preparation. Surface imperfections such as scratches or contaminated surface layers will reduce the formability of the material and may also make the titanium structurally unacceptable. Such imperfections, which often occur, should be avoided during the processing of the material. Before a part is formed the blank should be inspected for imperfections and defects removed before the next forming step.

All scratches that are coarser than the finish produced by emery grit No. 180 should be removed by surface sanding. The sanding should be parallel with the grain direction of the sheet. Since surface sanding is normally a time-consuming hand operation, avoiding scratches during handling is very important.

Oil, grease, and other soluble matter should be removed before any hot forming of titanium by using methyl ethyl ketone (MEK) as a solvent on a wiping cloth.

When the surface of the material has been contaminated by prior processing, a light acid etch can be used to remove the contaminated surface. Etching may also remove light scratches from the metal surface. Most manufacturers will permit a removal of 0.003 inch from each surface of the blank. If the contaminated surface layer is thicker, the material will normally be scrapped unless all of the contamination can be removed, and the material will be used for thinner sheet. Before a material can be etched, all soluble matter such as mill stenciling and finger prints must be removed from the surface to assure even etching.

An etchant considered suitable for removing contaminated surface layers from titanium is:

Concentration	Material
25 to 35 per cent by weight	Nitric acid, 38-deg Baume
1.0 to 5.0 per cent	Hydrofluoric acid, 70 per cent
Balance	Water

It is essential to maintain the proper concentration in order to avoid hydrogen absorption. The HNO_3 should be on the high side of the concentration range and the HF on the low side to minimize hydrogen pickup. Parts should be rinsed carefully after etching.

When titanium is to be heated in air above 1000 F for a long period of time, scale-inhibiting coatings such as Turco "Pre-Treat" can be used to minimize surface contamination. The scale inhibitor must be removed from the material after it has cooled to room temperature before the parts are ready for final assembly. This can be accomplished by vapor blasting followed by alkaline cleaning and acid etching.

Phosphate-fluoride coatings have been recommended for use on titanium alloys in forming operations likely to result in wear or galling. Good results are reported (Ref. 51) when parts were lightly etched and then immersed for 2 or 3 minutes in baths with the compositions indicated in Table XI. After air drying the chemical-conversion coating produced by the treatment is a good host for metal-working lubricants.

TABLE XI. BATH COMPOSITIONS FOR PRODUCING FLUORIDE-PHOSPHATE CONVERSION COATINGS ON TITANIUM (REF. 51)

Material	Unalloyed Titanium	For Ti-3Al-2.5V and Ti-13V-11Cr-3Al
$Na_3PO_4 \cdot 12H_2O$, grams	50	50
$KF \cdot 2H_2O$, grams	20	30
HF (50 weight per cent), cc	25	120
Water, cc	1000	1000

BRAKE BENDING

Introduction. Brake forming is a simple, versatile forming operation widely used for forming flat sheets into sections such as angles, channels, and hats. The process uses inexpensive, simple tooling that can be quickly adapted to different part shapes. Brake forming is used mostly for making parts to wide tolerances and for preforming operations on close-tolerance parts. Handworking or hot-finish-forming methods are required to produce parts with close-dimensional tolerances.

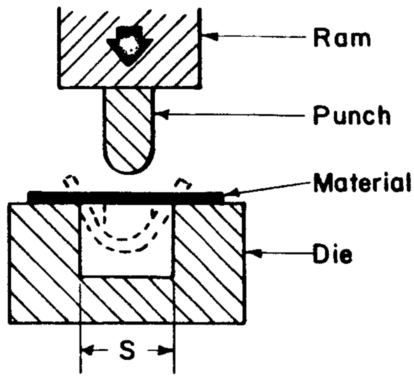
The springback allowance for titanium and its alloys is normally about 15 degrees for cold forming. If the bend radii are sufficiently large, no unusual problems are encountered. When small bend radii are required, it may be necessary to use elevated temperatures to avoid cracking. No springback allowance is ordinarily required when forming is done at elevated temperatures.

Principles of Bending. In bending, the metal on the inside of the bend is compressed, or shrunk, while that on the outside of the bend is stretched. This is shown in Figure 20 for two typical brake-forming setups. In air bends, the workpiece is supported only at its outer edges so that the length of the ram stroke determines the bend angle, α, of the part. The radius of the punch controls the inside radius of the workpiece. In die bending, the sheet is forced into a female-die cavity of the required part angle, α.

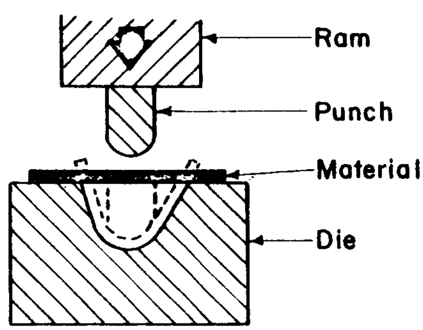
The limiting span width, S in Figure 20a, depends on the sheet thickness, T, and the punch radius, R. According to Wood (Ref. 53), the practical limits for brake bending lie between:

$$S = 3R + 2T \text{ and } S = 2.1R + 2T \quad . \qquad (1)$$

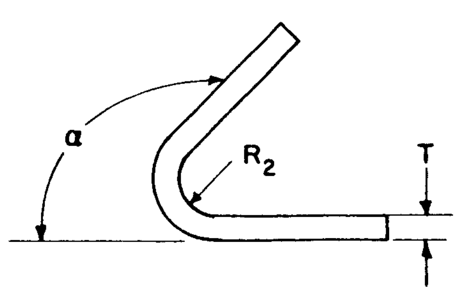
These variables and the bend angle control success or failure in bending. Larger radii are needed for thicker sheet and the ratio of R/T should also be increased for larger bend angles. The limiting bend angle and bend radius depend on the ability of the metal to stretch. If the operation is too severe, the metal cracks on the outer surface of the bend. Since titanium exhibits directional variations in ductility, smaller R/T values are usually practical for bends perpendicular to the major rolling direction than for those oriented in other directions.



a. Air Bending (Ref. 52)



b. Die Bending (Ref. 52)



c. Parameters (Ref. 53)

FIGURE 20. TYPICAL BRAKE-FORMING SETUPS AND PARAMETERS

Presses Used for Brake Forming. Brake presses are commercially available having capacities ranging from about 8 to 2000 tons. For the bending of thin sheet metal, the press capacity can be relatively small. Presses of 8-ton capacity may be hand operated. For example, a 60-ton Verson brake press was used by Wood, et al. (Ref. 53) in the experimental portion of their study to establish parameters for brake forming. This press used a 3-inch ram stroke at a speed of 8.77 feet per minute. Figure 21 is a photograph of a 500-ton press. Table XII lists the capacities and other pertinent information on brake presses available from one manufacturer. Another fabricator used a 12-foot Niagara press for brake-forming experiments.

Tooling. Dies and punches for press-brake forming at room temperature may be made from suitably heat-treated low-alloy steels such as SAE 3140 and 4340. Tool steels and Meehanite cast irons are used for punches and dies that are to be used both at room and elevated temperatures up to about 1400 F. The punches are made to the desired bend radii. The female die may be a "V" or a channel die. For room-temperature brake forming, a hard-rubber insert is sometimes placed in the channel die to avoid scratching the formed parts. The surface of the punch must be polished and free of defects such as nicks where it contacts the blank. Zinc-alloy (Kirksite) dies also can be used for producing limited quantities of brake-formed parts if the surface is covered with hard rubber or other material so that the titanium does not contact the soft alloy.

When steel tooling is used for hot forming, it is sometimes covered with a protective coating to prevent scaling and pitting. A satisfactory coating can be built up by spraying a thin layer of Ni-Cr-B alloy on the surface of the grit-blasted tool and fusing the deposit at 1875 F. The coating then can be polished to the desired surface smoothness.

Figure 22 is a sketch of a brake die used at Convair (Ref. 55) for an experimental study of the formability of titanium alloys. This assembly uses a Meehanite punch and die and was heated to a maximum temperature of 1400 F by means of cartridge heaters. This die was modified to use multiradiused punches so that forming with different die radii could be accomplished without the necessity for cooling the entire assembly to room temperature to change punches. Figure 23 shows a sketch of the multiradius brake die. The matching die sections at the bottom half of the tool are not shown.

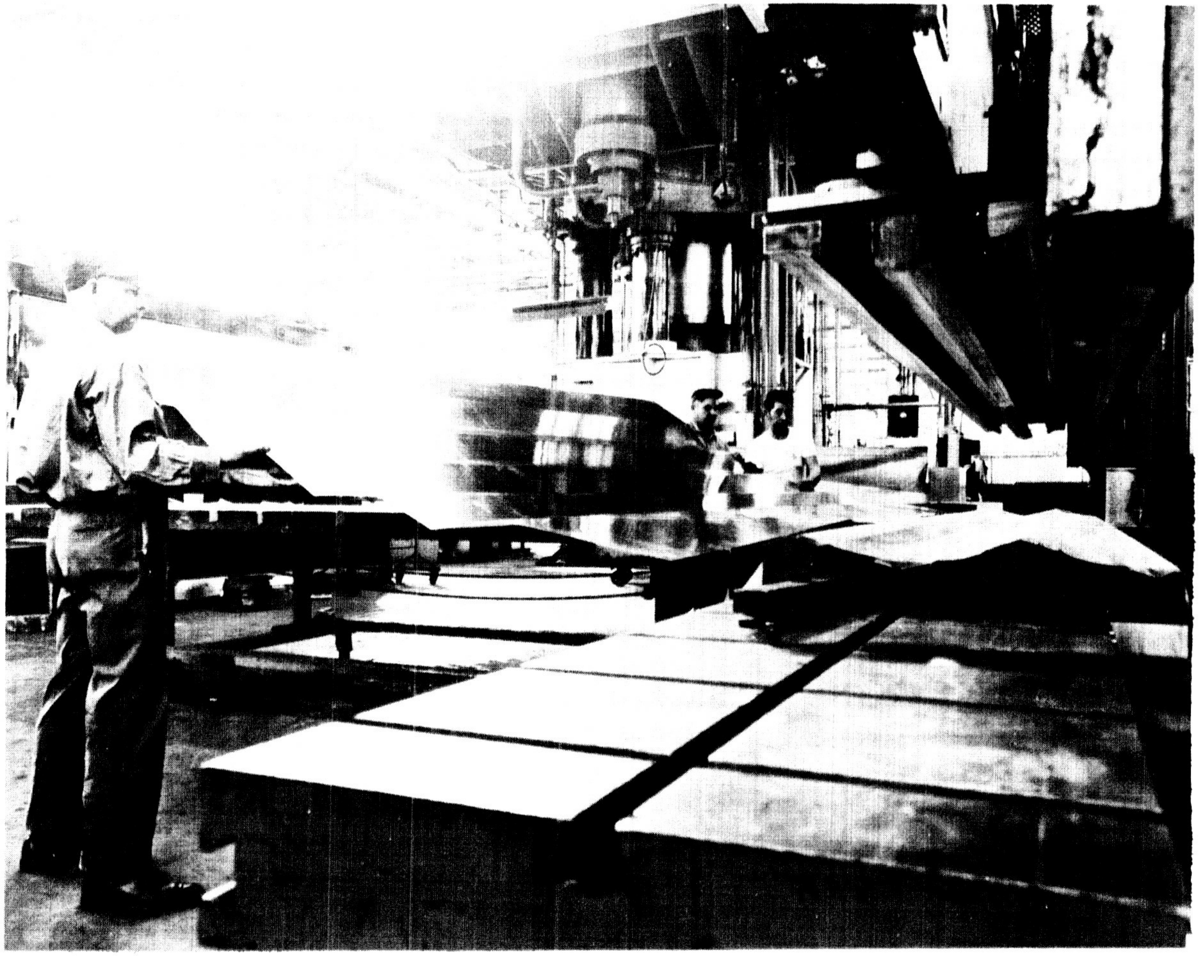


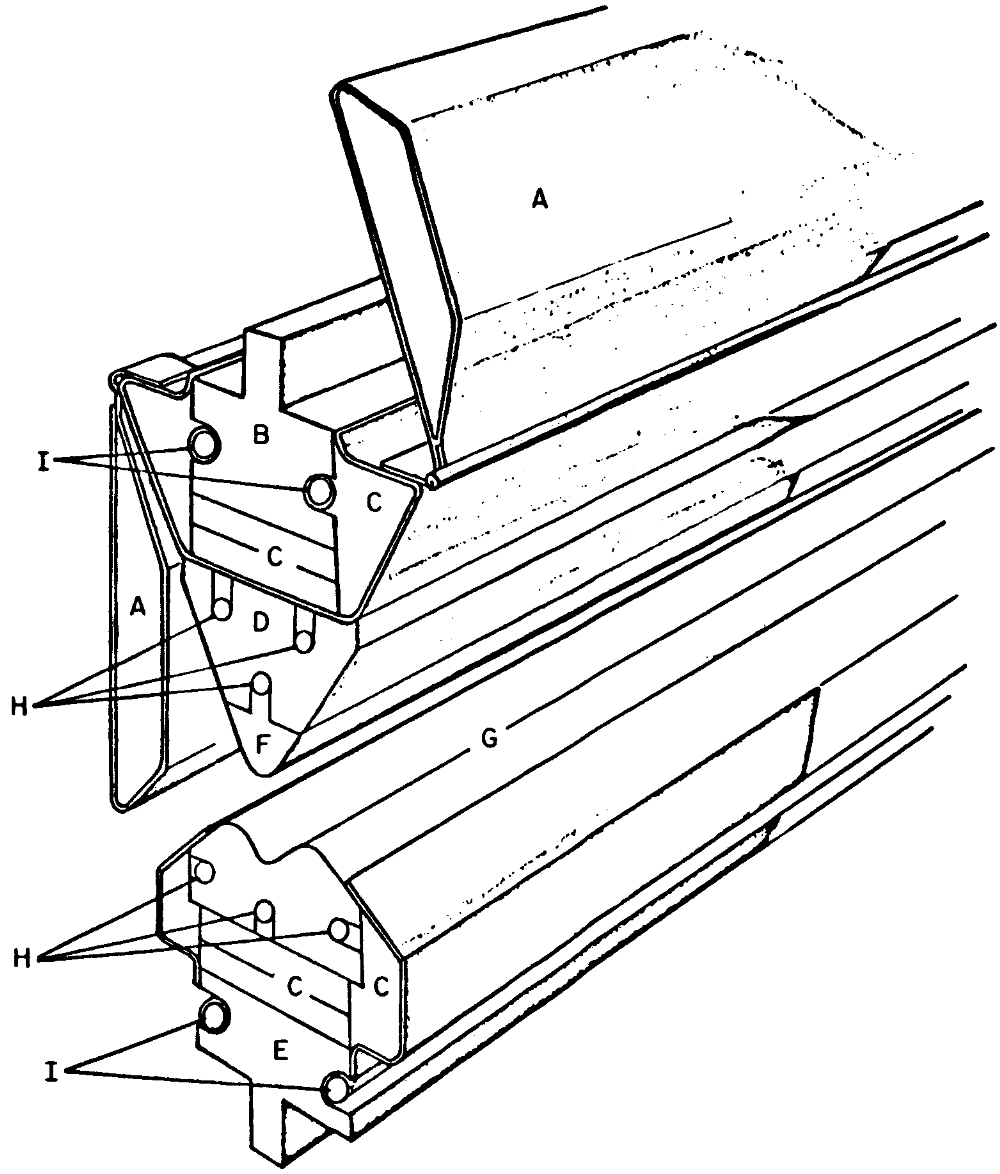
FIGURE 21. 500-TON HYDRAULIC PRESS BRAKE WITH BED ABOUT 30 FEET LONG

Courtesy of Columbus Division of North American Aviation.

TABLE XII. CAPACITIES AND OTHER TYPICAL INFORMATION ON BRAKE PRESSES (REF. 54)

Model	Capacity, tons: Mid-Stroke	Capacity, tons: Near Bottom of Stroke	Range of Bed Lengths, feet: Longest	Range of Bed Lengths, feet: Shortest	Stroke: Standard Length, in.	Stroke: Speed, surface feet/minute	Bending Capacity, Feet, Mild Steel with Standard Stroke for Thicknesses: 16 Gage	3/16 in.	1/4 in.	1/2 in.	3/4 in.	1 in.	Motor HP	Range of Shipping Weight, pounds: Largest	Smallest
						Mechanical Press Brakes									
1B-15	--	15	10	4	2	20-50	4	3/4	--	--	--	--	3/4-1	3,800	2,500
1B-25	--	25	12	6	2	20-50	6-1/2	1-1/2	--	--	--	--	1-1/2	5,200	4,500
1B-36	36	55	12	6	2-1/2	40	12	3	--	--	--	--	3	8,300	6,900
1B-60	60	90	14	6	3	40	18	6	--	--	--	--	5	17,800	10,925
N-90	90	135	14	6	3	36 and 12	--	11	6	--	--	--	7-1/2	25,350	12,500
N-115	115	175	14	6	3	36 and 12	--	15	10	--	--	--	10	30,000	15,400
N-150	150	225	16	6	3	33 and 11	--	19	13	--	--	--	15	50,000	24,800
N-200	200	300	18	8	4	30 and 10	--	23	18	6	--	--	20	53,000	32,000
N-260	260	400	18-2/3	8-2/3	4	30 and 10	--	--	24	8	--	--	20	67,500	37,000
N-335	335	500	18-2/3	8-2/3	4	30 and 10	--	--	25	10	5	--	25	90,000	60,000
N-400	400	600	24	10	4	30 and 10	--	--	30	12	5	--	30	120,000	64,000
N-520	520	750	24	10	4	23 and 7	--	--	--	18	10	--	40	157,000	79,500
N-650	650	1000	24	10	5	23 and 7	--	--	--	24	12	6	40	180,000	92,000
N-825	825	1250	22	14	6	20 and 6	--	--	--	30	17	10	50	194,000	133,000
N-1000	1000	1500	24	14	6	20 and 6	--	--	--	--	21	12	50	230,000	141,000
						Hydraulic Press Brakes									
HD-200	--	200	18-2/3	8-2/3	12	21 and 34[(a)]	--	14	12	--	--	--	25	50,000	26,500
HD-300	--	300	18-2/3	8-2/3	12	25[(a)]	--	--	16	8	--	--	30	52,600	29,000
HD-400	--	400	18-2/3	8-2/3	12	26[(a)]	--	--	--	12	6	--	40	67,000	33,000
HD-500	--	500	18-2/3	8-2/3	12	25[(a)]	--	--	--	14	9	--	40	85,500	50,000
HD-600	--	600	24	10	12	25[(a)]	--	--	--	16	10	--	50	119,000	59,800
HD-750	--	750	24	14	12	21[(a)]	--	--	--	22	14	10	60	120,000	79,500
HD-1000	--	1000	24	14	18	21[(a)]	--	--	--	--	18	14	75	204,000	102,000

(a) Normal press speed gives rated capacity. Fast press speeds are along with press tonnage ratings as follows: HD-200, 57 and 65 in./min at 70 tons; HD-300, 44 and 62 in./min at 120 tons; HD-400, 51 and 62 in./min at 160 tons; HD-500, 54 and 58 in./min at 200 tons; HD-600, 56 and 51 in./min at 240 tons; HD-750, 48 and 47 in./min at 300 tons; and HD-1000, 58 and 44 in./min at 400 tons.



A - Insulated cover (used to reduce heat loss during elevated temperature operation)
B - Hot-rolled steel punch holder
C - Marinite insulation
D - Meehanite punch section
E - Hot-rolled steel die holder
F - Meehanite punch (interchangeable)
G - Meehanite die
H - Electric tubular heaters
I - Water-cooling tubes
J - Formed part
K - Power input

FIGURE 22. BRAKE DIE DESIGNED TO OPERATE UP TO 1400 F (REF. 55)

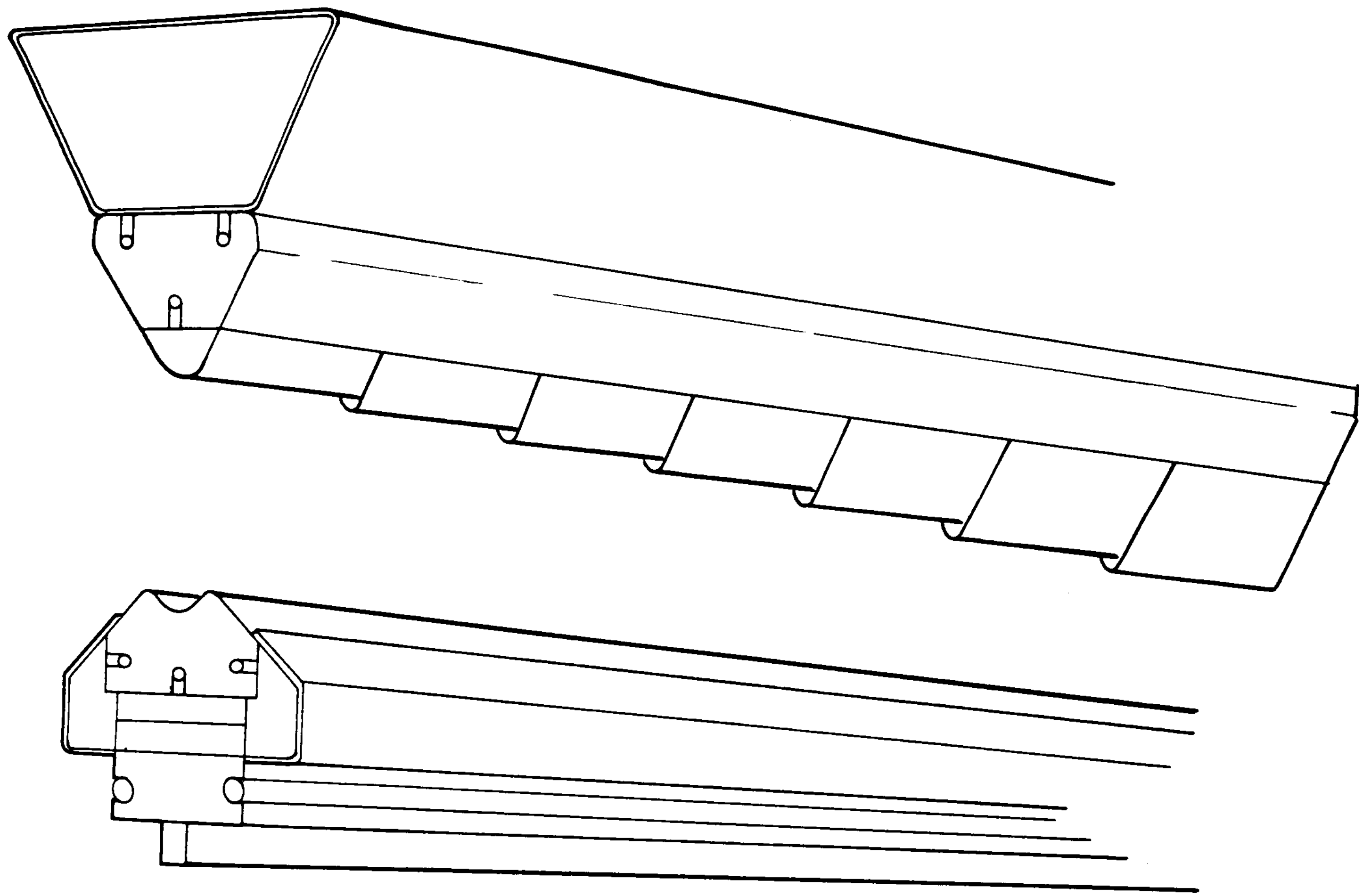


FIGURE 23. MULTIRADIUS BRAKE DIE (REF. 55)

Dies may also be heated by means of resistance-heating methods. Resistance heating is probably the most efficient and desirable method of heating brake-forming dies. Figure 24 shows a split female die with the electrical-resistance-heating cables attached. This assembly was used for formability studies at North American Aviation (Ref. 56). Sometimes dies are heated by means of gas torches.

Bending Procedures. Titanium blanks for bending on a brake press are prepared by methods described in the section on blank preparation. Normally lubricants are more important for elevated-temperature brake bending than for bending at room temperature. In one laboratory study (Ref. 56), powdered molybdenum disulfide was used as a lubricant for bending at temperatures between 70 and 700 F; powdered boron nitride was used for bending at temperatures above 700 F. Both of these materials adhered to the titanium; flaked graphite, which tests proved to be a better lubricant, was not used because it would not adhere. A lubricant identified as Everlube T-50* was used for brake forming at room and elevated temperatures in production applications. Dag-41** is another lubricant sometimes used in the hot forming of titanium alloys. The use of coatings, such as fluoride phosphate or fluoride borate, does not appear to be warranted for the brake-press bending of titanium alloys.

Blanks can be heated in a suitable muffle furnace or by conduction and radiation from heated dies. The latter method for heating blanks between a hot punch and die is slow for production use. In one application (Ref. 57), 2 minutes were required to heat 0.032-inch-thick sheet and 4 minutes to heat 0.063-inch material to 1200 F. In some applications, the titanium blanks are heated to the forming temperature by ribbon gas burners (Ref. 58). This method is relatively fast; Ti-6Al-4V alloy blanks were heated to 1400 F in 6 to 32 seconds, depending on thickness, in one application.

The heating of titanium alloys to temperatures of 1200 F and higher for times longer than 5 to 10 minutes must be avoided to minimize both scaling and embrittlement. This was shown by results of tests performed at Ryan (Ref. 57). Work at Boeing (Ref. 58) established the time-temperature limits for the Ti-6Al-4V alloy shown in Table XIII. These data may serve as a guide for time-temperature limits of other titanium alloys.

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*Produced by Everlube Corporation, North Hollywood, California.

**Uses graphite in lacquer-base carrier; produced by Acheson Colloids Company, Port Huron, Michigan.

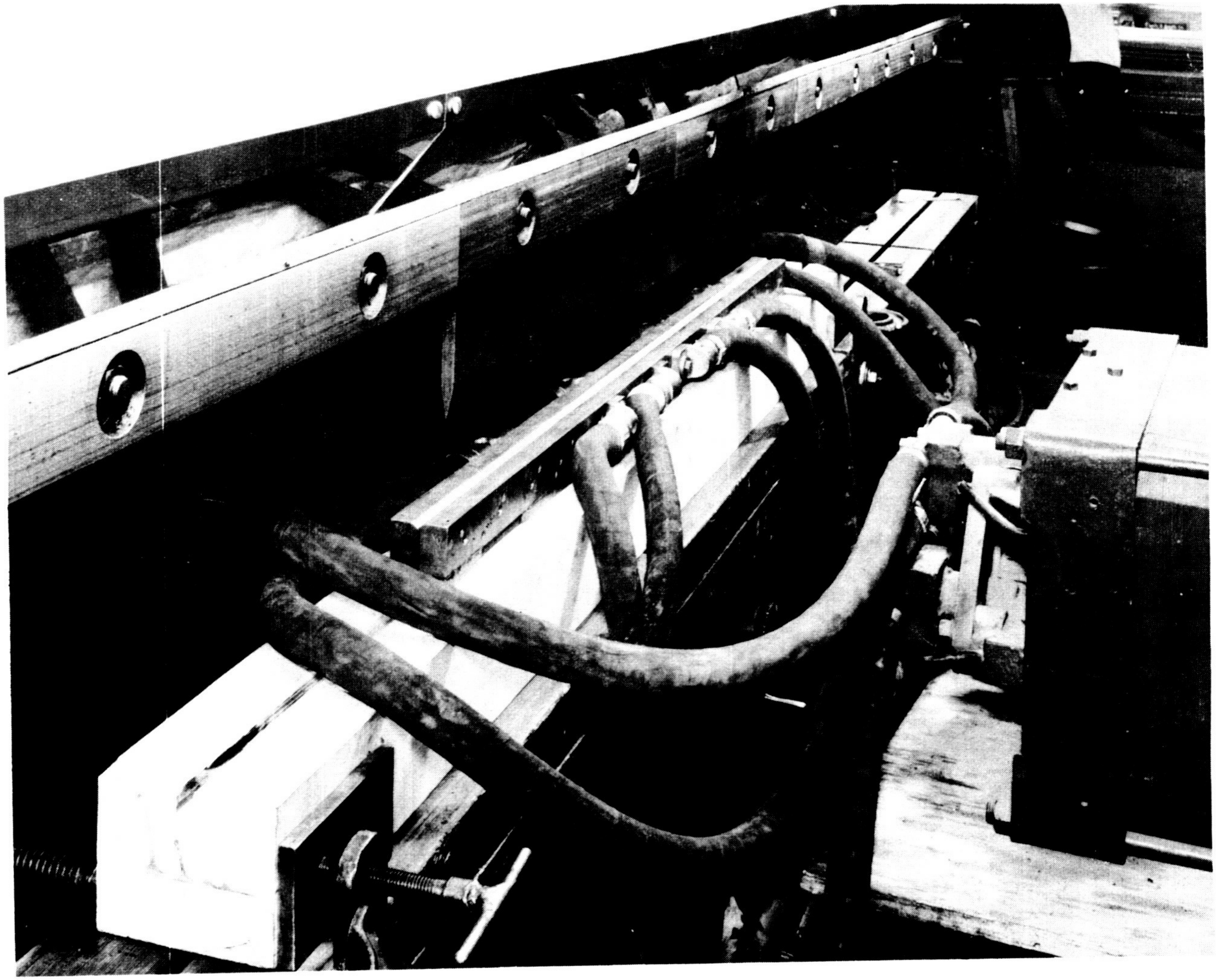


FIGURE 24. SPLIT FEMALE BRAKE-FORMING DIE WITH ELECTRICAL-RESISTANCE-HEATING CABLES ATTACHED (REF. 56)

TABLE XIII. TIME-TEMPERATURE LIMITS FOR Ti-6Al-4V ALLOY (REF. 58)[a]

Material Condition	Temperature, F[b, c]	Maximum Time, minutes[b]
Annealed	1500	0 - 30
Solution heat treated or solution heat treated and partially aged	1100	15
	1200	5
	1300	2

(a) These limiting time-temperature relationships were developed under Contract No. AF 33(600)-31802.

(b) If material is held beyond the indicated time-temperature relationship, strength may be lowered.

(c) The contractors standard 2 to 5 per cent HF, 30 to 35 per cent HNO_3 pickling solution will not remove scale formed by heating bare material (not protected by ceramic or aluminum-paint coating) beyond the following time-temperature limits:

Temperature, F	Time, minutes
1500	4
1400	8
1300	16
1200	32

Bending Limits for Titanium. Basic equations for predicting the bending behavior of materials in brake forming were developed by Wood and his associates (Ref. 53). Their analysis indicates that the natural or logarithmic strain ($\bar{E}$) in bending is related to the ratio of the sheet thickness to the bend radius:

$$\bar{E} = \ln \sqrt{1 + T/R} \quad . \tag{2}$$

The limiting strain can be taken as the strain in a 0.25-inch gage length tensile specimen corrected for width strain ($\dot{E}$). When it is desirable to predict bending limits, tension tests should be made on the material of interest using specimens gridded with 0.25-inch squares as indicated in Figure 25. From measurements of the changes in width and length of the grid where the failure occurs, the corrected values of natural strain ($\dot{E}$) are calculated as follows:

$$\dot{E} = \ln\left[1 + \frac{\Delta L}{0.25}\right] - \frac{\left(\ln\left[1 + \frac{\Delta W}{0.25}\right]\right)^2}{\ln\left[1 + \frac{\Delta L}{0.25}\right]} \quad , \tag{3}$$

where ΔL is the change in length in a 0.25-inch gage length at point of failure, and ΔW is the change in width of 0.25-inch-wide grid at point of failure.

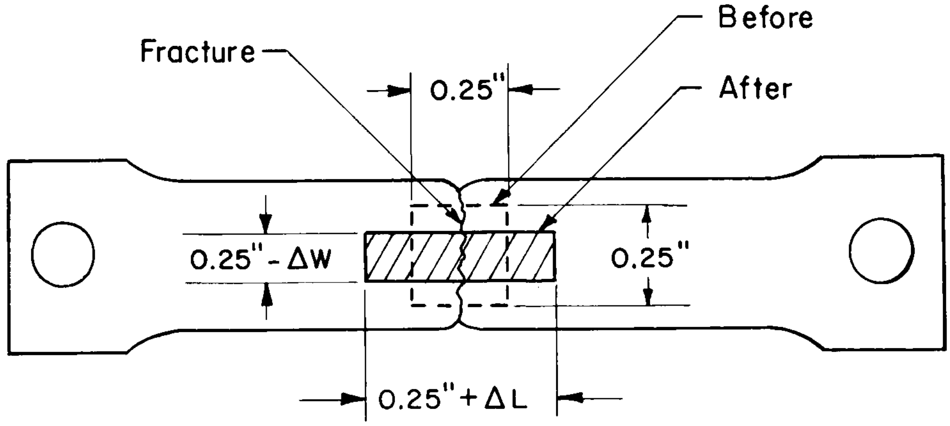


FIGURE 25. TYPICAL GRIDDED TENSION SPECIMEN (REF. 53)

A knowledge of the maximum-corrected, natural strain-value characteristic of a material permits construction of a diagram showing the limits for brake forming without cracking or splitting. A general diagram of this type is shown in Figure 26. The procedures for constructing such diagrams are indicated in Table XIV.

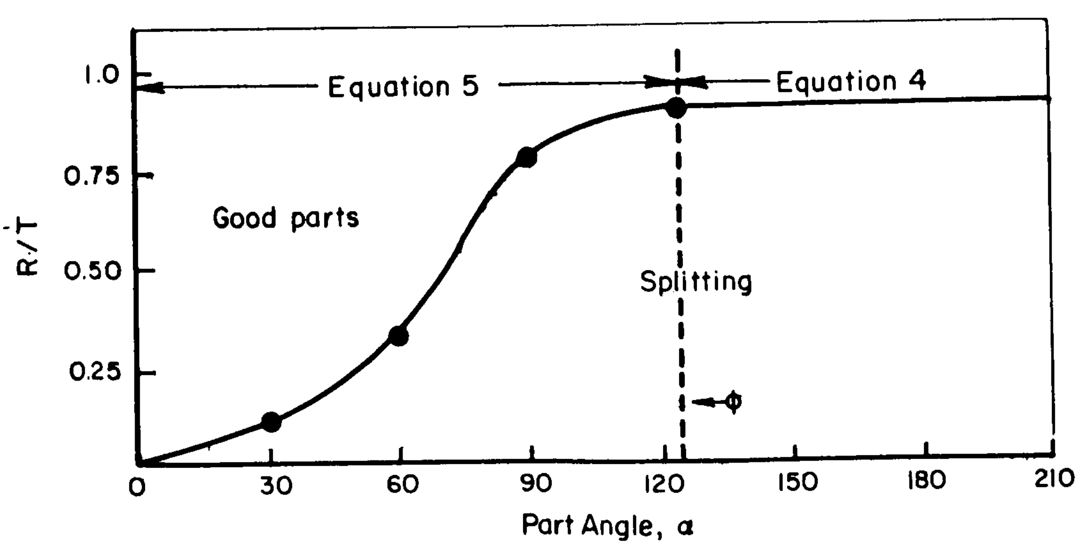


FIGURE 26. SPLITTING-LIMIT CURVE FOR BRAKE FORMING (REF. 53)

TABLE XIV. EQUATIONS FOR CONSTRUCTING SPLITTING-LIMIT DIAGRAMS FOR BRAKE FORMING (REF. 53)

Terms:

R = radius of punch or inside of bend

T = thickness of workpiece

e = base of natural logarithms, or 2.718

α = part angle

ϕ = part angle where curve reaches a maximum; further bending does not increase strain (see Figure 26).

θ = angle of interest ranging from 0 to 180 degrees

$\dot{E}$ = corrected value of maximum strain based on 0.25-inch gage length

Equations:

where $\alpha > \phi$,

$$R/T = 1/(2.718)^{2\dot{E}} - 1 \tag{4}$$

where $\alpha < \phi$,

$$R/T = 0.5\ [R/T \text{ from Equation (4)}]\ [1 + \text{Sin}\ (\theta - 90\ \text{deg})] \tag{5}$$

$$\phi = \frac{11.4 - R/T \text{ from Equation (4)}}{0.0845} \tag{6}$$

$$\alpha = \theta\ \frac{\phi}{180\ \text{deg}} \tag{7}$$

$$R/T = 0.5\left[2.718^{2\dot{E}} - 1\right]^{-1}\left[1 + \sin\left(\frac{15.21\ \alpha}{11.4 - 2.718^{2\dot{E}} - 1)^{-1}} - 90\ \text{deg}\right)\right] \tag{8}$$

The use of these equations can best be illustrated by solving a problem (Ref. 53).

Problem: Find the R/T value splitting limits for all part angles of a material and plot on graph.

Given $\overline{E}_{0.25\ corr} = 0.4$.

Step 1. Solve for R/T where $\alpha > \phi$ using Equation (4) (Table XIV)

$$\frac{R}{T}\,max = \frac{1}{\epsilon^{2\dot{E}} - 1} = \frac{1}{\epsilon^{2 \times 0.4} - 1} \,,$$

$$\frac{R}{T}\,max = \frac{1}{\epsilon^{0.8} - 1} = \frac{1}{2.225 - 1} = 0.815 \quad .$$

Step 2. Solve for ϕ using Equation (6)

$$\phi = \frac{11.4 - R/T\ max}{0.0845} = \frac{11.4 - 0.815}{0.0845}$$

$$\phi = \frac{10.585}{0.0845} = 125\ deg \quad .$$

Step 3. Solve for R/T where $\alpha < \phi$ using Equation (8) when $\alpha = 30$ deg.

$$\frac{R}{T} = \frac{1}{2}\left[e^{2\dot{E}} - 1\right]^{-1}\left[1 + \sin\left(\frac{15.21\ \alpha}{11.4 - (e^{2\dot{E}} - 1)}\right) - 90\ deg\right]$$

$$= \frac{1}{2}\left[e^{2 \times 0.4} - 1\right]^{-1}\left[1 + \sin\left(\frac{15.21 \times 30}{11.4 - (e^{2 \times 0.4} - 1)} - 90\,deg\right)\right]$$

$$\frac{R}{T} = \frac{1}{2}(0.815)\,(1 + \sin 41.6 - 90\ deg)$$

$$= \frac{1}{2}(0.815)\,(1 - 0.748)$$

$$= 0.1025 \quad .$$

Step 4. Repeat Step 3 for values of $\alpha = 60$ and 90 deg.

Step 5. Construct a graph with R/T values on the ordinate and part angle, α, on the abscissa.

Step. 6. Plot the calculated values of R/T on the graph and connect with a smooth curve. It should be noted that R/T is a maximum when $\alpha = \phi$ and the slope of the curve becomes zero.

The resulting graph is shown in Figure 26. With this graph, it is possible to select an R/T value for any angle, α. The correct punch radius could then be selected by knowing the thickness of the sheet material. It should be noted that good parts would be produced by selecting R/T values above the line for a given angle; splitting will occur for values of R/T below the line.

Brake-bending limits for a number of titanium alloys are given in Table XV (Refs. 52,59). These data show that for room-temperature brake bending, the Ti-6Al-4V alloy is considerably more difficult to bend than either the Ti-8Al-1Mo-1V or the Ti-13V-11Cr-3Al alloys. The formability limits for brake bending may be extended by lubricating the die, reducing the surface roughness of the die and workpiece, decreasing the rate of strain, and applying heat. The Ti-13V-11Cr-3Al all-beta alloy was found to be extremely strain-rate sensitive and the rate used to form the alloy was reduced from 8.77 feet per minute to approximately 1 foot per minute. In the same experiment, reducing the forming speed did not improve the formability results obtained with the Ti-6Al-4V alloy.

Splitting limits determined for various temperatures on the Ti-8Al-1Mo-1V and the Ti-13V-11Cr-3Al are plotted as a function of the rates of the punch radius to the sheet thickness for various part angles in Figure 27 (Ref. 52). The all-beta alloy is more easily formed than the Ti-8Al-1Mo-1V alloy. For example, the horizontal line showing the splitting limit for the beta alloy heated to 1200 F is only slightly higher than that of the Ti-8Al-1Mo-1V alloy heated at 2000 F. This is confirmed by data in Figure 28 where the elongation is plotted against temperature (Ref. 52). The Ti-13V-11Cr-3Al alloy is shown to be more ductile than the Ti-8Al-1Mo-1V alloy for all temperatures up to 2000 F, the highest temperature for which data were available.

Data in the literature on minimum bend radii for brake bending are summarized in Table XVI. These data are based on tests performed at Ryan (Ref. 57), Convair (Ref. 55), and North American (Ref. 56). The data give the range for sheet from several producers. The ductility of all of the alloys, except that of the Ti-4Al-3Mo-1V alloy, increases with increasing bending temperature (Ref. 55).

TABLE XV. BRAKE-BENDING LIMITS FOR SEVERAL TITANIUM ALLOYS (REFS. 52, 59)

Alloy	Bending Temperature, F	Critical Bend Angle, α	Critical Bend Limits, R/T	Bending Limits R/T for Various Angles, α, Below Critical						
				30	45	60	75	90	105	120
Ti-8Al-1Mo-1V	RT	104	2.60	0.80	1.30	1.90	2.30	2.55	2.60	2.60
Ti-6Al-4V	RT	68	5.70	2.05	4.20	5.50	--	5.70	--	--
Ti-13V-11Cr-3Al	RT	105	2.40	0.34	0.68	1.16	--	1.80	2.25	2.40
Ti-8Al-1Mo-1V	1500	128	0.60	0.05	0.07	0.13	0.23	0.43	0.57	0.60
Ti-13V-11Cr-3Al	1000	126	0.75	0.08	0.10	0.15	0.23	0.38	0.60	0.73
	1200	129	0.48	0.03	0.05	0.07	0.14	0.26	0.38	0.47

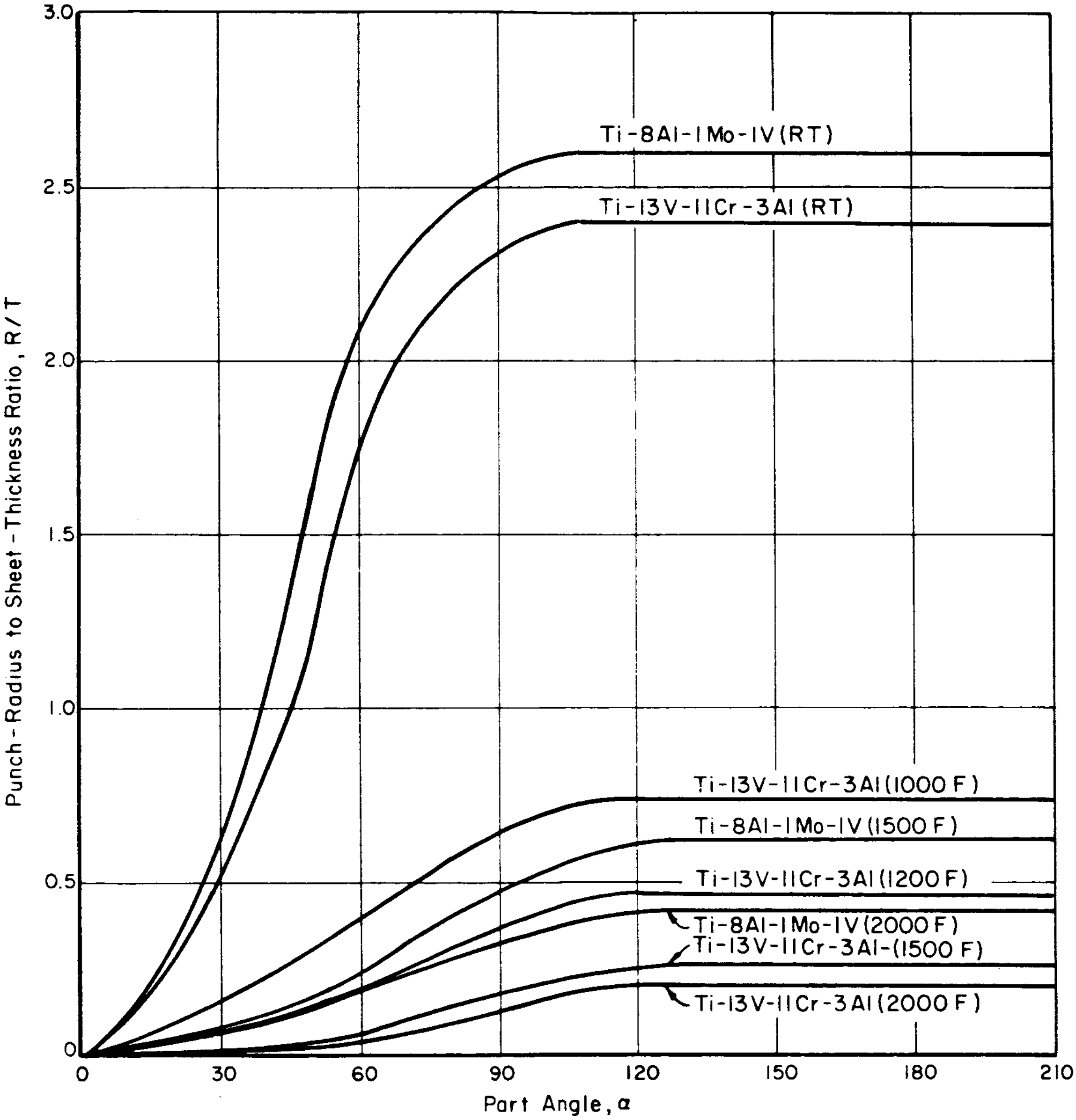


FIGURE 27. COMPOSITE OF SPLITTING LIMITS FOR TWO TITANIUM ALLOYS AT VARIOUS TEMPERATURES (REF. 52)

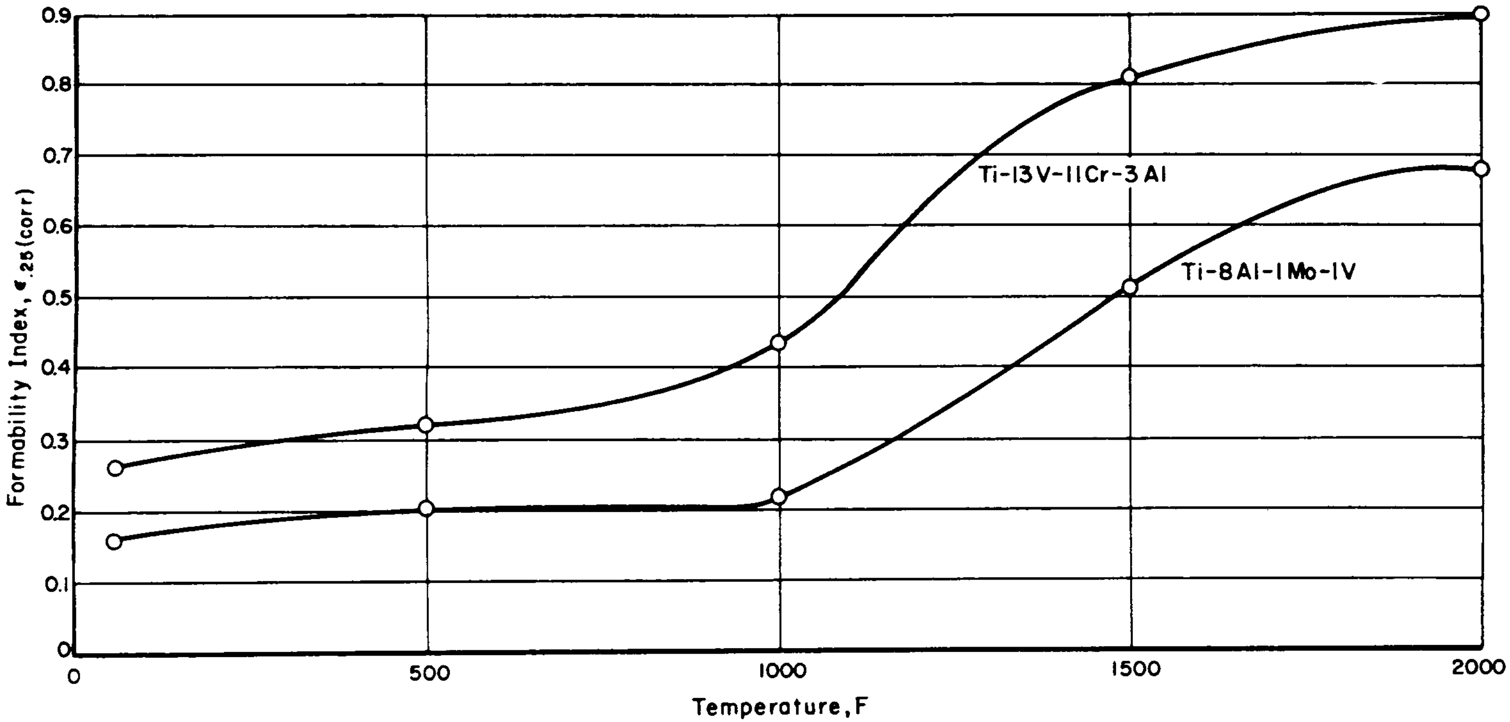


FIGURE 28. OPTIMUM FORMING-TEMPERATURE CURVES FOR BRAKE FORMING TWO TITANIUM ALLOYS (REF. 52)

TABLE XVI. MINIMUM BEND RADII FOR TITANIUM ALLOYS

Alloy	Reference	Condition of Heat Treatment[a]	Sheet Thickness, in.	Minimum Bend Radii at Indicated Temperature, F, as a Function of Sheet Thickness, R/T							
				70	400	600	800	1000	1200	1400	1500
Ti-8Mn	57	SHT	0.025-0.036	3.0-3.5	2.5	2.0-2.5	2.5	1.0-2.0	-	-	-
	56	--	<0.070	3.0	-	-	-	-	-	-	-
Ti-5Al-2.5Sn	57	SHT	0.032 and 0.063	4.6	-	-	-	-	2.0-3.5	-	-
	57	SHT	0.025-0.032	6.0-7.0	4.5-6.0	4.5-6.0	4.0-5.5	3.5-5.0	3.0-3.5	2.5	1.5-2.0
	56	--	<0.070	3.5	-	-	-	-	-	-	-
Ti-6Al-4V	57	SHT	0.035 and 0.045	4.5-7.0	3.5-6.0	3.5-5.5	3.0-5.0	2.5-4.0	1.0-3.0	1.5-2.0	1.0
	56	--	<0.070	4.5	-	-	-	-	-	-	-
	55	SHT	0.035-0.045	4.7	-	-	-	-	-	-	-
	61	SHT	0.032-0.125	3.6-4.1	-	-	-	-	-	-	-
Ti-5Al-2.75Cr-1.25Fe	61	SHT	0.035-0.045	3.0	1.0	-	-	1.0	1.0	-	-
	55	SHT	0.035-0.045	3.5	1.5	-	1.5	1.5	1.5	-	-
Ti-4Al-3Mo-1V	55	SHT	0.035-0.045	3.3	2.3	2.3	5.3	6.0	1.0	-	-
Ti-2.8Al-3.5Mn	57	SHT		2.5-4.0	2.0-2.5	1.5-2.0	1.5	1.0	-	-	-
Ti-2.5Al-16V	55	SHT	0.035-0.045	3.6	1.9	-	-	1.0	-	-	-
Ti-2.25Al-3.25Mn	56	SHT	0.025-0.032	3.5	-	-	-	-	-	-	-
Ti-1.5Al-3Mn	57	SHT		4.0	3.0	2.5-3.0	2.0-2.5	1.5-2.0	-	-	-
Ti-2Fe-2Cr-2Mo	57	SHT	0.035-0.045	2.5-3.0	2.0	2.0	1.5	1.0-1.5	-	-	-
Ti-12.5V-10.5Cr-3Al	56	--	<0.070	1.5	-	-	-	-	-	-	-
Ti-13V-11Cr-3Al	55	SHT	0.035-0.045	3.2	1.0	-	-	1.0	-	-	-
Ti-2Fe-2Cr-2Mo	57	--	0.035-0.045	5.0	-	-	-	-	-	-	-

(a) -- = not specified but presumed to be the solution-heat-treated condition; SHT = solution heat treated.

The solution-treated Ti-4Al-3Mo-1V alloy is aged rapidly by heating to temperatures up to about 1000 F. This causes the material to become stronger and stiffer and the resultant minimum bend radius must be increased, a value of 6.0 T being required at 975 F. However, at 1200 F, the alloy apparently has overaged and again softened, permitting bending over a 1.0 T bend radius.

The most ductile alloys studied were the two all-beta alloys, Ti-13V-11Cr-3Al and Ti-12.5V-10.5Cr-3Al, and the Ti-5Al-2.75Cr-1.25Fe alloy. These three alloys could be bent over a 1.0 T radius at temperatures as low as 400 F.

The most difficult alloys to bend are the Ti-6Al-4V and the Ti-5Al-2.5Sn alloys. For these alloys to be bent over a 1.0 T radius, temperatures of the order of 1500 F or higher are required.

The following temperatures have been reported to be satisfactory for brake forming commercially pure titanium and some of the titanium alloys on a production basis (Ref. 21):

Titanium Alloy	Temperature, F Blank	Temperature, F Punch and Die
Commercially pure	400-600	500
Ti-8Mn	900-1100	500
Ti-6Al-4V	1000-1200	500
Ti-5Al-2.5Sn	1000-1300	500
Ti-8Al-1Mo-1V	1100-1200	1150
Ti-6Al-4V[a]	1200[b]	1200

(a) Reference 57 (12-inch-long sheet samples, 0.032 or 0.063 inch thick).
(b) Heated by contact with hot punch and die.

The values in Table XVI for minimum bend radii were determined experimentally and are not design values. Handova and Winslow (Ref. 56) indicate that the relationship between experimentally determined radii and radii used in design are as given in Table XVII. Generally the design bend radii are 0.5 to 1.0 T higher than those determined experimentally. This "safety factor" is employed to compensate for the sheet-to-sheet differences that occur in titanium alloys of the same grade and often the same heat.

TABLE XVII. EXPERIMENTALLY DETERMINED BEND RADII AND DESIGN BEND RADII FOR FIVE TITANIUM ALLOYS (REF. 56)

Alloy	Sheet Thickness, in.	Experimental Bend Radii, XT	Design Bend Radii, XT
Ti-8Mn	<0.070	3.0	4.0
	>0.070	--	4.5
Ti-5Al-2.5Sn	<0.070	3.5	4.5
	>0.070	--	5.0
Ti-6Al-4V	<0.070	4.5	5.5
	>0.070	--	6.0
Ti-2.25Al-3.25Mn	<0.070	3.5	4.5
	>0.070	--	5.0
Ti-12.5V-10.5Cr-3Al	<0.070	1.5	2.5
	>0.070	--	3.0

Springback. A sizeable amount of springback is encountered when bending the titanium alloys at room temperature. Springback is less in the annealed alloys than in the harder and stronger solution-treated or solution-treated and aged alloys. Bending at elevated temperatures minimizes or eliminates springback. Springback usually is expressed in degrees for a specified bend angle.

In production bending, an allowance for springback can be made by overbending and then permitting the bend to return to the desired angle. However, the variability among sheets of titanium makes it difficult to compensate adequately for springback. Therefore, it is often necessary to employ handwork, hot sizing, or hot-bending techniques to produce the desired shapes.

Values of springback are given in Table XVIII for room-temperature bend tests performed at North American Aviation (Ref. 56) and at Convair (Refs. 55,60). These values are companion values to the bend data in Table XVI. The solution-treated and aged samples of the Ti-4Al-3Mo-1V and the Ti-2.5Al-6V alloys exhibited considerably less springback than the solution-treated sheet specimens of the same alloys.

Post-Forming Treatments. Brake-formed parts that require closer tolerances may be finished by handworking or hot-finish-forming methods. Defects such as slight twisting or straightening in cold-brake-formed parts can often be corrected by hand forming when

TABLE XVIII. SPRINGBACK IN 90-DEGREE BENDS FOR SEVERAL TITANIUM ALLOYS

Alloy	Reference	Condition of Heat Treatment[a]	Sheet Thickness, in.	Degrees of Springback in 90-Degree Bend at Indicated Temperature, F							
				RT	400	600	800	900	1000	1100	1200
Ti-8Mn	56	--	< 0.070	14	--	--	--	--	--	--	--
Ti-6Al-4V[b]	57	SHT	0.032 and 0.063	15	--	--	--	--	--	--	3.5
	56	--	< 0.070	20	--	--	--	--	--	--	--
Ti-6Al-4V	55	SHT	0.040	16	--	--	--	--	--	--	--
Ti-5Al-2.5Sn	56	--	< 0.070	17	--	--	--	--	--	--	--
	57	SHT	0.032 and 0.063	15	--	--	--	--	--	--	2
Ti-5Al-2.75Cr-1.25Fe	55, 60	SHT	0.040 and 0.060	26	16	--	--	13	--	12	--
	55, 60	SHT	0.090	28	16	--	--	14	--	11	--
Ti-4Al-3Mo-1V	55	SHT	0.040	18	16	16	26.5[c]	--	13	11	--
	55	SHA	0.040	0.5	0.2	0.1	1.0	--	0.5	0.2	--
	61	SHT	0.032	24.5	--	--	--	--	--	--	--
	61	SHT	0.063	24.1	--	--	--	--	--	--	--
	61	SHT	0.125	22.0	--	--	--	--	--	--	--
Ti-2.5Al-16V	55	SHT	0.040	24	17	10	9[d]	--	3	2.5	--
	55	SHA	0.040	2.5	0.2	-0.2	-1.8	--	--	--	--
Ti-2.25Al-3.25Mn	56	--	< 0.070	20	--	--	--	--	--	--	--
Ti-12.5V-10.5Cr-3Al	56	--	< 0.070	5	--	--	--	--	--	--	--
Ti-13V-11Cr-3Al	55	SHT	0.025	17	--	--	--	--	--	--	--
	55	SHT	0.040	15[e]	9[e]	--	--	--	--	--	--

(a) -- = not specified but presumed to be the solution-heat-treated condition; SHT = solution heat treated; SHA = solution heat treated and aged.

(b) 105-degree bend.

(c) A value of 5.5 deg was reported for springback of 0.040-inch-thick sheet (Ref. 60).

(d) A value of 1 deg was reported for springback of 0.040-inch-thick sheet (Ref. 60).

(e) Values of 24 deg and 17 deg also were reported for the bending of 0.040-inch-thick sheet at room temperature and 400 F, respectively (Ref. 60).

relatively few parts are involved. For larger lots, consideration should be given to using hot-forming techniques to form the required part or to add a hot-sizing step to the operation.

The usual requirements for post-forming operations might include deburring, cleaning with MEK, visual or penetrant inspection for cracks, shearing length or width when required, and pickling, washing, protective wrapping, and identification. Parts formed at elevated temperature also need to be descaled. Pickling in acid baths approved for titanium is an effective way of removing such scale and oxide.

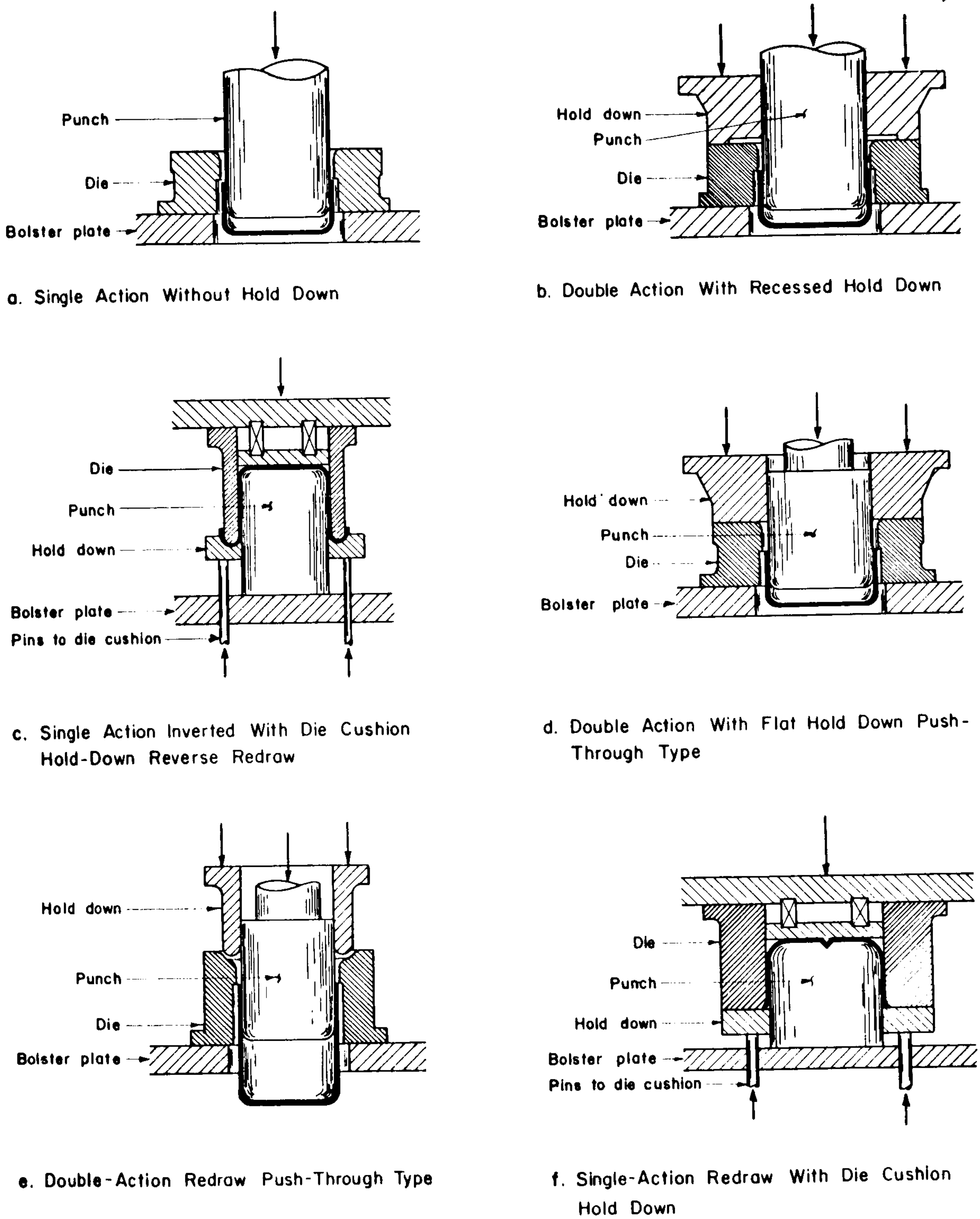
DEEP DRAWING

Introduction. Deep drawing is a process used to produce cylindrical, prismatic cups, with or without a flange on the open end, from sheet metal. Cups or tubes can be sunk or redrawn to increase their length and to reduce their lateral dimensions. These types of operations are illustrated by the sketches in Figure 29. The drawing stresses result principally from the action of the punch on the central section of the blank. If the ratios of the blank diameter to sheet thickness and punch diameter are sufficiently small the metal will draw in around the punch without buckling. Under such conditions, and by using other expedients, sheet metals can be deep drawn in single-action presses. Double-action presses, however, are used more commonly. They apply pressure on a blank holder to prevent buckling in the flange.

The deep-drawing process is well suited to producing large numbers of identical, deeply recessed parts. Precise tooling and carefully controlled forming conditions must be used to insure successful operations. The expense of setting up suitable equipment and procedures usually limits economical operations to rather large lots, over 500 pieces.

Titanium and its alloys are deep drawn commercially at both room and elevated temperatures. Cups, oxygen bottles, and heads for pressure vessels are produced from titanium by deep drawing.

Presses for Deep Drawing. Both mechanical and hydraulic presses are used for deep drawing. The punch speed and the force available on a mechanical press ordinarily varies during the stroke. Furthermore, it is more difficult to provide a controlled double action or blank holder pressure on mechanical presses than on hydraulic presses. For these reasons, the use of mechanical presses is



a. Single Action Without Hold Down

b. Double Action With Recessed Hold Down

c. Single Action Inverted With Die Cushion Hold-Down Reverse Redraw

d. Double Action With Flat Hold Down Push-Through Type

e. Double-Action Redraw Push-Through Type

f. Single-Action Redraw With Die Cushion Hold Down

FIGURE 29. TYPES OF DEEP-DRAWING OPERATIONS (REF. 62)

normally restricted to shallow parts where the depth of draw is 5 inches or less.

Hydraulic presses operate at lower punch speeds than mechanical presses. This is often an advantage in deep drawing titanium. Hydraulic presses for drawing operations are generally equipped with a die cushion that is operated hydraulically. The hold-down pressure on the blank holder is normally preset to remain constant during the drawing operation although auxiliary pumps are sometimes used to vary the pressure during the stroke.

The blank holder must be constructed and adjusted to allow the metal to thicken as the edge of the blank moves radially toward the punch. The pressure needed to prevent wrinkling in the flange is of the order of 1-1/4 per cent of the ultimate strength of the workpiece material. This pressure, ranging from 500 to 1800 psi for titanium and its alloys is exerted on the area of the blank holder in contact with the blank. It normally raises the drawing load by about 20 per cent. The hold-down pressure can be applied to the blank holder by air or hydraulic cushions or springs. Devices for this purpose can be added to single-action presses.

Presses are available in various sizes for deep-drawing parts as small as cooking utensils and as large as automobile roofs. The characteristics of a few commercial presses used for typical operations are indicated in Table XIX. Figure 30 shows an 800-ton double-action hydraulic press used in forming domes from aluminum. Figure 31 is a picture of a large triple-action press. It has separate hydraulic systems for applying force to the punch, the hold down, and for ejecting parts. The press is shown being used for cupping and redrawing to a smaller diameter in one stroke of the press.

The maximum load in drawing a blank is normally reached when the flange has decreased in diameter by about 15 per cent or when the punch travel is about one-third complete. The maximum drawing load can be estimated from the following formula (Ref. 63):

$$P = \pi d T S (C - 1 + D/d) , \qquad (9)$$

where

P = punch load, pounds

D = blank diameter, inch

d = punch diameter, inch

TABLE XIX. CHARACTERISTICS OF TYPICAL DEEP-DRAWING PRESSES

Manufacturer	Type Press	Platen Size, in.	Tonnage
Bliss	Mechanical single-action air die cushion	24 x 24	100
		120 x 72	1200
	Mechanical double-action toggle press	24 x 24	100
		120 x 72	1200
H.P.M. Corporation	Hydraulic or triple single action with die cushion	36 x 36	150
		36 x 36	300
		60 x 48	400
		60 x 60	800
		60 x 60	1000
		72 x 72	2000

Notes:

(1) Most draw presses are single action with a die cushion. Some may require the use of an ejector for part removal.

(2) Increased platen area is generally coincident with increased press tonnage.

(3) Mechanical presses are more adaptable to high-speed and automated operation. They are also more difficult to control and tool up.

(4) Additional sizes and tonnages of presses are available and the manufacturers should be consulted for specific requirements.

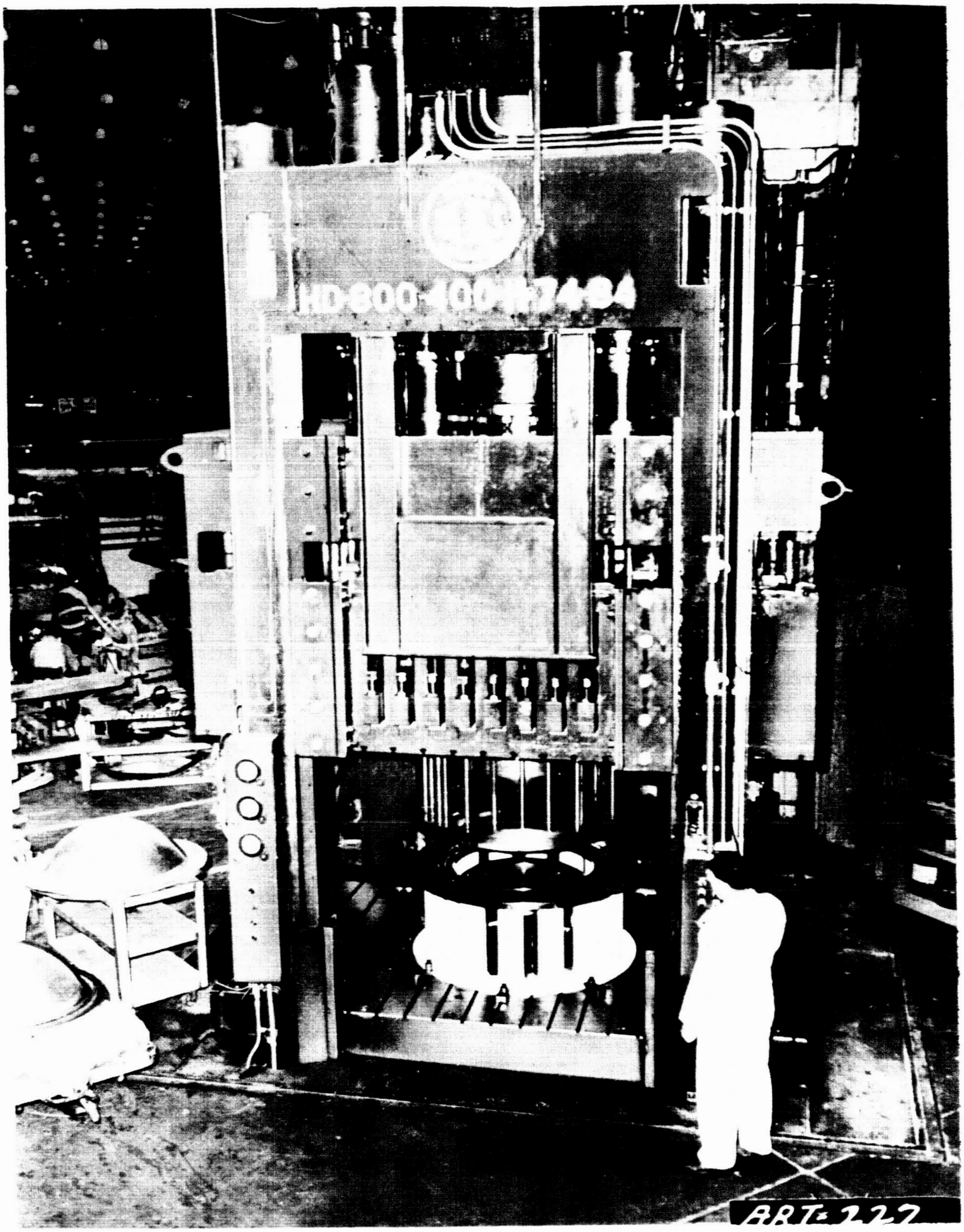


FIGURE 30. 800-TON DOUBLE-ACTION HYDRAULIC PRESS DEEP DRAWING 52-INCH-DIAMETER HEMISPHERICAL ALUMINUM SHELLS (REF. 63)

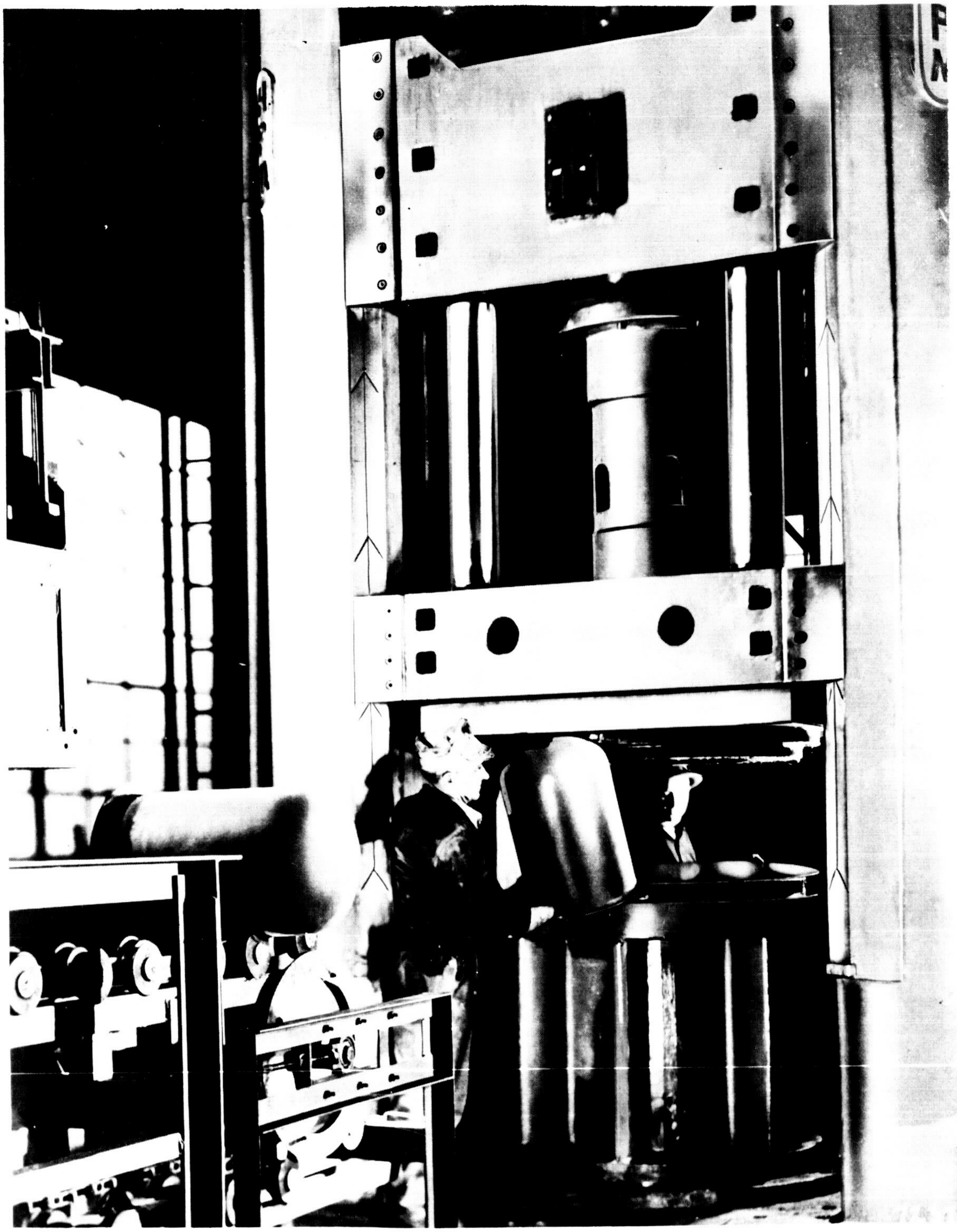


FIGURE 31. TRIPLE-ACTION HYDRAULIC PRESS FOR DEEP DRAWING 750-TON CUPPING AND REVERSE DRAW IN ONE OPERATION (REF. 64)

T = blank thickness, inch

S = maximum stress in metal, psi

C = an empirical constant to tube bending and blank-holding loads into account approximately 0.40 for titanium.

Tooling for Deep Drawing. The design of the tooling used in deep drawing depends on the type of press to be used. In the simplest terms the tooling consists of three parts: the die, punch, and hold-down ring. The punch may be attached to the ram or, in inverted drawing operations, to the base platen. The die will be attached to the press member opposite to the punch. The hold-down ring would be attached to the die cushion in an inverted operation by means of pusher rods, as shown in Figure 32, or might be connected directly to a die cushion that can pull down instead of push. In single-action presses an air-operated die cushion might be used or the hold-down ring might be attached to the ram and spring loaded.

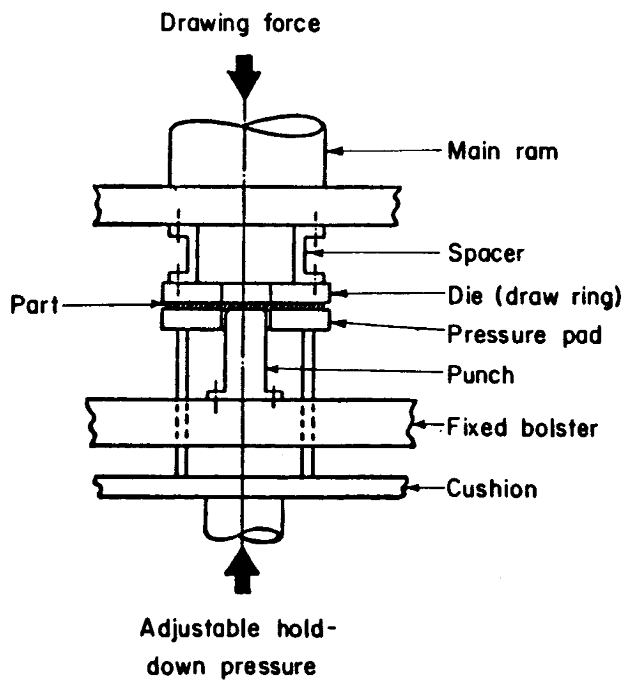


FIGURE 32. DOUBLE-ACTION DRAW DIE (REF. 53)

Although not widely used in production operations there are two alternative methods for preventing wrinkling without supplying controlled pressures to the hold-down ring. A rigid blank holder with a flat surface is the simplest type of hold-down ring. It requires careful adjustment of the gap between the die and the hold-down surface to allow for thickening as the blank is drawn and to prevent wrinkling. The drawing load is increased when the gap is either too small or too large. According to Sacks (Ref. 65) the gap should be 25 to 50 per cent smaller than the thickness developed as the edge of the flank moves from its origin to final position. This amount of thickening is given by the equation:

$$T/T_1 = D/D_1 \quad , \tag{10}$$

where

T = blank thickness

T_1 = thickness of the flange during drawing

D = blank diameter

D_1 = diameter at the edge of flange or the mean diameter of cups drawn without a flange.

The difficulty of adjusting rigid blank holders can be avoided by tapering the hold-down surface. The taper, which is not very critical, can be based on the above equation. Experiments indicate that conical blank holders result in lower drawing loads than other types (Ref. 65).

A number of tooling materials have been used for deep-drawing operations at room temperature. Some of these materials in order of production capability starting with the shortest life are AISI Type W1, O1, A2, S1, and D2 (Ref. 49). The punches are generally chromium plated 0.0002 to 0.0004 inch for easier removal of the part from the punch. Some of the less expensive alloy steels like AISI Type 1040, 2340, 3140, and 4140 can be used as punches if they are case carburized. The punches are generally hardened to R_C 60 minimum.

Similar tool steels may be used for elevated-temperature operations. The associated hardware for tooling assembly should be made of stainless steel to reduce difficulties with disassembly after the tooling has been heated. The most common method of heating tooling in deep-drawing operations is with cartridge-type electrical heaters that are integral with the die. The dies must be insulated from the platens of the press with a material such as compressed "Marinite" to prevent heat conduction to the press. A heat shield should also be placed around the die to prevent unnecessary heat radiation for ease of working on the machine. A typical die setup for elevated-temperature forming of titanium is shown in Figure 33. This tool is

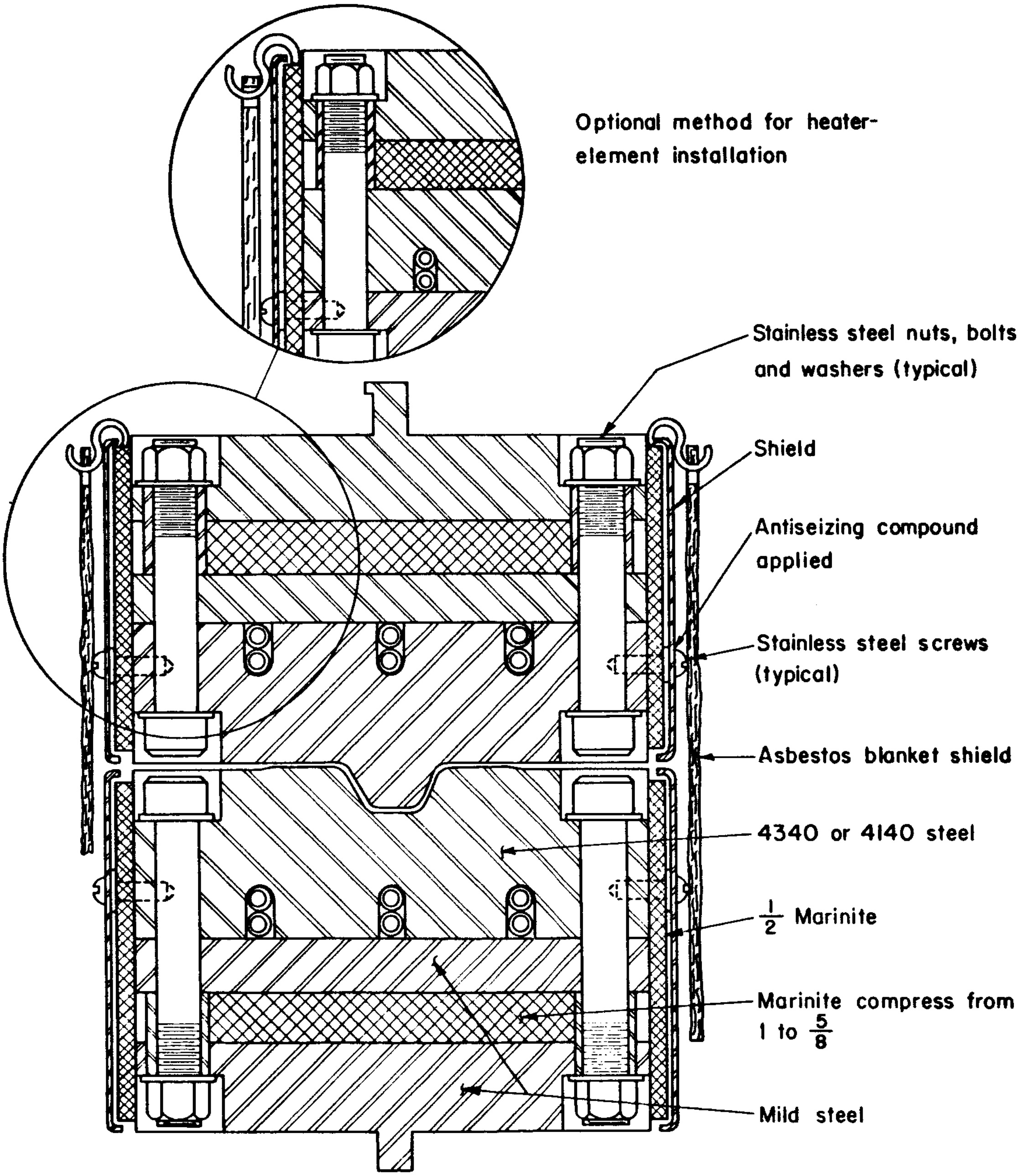


FIGURE 33. HEATING ARRANGEMENT FOR MATCHED DIES (REF. 58)

for a single-action press and does not have a hold-down ring for control of wrinkling in the flange.

A typical set of tooling for an inverted deep-drawing operation on a double-action press is shown in Figure 32. The die cushion first applies a load through the pressure pad to hold the blank against the die or draw ring attached to the ram. The ram then moves the blank down over the punch carrying the pressure pad with it. It is sometimes also necessary to have a stripper that will remove the part from the punch. In the inverted drawing operation the pressure pad acts as the stripper provided the blank is not drawn completely through the die.

Clearances between the punch and die must be controlled to prevent galling, rupture, or buckling in the cup wall. Variations in thickness within sheets from the same lot or between lots can cause difficulty. The selection of the clearance between the punch and draw ring depends to come extent on the dimensional requirements of the part. If the clearance is larger than the amount of thickening predicted by the preceding equation, the cupped part will not be in contact with both the punch and the die. This permits a minimum drawing load but results in a part with a variable wall thickness. If the clearance is smaller than necessary to accommodate the thickening in the upper part of the cup some ironing or wall thinning will occur. Severe ironing increases drawing loads. No specific recommendations about clearances for deep-drawing titanium were found in this survey. Therefore, it appears that ironing should be avoided in severe drawing operations. This is the practice for stainless steel. For less severe forming operations, clearances of 10 to 20 per cent more than the metal thickness can probably be used safely. They will cause some ironing but will produce straighter parts with more uniform wall thicknesses.

The radii on the draw ring and nose of the punch are important in severe drawing operations because they affect the stress required for bending. If the punch radius is too small the metal will thin, neck, and rupture near the bottom of the cup. Radii slightly larger than the minimum permissible for bending will permit shallow draws. Larger radii permit parts to be formed with larger flanges or to deeper depths. In general, the radius on the draw ring should be 5 to 10 times the thickness of the metal. Excessively large radii, in excess of about 15 T, may cause the parts to pucker. For severe operations the punch radius should exceed 5 times the sheet thickness. In one study (Ref. 66), on the 0.05-inch Ti-5Al-2.5Sn at 1200 F, increasing the punch radius from 6 to 10 T increased the permissible drawing reduction from 35 to 50 per cent. On the other hand, the bottoms of spherical or dome-shaped parts are weakened if the radius exceeds about one-third of the punch diameter.

Techniques for Deep Drawing. The techniques used in deep drawing depend on the type of equipment available and the shape of the part to be produced. Shallow parts of cylindrical shape are the easiest to produce, as the complexity of shape and depth of draw increase so does the difficulty in setting up and producing the parts. In most drawing operations compressive stresses in the circumferential direction tend to buckle, or wrinkle the rim of the blank. Shallow wrinkles can be ironed out between the punch and the die but they should be prevented from forming by adjusting the force on the hold-down ring. For large production runs on a single-action press the clamping force may be applied by means of springs. Where production runs are smaller, or a number of different size parts are to be made on the same equipment, it is better to have a readily adjustable hold-down force. This is a desirable feature when variations in thickness and properties of sheet material might be expected. The operator can readjust the machine settings to accommodate the variations and reduce the amount of scrap. The double-action press is more versatile with respect to adjustment of operating conditions but may be more expensive to tool up.

Some parts may be deep drawn in one stroke of the press, others require a number of operations in different dies. There is a limit, even with intermediate anneals, on how far a part can be reduced in one operation. The general practice is to take smaller reductions in redrawing operations than that used for the previous operation. As the number of operations increases so does the cost of the forming operation. Drawing operations on titanium are generally limited to part designs that can be made in one operation. The quantity of titanium parts required usually does not warrant the higher tooling costs of redrawing techniques. Parts that would require multiple draws are normally fabricated by forming of sections and welding to obtain the final shape.

The techniques used in elevated-temperature drawing of titanium are similar to those used at room temperature. Deeper draws are generally possible, but tooling life is shorter due to thermal distortion of the dies. For deep drawing at elevated temperature, the blanks should be furnace heated and placed on warm dies. This will save time in the operation as well as reduce thermal shock to the tooling. Once a set of tools has been heated it should be maintained at temperature until the production run is completed. Oxidation of the tooling during down periods can be reduced by covering the dies with an asbestos blanket or closing the tools on a stainless steel part. Chromium plating of the tooling also minimizes oxidation due to elevated-temperature operations.

Lubrication of the blanks in deep drawing is necessary to obtain maximum drawability. It minimizes the energy or pressure required to overcome friction between the blank and the tooling and reduce the possibility of galling or seizing. In hot working it reduces the rate of heat transfer between the blank and the tooling, which is important where the blank is heated while the tooling is not. Lubricants should be prevented from building up a residue on the tooling. Frequent cleaning of the tooling is necessary especially with elevated-temperature operations.

For room-temperature deep-drawing operations, an organic non-chlorinated oil can be used. At elevated temperatures, boundary-type lubricants with added solids such as graphite or molybdenum disulfide, appear to be best. Lubricants like Everlube T-50 and Dag-41 have been used successfully for deep drawing of titanium at elevated temperature.

Lubrication between the blank and the die and blank holder, and between the part and the die, is desirable. Friction in those locations raises the drawing load and may lead to galling or nonuniform movement of material over the tooling. On the other hand, friction at the radius and bottom of the punch is desirable. Higher friction on the punch side of the blank reduces the tensile stresses which cause stretching, and sometimes rupture, at those locations. Therefore, benefits are sometimes obtained from rough or unlubricated (Ref. 67) punches.

Titanium-Blank Preparation for Deep Drawing. The size of the blank for deep drawing is normally based on the assumption that the surface area will not change during forming. This approach is useful, although light draws with generously rounded punches can result in a slight decrease in surface area while deep draws involving ironing and sharp radii on the punches can result in an increase in surface area (Ref. 62). For parts to be trimmed to size after forming the exact development of the blank is not critical.

The blank shape should be carefully developed to avoid cracking or excessive thinning of the part. Cups and boxes frequently are made using circular blanks, while the blanks for other deep-drawn parts may require special contours. In order to control the thickness of drawn articles to close tolerances the blanks are sometimes ground to compensate for uneven thinning. Garfield (Ref. 68) reports that the 50-inch-diameter blank used for forming a particular 32-inch-diameter hemispherical head was ground so that the central 14-inch-diameter region, which was 0.118 inch thick, was connected by a tapered section to the outer 12-inch annulus, which was 0.106 inch thick.

A number of factors generally require that the part be trimmed after forming. Some of these include variations in the material properties and thickness, anisotropic material properties, unevenly distributed hold-down pressure, and inaccuracy in centering the blank. A trim allowance of 1/8 to 1/2 inch may be sufficient for simple shapes while more may be required for a box shape in order to control the metal flow. To improve the drawing performance, sometimes parts are made with flanges, which are later removed by trimming.

The preparation of the blank for deep drawing is the same as for other forming process as listed in that section of this report.

Principles of Deep Drawing. Failures in drawing operations result from complex phenomena. Unlike the situation in some other forming operations, failure conditions are controlled by the general change in shape rather than by the strain requirements in certain locations. The forces developed at the punch originate from

(1) The stress required to bend the sheet around the nose of the punch

(2) The stress necessary for circumferentially compressing and radially stretching the metal in the flange

(3) The stress required to bend the metal around the draw ring and unbend it as it flows from the flange into the wall of the part

(4) The stress used in overcoming friction at the die radius and under the blank holder

(5) The stress developed by ironing the wall.

For these reasons, it is difficult to predict success or failure in a particular deep-drawing operation from ordinary tensile data for the workpiece materials.

A considerable background of information is available about the influence of characteristics determined in true-stress true-strain tensile tests on the performance of steel in deep-drawing operations. Although the principles would be expected to hold for titanium, pertinent data on that point are scanty. Studies on steel indicate that better performance in drawing operations correlates with higher values of work-hardening coefficients and uniform elongation and more severe "normal" anisotropy. The relative importance of these characteristics varies with the geometry of the drawing operation.

Uniform elongation is particularly important in drawing operations characterized by significant amounts of stretch forming. For example, it is more important in controlling forming limits for cups with hemispherical rather than flat bottoms. Even when stretching is not of major importance the workpiece must be ductile enough to withstand bending. Higher work-hardening coefficients indicate resistance to thinning and permit deeper draws without tearing.

The concept that pronounced "normal" anisotropy is desirable for deep drawing is a little more complicated. For maximum drawability in ductile metals it is desirable for the material to be resistant to thinning from radial stretching but weak in upsetting from circumferential compression. This results in a high strength in the wall of the cup compared with the stresses needed to upset material in the flange. This condition is better satisfied by materials exhibiting higher ratios of width-to-thickness strains in tensile tests. This type of anisotropy termed "normal" in contrast to directional variations in properties in the plane of the sheet is expressed by the following relationship:

$$R = \frac{\ell n \ W_o/W}{\ell n \ T_o/T} \quad , \tag{11}$$

where

R = anisotropy ratio

W_o = original width of specimen

W = width after straining

T_o = original thickness

T = final thickness.

The anisotropic parameter of a sheet material can be determined by measuring strain ratios of specimens oriented at 0, 45, and 90 degrees from the rolling direction. The component of normal anisotropy can (Ref. 69) be defined as:

$$R = 1/4\ (R_0 + 2\ R_{45} + R_{90}) \quad . \tag{12}$$

The degree of normal anisotropy in terms of relative flow strengths in the thickness, Z, and planar, X, directions of sheet is given by the expression

$$\frac{Z}{X} = \sqrt{\frac{1 + R}{2}} \quad . \tag{13}$$

A completely isotropic material would have R values of one for tests in all directions, and a uniform strength in the thickness and plane of the sheet.

A classic example of the importance of normal anisotropy on performance in cup-drawing tests is given in Figure 34. The advantage of high R values has also been demonstrated in commercial operations on steel. Figure 34 shows that a particular titanium sheet exhibited more anisotropy and better drawability than the steel and aluminum samples tested by Lloyd (Ref. 70).

The severity of a deep-drawing operation can be described by defining the geometry of the cup and blank. The important geometric variables are indicated in Figure 35. The deep-drawing properties of materials are often compared on the basis of the maximum reductions they will withstand under standardized conditions. The ratings are often expressed on the basis of the

$$\text{Maximum Drawability Percentage} = 100 \times \frac{D-d}{D} \quad ,$$

or the

$$\text{Limiting Drawing Ratio} = D/d \quad ,$$

where D and d are the diameters of the die and punch, respectively.

The ratio of the blank radius to the height of the cup is also used to indicate the severity of a drawing operation. The height, H, of flat-bottomed cups with sharp radii, if no stretching or ironing occurs, can be calculated from the relationship:

$$H/d = 1/4 \left[(D/d)^2 - 1\right] \quad . \tag{14}$$

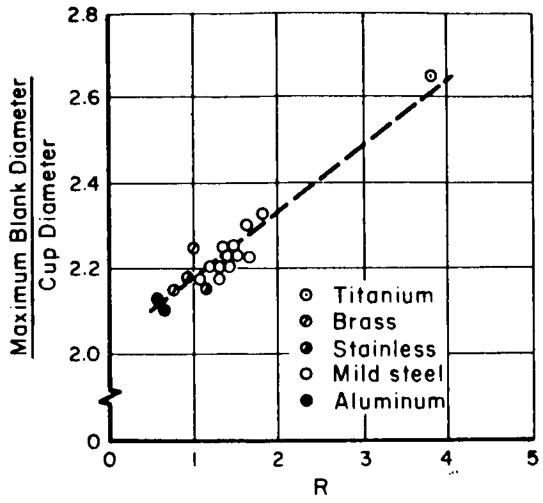


FIGURE 34. CORRELATION BETWEEN NORMAL ANISOTROPY (R VALUE) AND THE ABILITY OF MATERIALS TO BE DRAWN INTO FLAT-BOTTOMED CUPS (REF. 69)

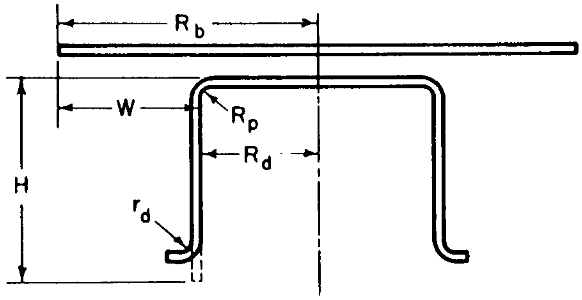


FIGURE 35. GEOMETRICAL VARIABLES FOR CUPPING (REF. 53)

R_b = radius of the blank
R_d = radius of the die
W = R_b - R_d
H = finished height of cup with no flange
R_p = radius of the punch
D = 2 R_b = blank diameter
d = 2 R_d = punch diameter.
r_d = draw radius

When there is a flange on the cup the relationship changes as shown in Figure 36. The ratio of the diameter or radius to the thickness of the blank may affect success in deep drawing. Wood (Ref. 53) considers it very important as indicated by his schematic diagram shown in Figure 37. In any case, the friction resulting from the hold-down pressure becomes an appreciable part of the load in drawing comparatively thin blanks. This, and variations in thickness, contributes to the inferiority sometimes reported for drawability of very thin sheet.

Deep Drawing of Titanium. Comparatively little specific information is available about the practices and forming limits for deep drawing titanium.

Figure 38 shows the shapes of a variety of parts that were deep drawn from the Ti-5Al-2.5Sn alloy at elevated temperatures. Although the forming temperatures were not mentioned, they were probably in the range of 1000 to 1200 F.

Figure 39, based on data obtained at Worcester Pressed Steel Company (Ref. 66), shows that titanium exhibits much better ductility at 1000 F than at room temperature. In that study, poorer results were obtained at 400 F than at room temperature. The charts also indicate that the drawability percentage was significantly better for lower punch speeds. The data for commercially pure titanium indicated that the drawability decreased appreciably as the thickness increased. The reason for this is unknown. It may be a reflection of differences in normal anisotropy or in tooling details.

Wood (Ref. 53) explained the improvement in drawability of titanium at elevated temperatures on the basis of changes in the parameter

$$\frac{E}{Y_c} \times \frac{Y_c}{Y_t} , \tag{15}$$

where

E = Young's elastic modulus

Y_c = compressive yield strength

Y_t = tensile yield strength.

For titanium and its alloys this parameter, which affects buckling, increases rapidly above 800 F. From consideration of the mechanical properties and buckling equations, Wood predicted the deep-drawing

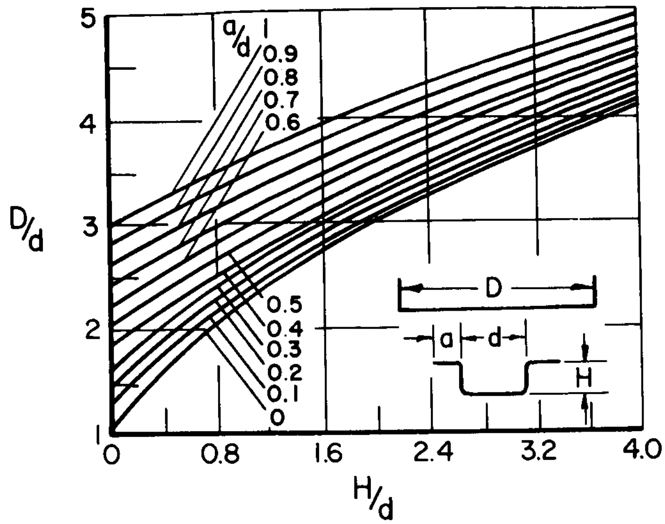


FIGURE 36. THEORETICAL RELATIONS BETWEEN THE DIMENSIONS OF A SHARP-RADIUSED CYLINDRICAL PART AND THE BLANK DIAMETER (REF. 65)

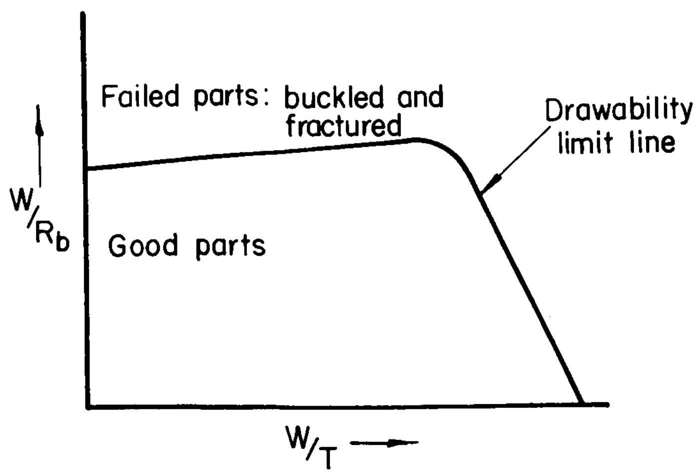


FIGURE 37. SCHEMATIC DIAGRAM INDICATING EFFECT OF GEOMETRICAL FACTORS ON FORMING LIMITS IN DEEP DRAWING (REF. 53)

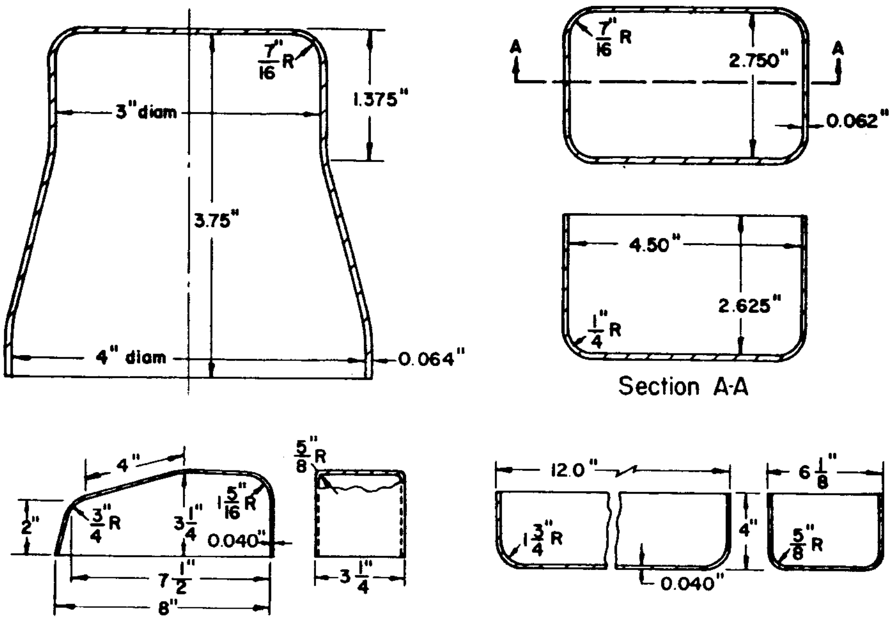


FIGURE 38. SECTIONS OF FOUR PARTS DEEP DRAWN AT ELEVATED TEMPERATURES FROM THE Ti-5Al-2.5Sn ALLOY (REF. 71)

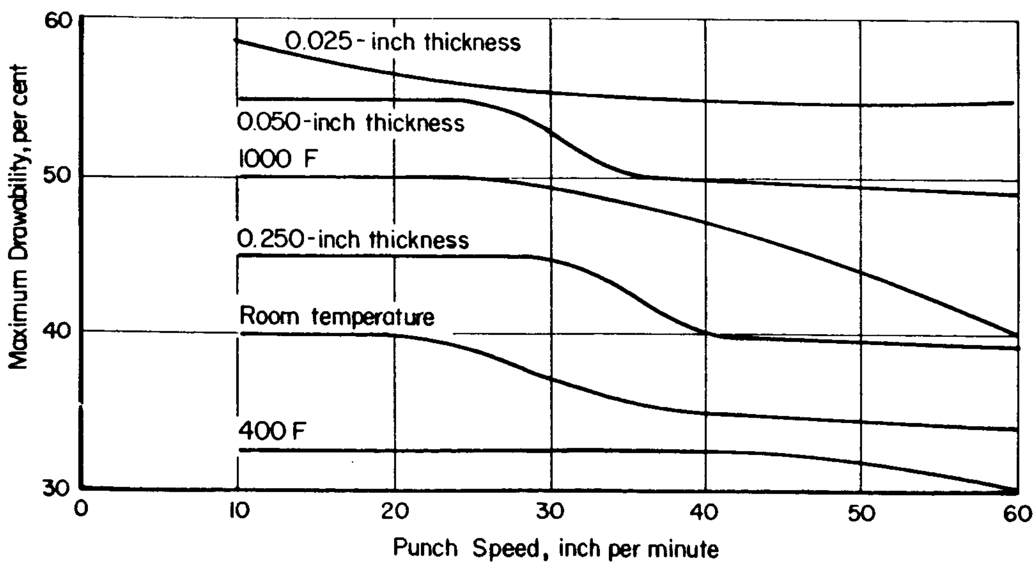


FIGURE 39. EFFECTS OF TEMPERATURE, RAM SPEED, AND THICKNESS ON DRAWABILITY OF TITANIUM (REF. 66)

limits shown for two alloys in Figures 40 and 41. Increasing the drawing temperature shifts the limits toward better formability and permits more severe deformations. The experimental results at 1200 F, which included the production of both satisfactory and failed parts, are in fair agreement with the predicted forming limits. Other information obtained in the same investigation (Refs. 52,59) indicates that the forming limits for the Ti-6Al-4V alloy are identical at room temperature with those shown in Figure 40 for the Ti-13V-11Cr-3Al alloy.

Figure 42 shows the loads developed in deep drawing 3-inch-ID cups from 0.05-inch-thick blanks at various temperatures (Ref. 66). As would be expected, alloyed titanium requires higher drawing loads than unalloyed titanium. Furthermore, the latter required higher loads than 1010 steel. The load requirements increased rapidly with the reduction and with decreasing forming temperature.

Some laboratory data reported by Wright (Ref. 72) for titanium and its alloys are given in Table XX. The tensile data are averages for specimens taken at 0, 45, and 90 degrees from the rolling direction. There is a direct correlation between the average elongation values and the stretch-formability ratings judged by the Erichsen cupping-test values. The three materials with the poorest elongation value also had low n values or work-hardening coefficients.

Contrary to the experience on steel indicated in Figure 43, the titanium sheets with higher anisotropy values did not perform better in the cup-drawing tests. This lack of correlation between R values and critical drawing ratios is illustrated in the top section of Figure 43. The middle section of that chart shows that the cup-drawing ratings correlated with the average elongation values. These discrepancies fit the idea that high R values will not insure good results in deep drawing unless the ductility of the material exceeds the minimum needed to withstand bending and stretching. In Wright's deep-drawing tests (Ref. 72) titanium and aluminum alloys performed poorly unless the elongation values exceeded about 13 per cent.

Butler's analysis (Ref. 73) of operations in which stretch-forming rather than pure-drawing action causes failure indicates that the performance of a metal depends on the function:

$$\left(\frac{\text{Tensile Strength}}{\text{Yield Strength}}\right) \times (\text{Elongation in Per Cent}) \times R \ .$$

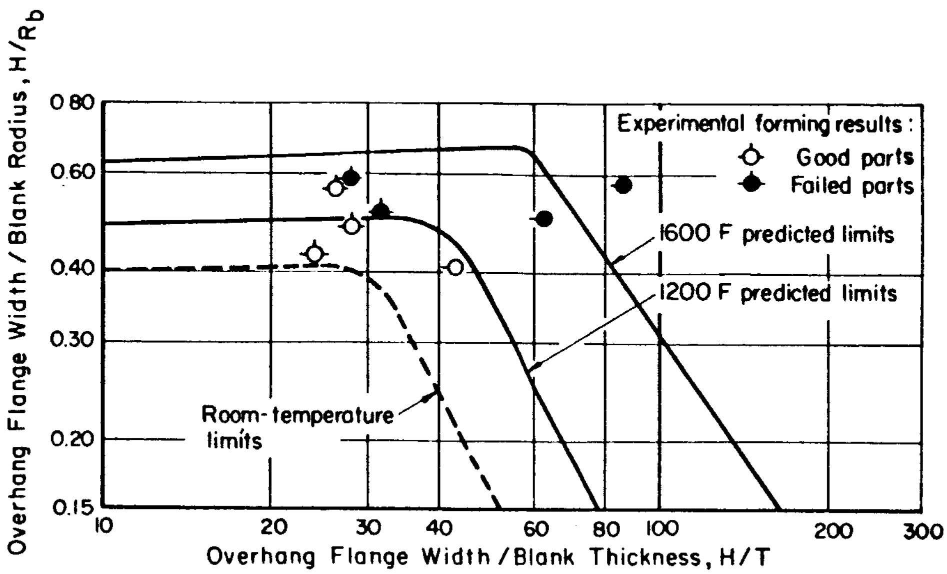


FIGURE 40. ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE PREDICTED DEEP-DRAW-FORMING LIMITS FOR Ti-7Al-1Mo-1V ALLOY (REFS. 52,59)

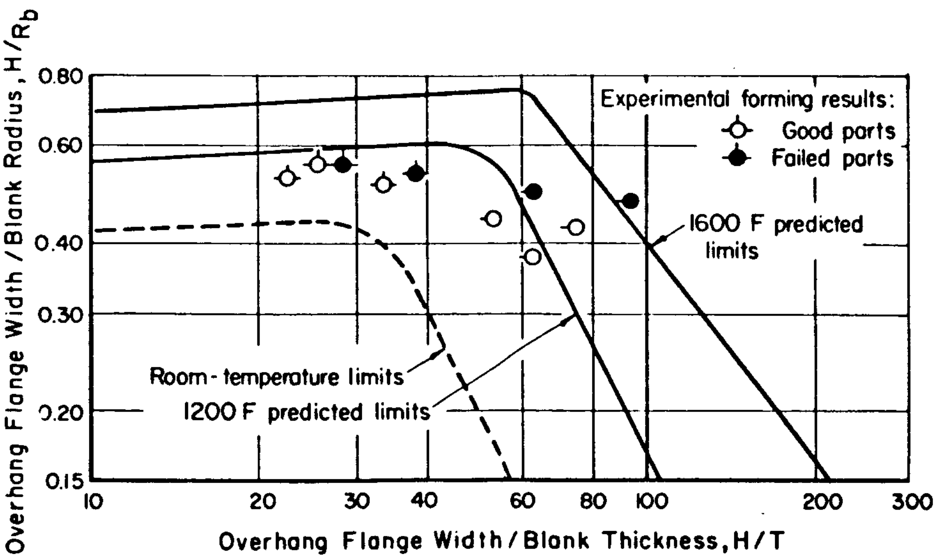


FIGURE 41. ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE PREDICTED DEEP-DRAW-FORMING LIMITS FOR Ti-13V-11Cr-3Al ALLOY (REFS. 52,59)

TABLE XX. TENSILE, STRETCH-FORMING, AND DEEP-DRAWING TEST DATA FOR SHEETS OF TITANIUM AND ITS ALLOYS (REF. 72)

Alloy, per cent				5Al 2.5Sn	6Al 4V	6Al 4V	2Cu	15Mo
Proof Strength, psi	43,500							
Tensile Strength, psi	53,500							
Elongation, per cent	36.7	23.7	34.0	12.9	12.4	12.1	23.4	35.0
n value	0.12	0.13	0.11	0.05	0.01	0.00	0.13	0.22
R value	2.00	1.17	2.01	1.94	1.48	1.04	1.96	1.49
Erichsen Tests								
Cupping Value, mm	10.9	7.5	11.3	2.0	4.4	2.6	7.1	8.4
Cup-Drawing Values[a]								
Critical Diam, mm	83	63	81	<44	45	<44	66	77
Blank D/Cup D[a]	2.5	1.91	2.46	<1.3	1.36	<1.33	2.0	2.33
F value[b]	90.6	31.6	83.2	25.8	18.5	13.5	51.7	65.6

(a) The punch used for the cup-drawing test had a diameter of 33 mm. The author did not give the shape but it was probably hemispherical. At least six cups were made successfully from blanks with the critical diameter; at least one failure was encountered in tests on blanks larger in diameter by 1 mm.

(b) A function of tensile properties equal to: $\left(\frac{\text{Tensile Strength}}{\text{Proof Strength}}\right) \times (\text{Elongation Value in Per Cent}) \times R$.

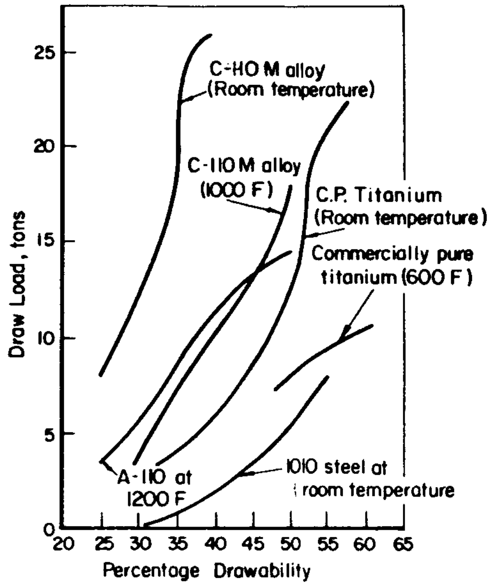


FIGURE 42. EFFECT OF TEMPERATURE, REDUCTION, AND COMPOSITION ON LOADS REQUIRED FOR DEEP DRAWING (REF. 66)

3-inch-ID cups, 0.050-inch sheet.

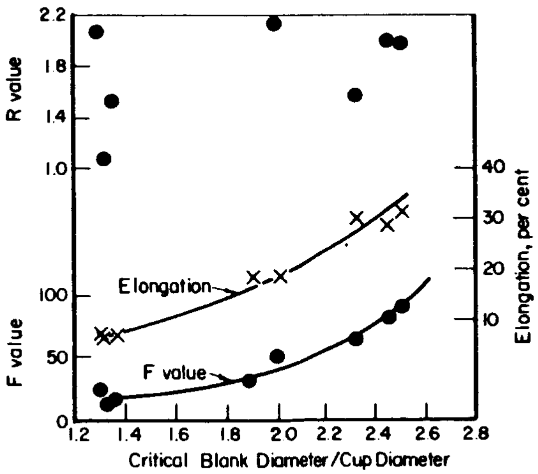


FIGURE 43. RELATIONSHIPS AMONG TENSILE PROPERTIES AND PERFORMANCE IN CUP-DRAWING TESTS

Based on data from Wright (Ref. 72) in Table XX.

The relationship between this function, using proof stress for yield strength, and the critical drawing ratio is shown at the bottom of Figure 43. The correlation is quite good, the rank correlation coefficient exceeds the value for a probability level of 0.01. This suggests that the failures in the Erichsen cup-drawing tests reported by Wright (Ref. 72) may have been caused by poor ductility in biaxial tension.

Post-Forming Treatments. The post-forming treatments of deep-drawn titanium parts are the same as those for other cold-worked components. Sometimes the parts can be trimmed in the forming die but this generally increases die costs.

Parts formed at elevated temperatures may or may not require a hot-sizing or stress-relief treatment. This depends to a great extent on the material and on the end use of the component. The residual lubricants from the drawing operation should be removed completely from the part before it is heated.

SPINNING AND SHEAR FORMING OF TITANIUM

Introduction. Spinning and shear forming are processes for shaping seamless, hollow sheet-metal parts by the combined forces of rotation and pressure. Only minor changes in material thickness occur during spinning; shear forming causes thinning.

Shear forming is different from spinning in two respects: (1) plate as well as sheet can be formed by shear forming and (2) reductions in metal thickness occur. Shear forming has a number of names that have been used since its development. Some of the proprietary names are "Floturn", "Spin Forge", and "Hydrospin". Some of the nonproprietary names used in the past are roll forming, rotary extrusion, shear spinning, flow turning, and power spinning. Throughout this report the term shear forming will be used to denote all of these processes. It describes the process, is nonproprietary, and appears to be emerging as the most accepted name for the process.

History of Process Development. Spinning is believed to have been developed in China around the beginning of the 10th century and to have been introduced in Europe during the 14th century. During this time metal spinning was developed as an art rather than a process and was used primarily for forming pewter and precious metals. After the 14th century spinning continued to be a craft and was applied to new materials such as aluminum for cooking ware. With the advent of press equipment, spinning could not compete because of the increased production requirements. The process continued to be used for the forming of items that, due to their shape, could not readily be made in one piece by pressing.

A renewed interest in spinning occurred during World War II. The process was ideally suited for making cylindrical shaped aircraft parts in relatively small quantities because the cost of tooling and setup time were far below that required for deep-drawing operations. Since highly skilled metal spinners were not available and there was no time to train personnel, the process had to be mechanized. This required replacement of the hand tools with mechanically or hydraulically actuated tools. With this change, higher tool forces could be applied and process capabilities for forming thicker parts made from higher strength materials were improved.

With the introduction of the space programs a need for very large bulkheads for fuel tanks again stimulated interest in spinning. However, the cost of designing and building large machines and the concurrent development of competing processes limited the growth of the spinning process. Several large machines were built that could spin a hemisphere of about 120-inch diameter (Ref. 74). The size requirements soon outstripped the feasible machine sizes.

The development of heavy-duty spinning equipment with tooling that could apply heavy loads permitted the start of an outgrowth of spinning, viz., shear forming. This process became very attractive because it results in a reduction of material thickness. New machines have been developed for this process by several companies within the last 10 years.

Basic Principles of Spinning. Spinning may be classified as manual or power spinning depending on the manner of applying the force to the blank. Manual spinning, illustrated in Figure 44, is limited to thin (less than 1/16 inch thick) low-strength (a yield strength under 30,000 psi) workpieces. Power spinning uses mechanical or hydraulic devices to apply greater tool forces to the blank and can consequently be used to form thicker and stronger materials.

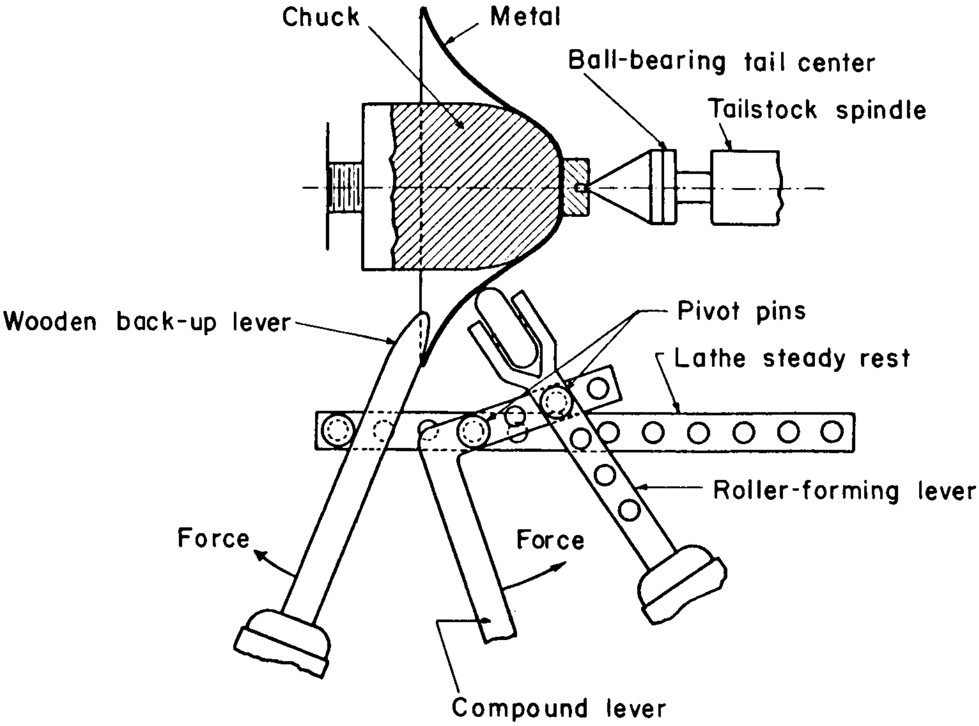


FIGURE 44. MANUAL SPINNING (REF. 62)

During spinning the metal blank is subjected to bending forces along the axis of spinning and compression forces tangential to the part. Difficulties are encountered with elastic buckling when the ratio of the depth of the spun part to the thickness of the metal becomes too great. The limits are related to the ratio of compressive yield (Ref. 59). Elastic buckling occurs in the unspun flange of the part as shown in Figure 45.

The ratio of depth to diameter of parts that can be produced by spinning is limited by plastic buckling. This is related to the material properties in terms of the ratio of tensile modules to the ultimate tensile strength (Ref. 59). Exceeding the formability limits causes shear splitting or circumferential splitting, as shown in Figure 46.

A typical spinning-limits curve is shown in Figure 47. Within the envelop good parts can be made; failures will occur by plastic buckling if the height-to-radius ratio becomes too large, and failure by elastic buckling will occur if the height-to-thickness ratio becomes too large. The position of the curves will vary according to the properties of the material and the forming temperature. Specific formability curves for various titanium alloys are given in a later section.

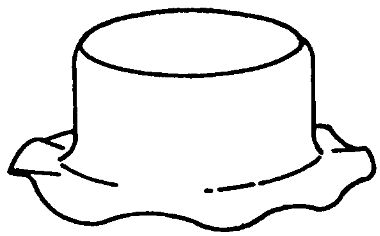


FIGURE 45. ELASTIC BUCKLING IN A SPUN PART (REF. 59)

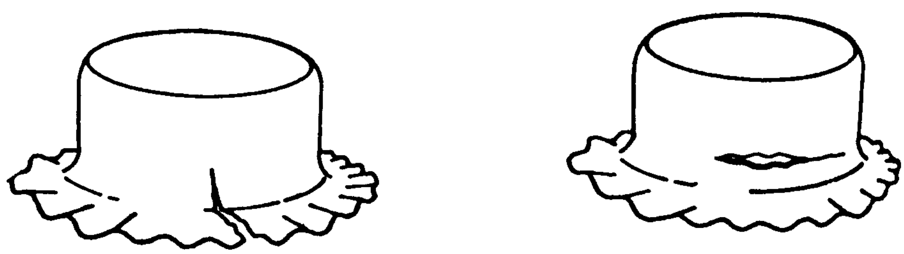


FIGURE 46. SHEAR SPLITTING AND CIRCUMFERENTIAL SPLITTING (REF. 59)

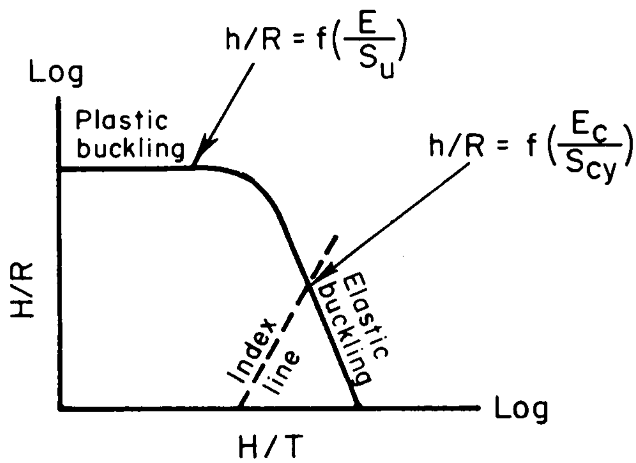


FIGURE 47. FORMABILITY-LIMIT GRAPH FOR SPINNING (REF. 52)

H = cup height

R = blank radius

T = blank thickness

E = elastic tensile modulus

S_u = ultimate tensile strength

E_c = elastic compression modulus

S_{cy} = compressive yield strength

Shear splitting is the result of exceeding the ultimate tensile strength of the material in the tangential direction, while circumferential splitting is caused by exceeding the ultimate tensile strength of the material in the axial direction.

Since plastic buckles are very difficult to remove, their formation should be prevented. This can be accomplished by limiting the amount of deformation to that permitted by the characteristics of the material or by improving the forming characteristics of the material so that the desired shape can be made. The best method available for improving ductility is to heat the material. Working at elevated temperatures permits spinning many materials that are not formable at room temperature.

Spinning differs from most metalworking processes in that the material is deformed at a point rather than over a broad area and that a large portion of the blank is unsupported during processing. These characteristics are advantageous in such operations as internal spinning where simple tooling can be used to make complex shapes. The application of internal spinning is shown in Figure 48.

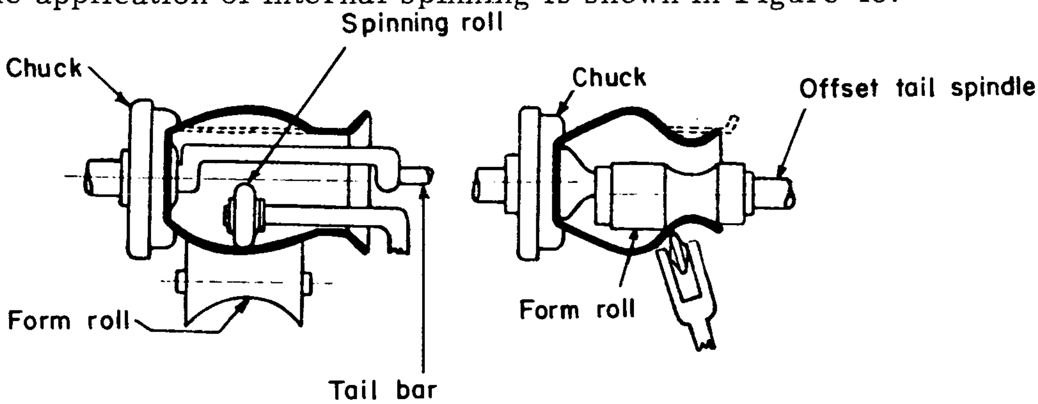


FIGURE 48. INTERNAL-SPINNING TECHNIQUES (REF. 74)

Spinning to the final shape desired may require a number of steps and intermediate anneals between them. The amount of reduction taken in each successive step should be reduced for a successful operation. For example, a part that receives 50 per cent reduction on the first step might be reduced 40 per cent on the next step and 30 per cent on a final step. The amount of reduction that can be obtained in each step is a function of the work-hardening characteristics of the material. Materials like aluminum, which do not work harden very severely, generally can be reduced more between annealing steps than a material such as stainless steel.

Basic Principles of Shear Forming. Shear-forming processes can be broken down into cone and tube shear forming. Any shapes other than a tube will be considered under cone or modified cone shapes such as hemispheres.

A typical example of cone shear forming is shown in Figure 49. The blank is a circular disk and is clamped to the rotating mandrel by the tailstock. Two rollers located at opposite sides of the mandrel apply a force along the axis of the mandrel and force the blank to take the shape of the mandrel. Figure 49 shows a progression of the forming sequence starting from top to bottom. The rolls are not driven but rotate due to contact with the rotating blank.

Cone Forming. The percentage reduction of material thickness during cone shear forming is a function of the part shape and is related by the "sine law". Figure 50 shows the geometric measurements that are important for shear forming a cone. The sine law states that the final thickness is related to the initial thickness of the blank by the sine of the half angle of the cone.

$$T = T_b \times \sin a/2 \quad , \qquad (16)$$

where

T = the final thickness, inches

T_b = the initial blank thickness, inches

a = the included angle of the cone, degrees.

The percentage reduction is therefore related to the sine of the cone's half angle as

$$R = 100\,(1 - \sin a/2) \quad , \qquad (17)$$

where R = the percentage reduction.

The same sine law applies to shapes other than a cone with the final thickness at any given point along the part determined by the angle the part makes with the axis at that point. The forming of a hemisphere would consequently result in a variation of thickness with the bottom of the hemisphere the same thickness as the blank and the edge being the thinnest section, as shown in Figure 51.

Constant-Thickness-Hemisphere-Blank Development. It is sometimes desirable to shear form a configuration other than a cone to a uniform thickness. The proper thickness of the preform can be

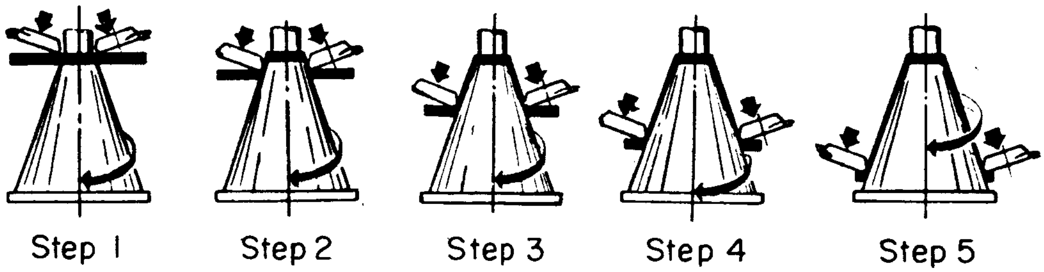


FIGURE 49. STEPS IN SHEAR FORMING A CONE (REF. 75)

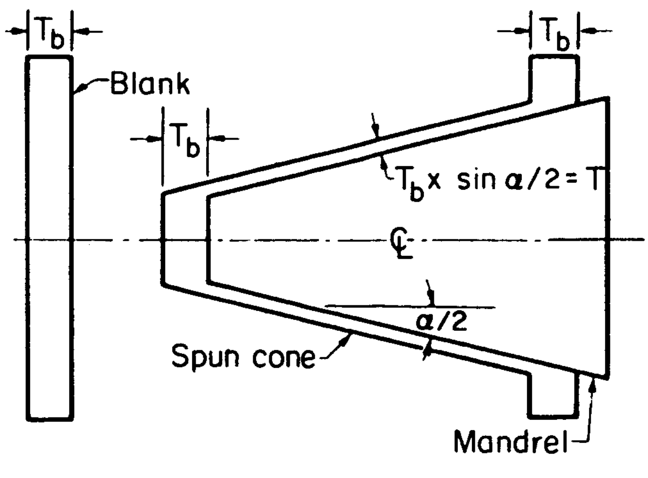


FIGURE 50. GEOMETRIC RELATIONS IN CONE SHEAR FORMING (REF. 76)

determined by calculation or by trial-and-error techniques. To calculate the appropriate blank thickness it is necessary to know the desired finished material thickness, the shape of the part, and the percentage reduction desired. For example, consider the production of the hemispherical part shown in Figure 52 in which a maximum reduction of 50 per cent is expected to produce a constant wall thickness of 0.150 inch. Using the sine law to determine the vertical height of an element in the shell at increments of about 1/2 degree gives a continuous plot of the blank thickness. Since only a 50 per cent reduction is permitted, however, the angle at which this occurs must be determined. In this case 0.150/0.300 = 0.500, which is the sine of 30 degrees. Consequently the edge of the blank cannot exceed 0.300 inch in thickness. Consequently the edge of the blank must be preformed from the 30-degree intersection to the lip of the hemisphere, as shown in Figure 52. The time involved in calculating the shape of a preform may not be warranted since some deviation from the sine law often occurs. Trial-and-error methods can be used by the operator to obtain the same results, often more accurately. With this approach the operator shear forms a trial blank of constant maximum thickness of 0.300 inch. After forming, the part thickness is measured at various locations and the data are used for correcting the thickness of the next trial blank. This process may have to be repeated several times but the final refinement should give a very accurate part thickness. This technique may be necessary even when the thickness of the blanks is precalculated.

Deviations From the "Sine Law". Deviations from the sine law resulting in under or over reduction of thickness are caused by improper adjustment of the roller force (Ref. 78). For plates up to 1/2-inch thickness it has been noted that the flange ahead of the forming roller will bend when deviations from the sine law occur. The direction of bending in the flange is dependent on the roller geometry.

Forces in Shear Forming. An analysis of the stress system operating in shear forming is given in Figure 53. The relationship among these factors is:

$$\frac{\sigma_c}{\tau_o} = (\cot \alpha/2 - \mu) - \frac{\sigma_n}{\tau_o}(1 + \mu \cot \alpha/2) \quad , \qquad (18)$$

where

σ_c = stress in spun cone section, lb/in.^{2}

τ_o = shear yield stress of material, lb/in.^{2}

α = included cone angle, degrees

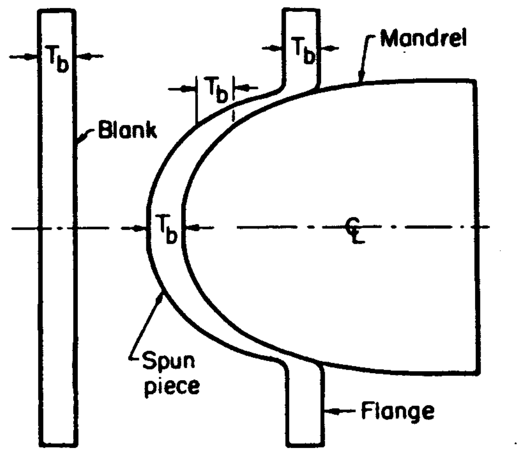


FIGURE 51. MATERIAL THICKNESS IN A SHEAR-FORMED HEMISPHERE (REF. 76)

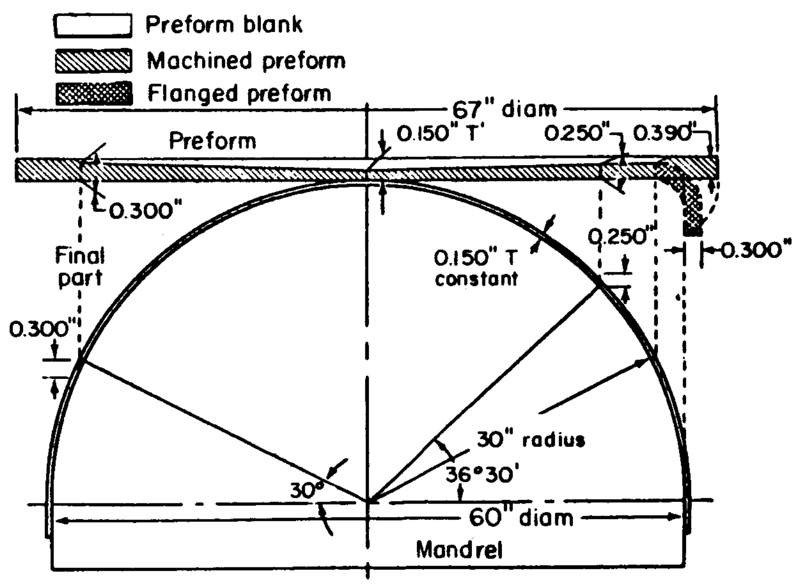


FIGURE 52. TYPICAL DEVELOPMENT OF A BLANK FOR CONSTANT SHEAR-FORMED THICKNESS (REF. 77)

μ = coefficient of friction between workpiece and mandrel

σ_n = normal stress on shear plane, lb/in.^{2}

The relationship of stresses as a function of mandrel angle is given in Figure 54. These curves can be used to predict the minimum cone angle to which a flat blank can be shear formed without fracture. The stresses in the spun cone section are compressive for large cone angles and change to tensile stress as the cone angle is decreased. The curves indicate that smaller cone angles are permissible with higher coefficients of friction between the workpiece and the mandrel and higher ratios between the normal and shear stress.

The tangential force developed in shear forming has been found to be a function of the initial material thickness, the feed rate, the cone angle, and the mean effective stress (Refs. 79,80). These are related by

$$F_t = Tf \sin \alpha/2 \ \sigma_m \cot a/\sqrt{3} \quad , \qquad (19)$$

where

F_t = tangential force, lb

T = initial material thickness, inches

f = feed, ipm

$\alpha/2$ = 1/2 included cone angle, degrees

σ_m = mean effective stress, psi.

An approximate solution to the power required in shear forming of cones has been derived as (Ref. 81):

$$W = 2/\sqrt{3}\,(\pi \sigma_o \cdot S_o NFR \cdot \cos \alpha/2) \quad , \qquad (20)$$

where

W = power required for deformation, in-lb

τ_o = yield limit of the material in tension, lb/in.^{2}

S_o = initial thickness of blank, in.

N = rotating speed of cone, rpm

F = feed of roller, ipr

R = radius at point considered, in.

$\alpha/2$ = 1/2 included angle of cone, degrees.

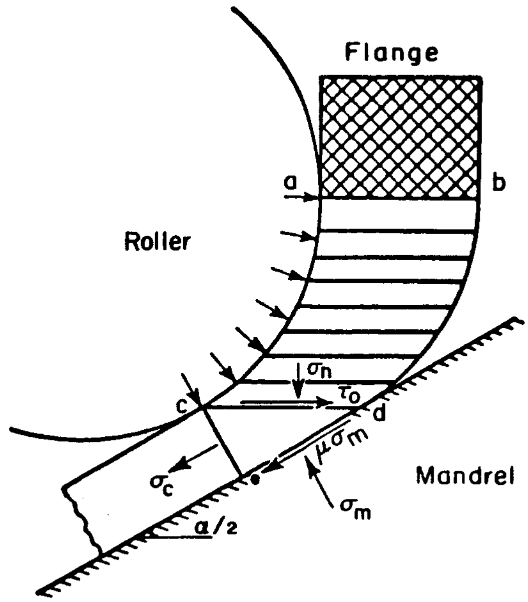


FIGURE 53. DEFORMATION ZONE IN SHEAR FORMING (REF. 78)

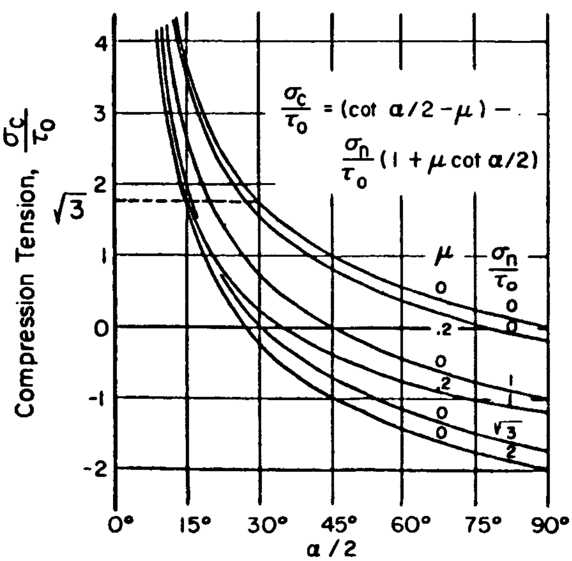


FIGURE 54. RELATIONSHIP OF STRESSES AS A FUNCTION OF MANDREL ANGLE (REF. 78)

This equation considers the tangential power as well as the feed power but not the efficiency of the equipment, which has a pronounced effect on the total power requirements.

Tube Shear Forming. As shown in Figure 55, shear forming of tubes can be of two basic types: forward and backward. In forward tube shear forming the material flows in the same direction as the tool motion, usually toward the headstock. In backward shear forming the material flow is opposite to the roller travel, usually toward the tailstock (Ref. 82).

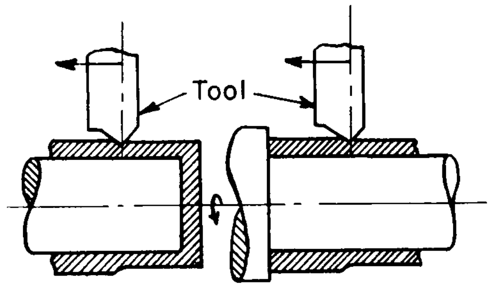


FIGURE 55. SCHEMATIC OF TUBE SHEAR FORMING (REF. 80)

Backward tube shear forming simplifies blank holding and can result in increased production since the tool travels only 50 per cent of the total part length. The process can produce parts that are beyond the normal length capacity of a specific machine. There are difficulties in backward shear forming with respect to holding axial tolerances. Since the first section of material formed must travel the greatest distance it is most likely to be out of plane. This is important where increased section thickness near the end of the part is required for welding applications.

Forward tube shear forming has found wide acceptance where longitudinal accuracy of sculptured sections is required. Since each increment of material that is formed is not required to move, errors in concentricity are swept away from the finished part and are left in the trim stock.

In shear forming of tubing the basic sine law of shear forming cannot be applied. The amount of reduction that can be taken in one pass is limited by the mechanical properties of the material.

The maximum permissible reduction for ductile materials depends on the state of stress in the deforming area and the material properties. The maximum reduction can be predicted from the tensile reduction in area both for cone and tube shear forming (Ref. 83). The experimental data shown in Figure 56 indicate that a maximum spinning reduction of about 80 per cent is obtained at a tensile reduction in area of 50 per cent. Beyond this tensile reduction there is no further increase in formability. Materials with a reduction in area less than 50 per cent require consideration of their ductility to determine formability.

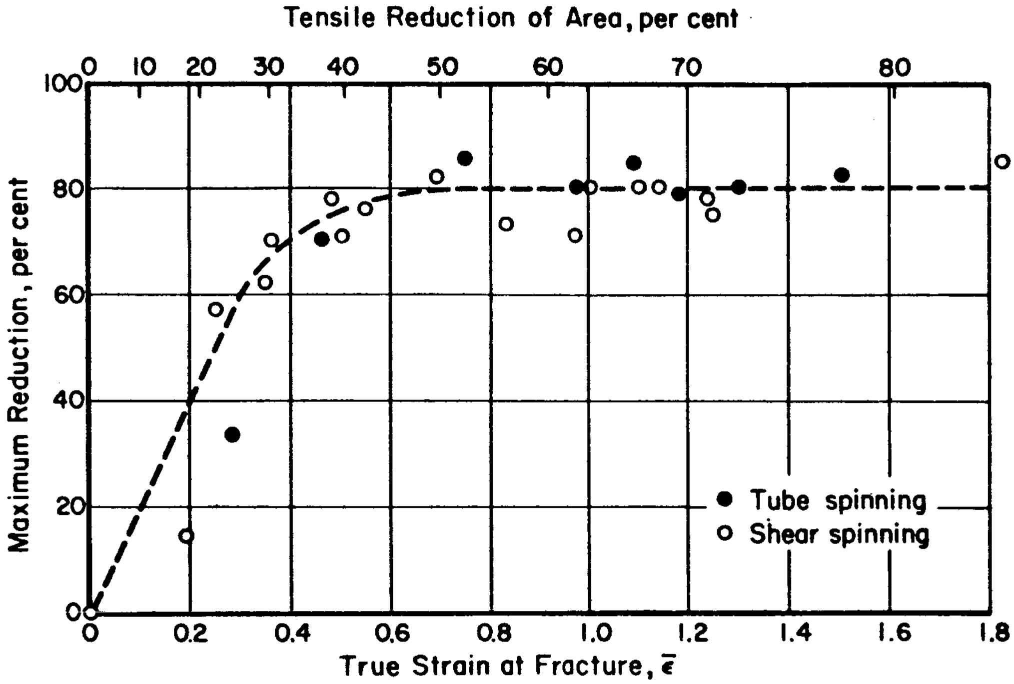


FIGURE 56. MAXIMUM SPINNING REDUCTION IN TUBE AND SHEAR SPINNING OF VARIOUS MATERIALS AS A FUNCTION OF TENSILE REDUCTION IN AREA (REF. 83)

Some of the process parameters that will affect the maximum reduction possible are the feed rate, corner radius of the tool, the depth setting of the tool, and the angle of the tool. In general as the feed is increased the maximum reduction is decreased. The increase of corner radius will also decrease the maximum reduction. The roller angle appears to have very little effect on the maximum reduction between 15 and 45 degrees. Beyond these limits the effects are not known.

Tube-Shear-Forming Forces. The forces required for shear forming tubes either forward or backward have not been clearly defined. Some work in this area has been conducted that gives two different solutions for the forces involved at various reductions (Ref. 80). The agreement between the two solutions is fairly good at large reductions but not at small reductions, as indicated in Figure 57.

Basic Principles of Blank Development.

Blanks for Spinning. Spinning requires the use of a circular blank with sufficient material to complete the part plus, generally, some allowance for trimming after forming. The radius for the blank can be determined by examining a section through the completed part and measuring the total length of material required to make the shape starting from the center of the part to one edge. The allowance for trim stock is added to this. The allowance for trimming should be a minimum of 1 inch. The maximum is dictated by the scrap allowed and the swing of the machine.

Blanks for Cone Shear Forming. Cone shear forming requires a blank with the same diameter as that of the finished part. Some additional allowance for trim stock is desirable to reduce the possibility of cracking in the edge of the part that is likely to occur when shear forming is carried to the end of the blank. The trim allowance should be at least equal to the original blank thickness. A greater allowance is controlled by the amount of trim scrap to be accepted.

Blanks for Tube Shear Forming. Forward tube shear forming requires a blank with an inside diameter equal to the diameter of the finished part. The length of the tube blank is determined by the length of the finished part desired and the reduction to be accomplished. For a part shear formed to a 50 per cent reduction the length of the blank would be 1/2 of the finished part length. Some allowance for trim should be made in forward shear forming. An allowance of 1 inch for each 10 inches of finished length is normal practice.

Backward tube shear forming requires the same consideration in blank development as forward shear forming. The same reasoning is used in selection of the blank length. The blank inside diameter is the same as the finished tube diameter.

Types of Equipment. Most engine-lathe manufacturers will make equipment for spinning. The manually operated machines have

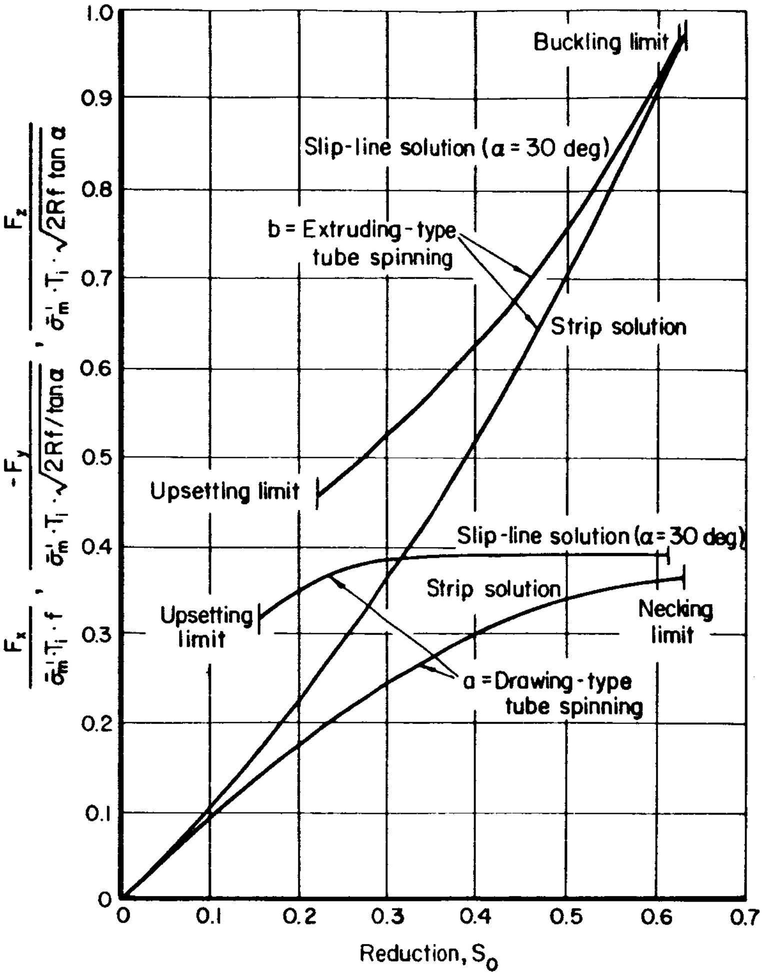


FIGURE 57. FORCE COMPONENTS IN SHEAR FORMING TUBING (REF. 80)

F_x = the tangential-force component
F_y = the radial-force component
F_z = the axial-force component
$\bar{\sigma}'_m$ = the tensile limit of the average effective stress
T_i = initial material thickness, in.
f = the feed, ipm
R = radius of tube, in.
α = deformation-zone angle, degrees.

given way to the mechanically or hydraulically operated equipment. The latest equipment incorporates numerical control for automatic programming of the spinning operation.

Shear-forming machines are an extension of the capabilities of the spinning lathe. The machines are heavier and have considerably more power than the spinning lathes. Spinning can, however, be conducted on a shear-forming machine that can be used in the production of cones.

Some of the newer large shear-forming machines are shown in Figures 58, 59, and 60. These machines are available for forming. Some of the machine specifications are given in Table XXI for machines manufactured by Lodge & Shipley, Cincinnati Milling Machine, and Hufford. Additional sizes of machines may be available so that the manufacturers should be informed of specific requirements.

Types of Tooling.

Tooling for Spinning. Planishers for manual spinning are generally made of relatively soft material like brass to prevent gouging of the workpiece. For mechanical or hydraulic spinning, rollers of hardened tool steel are used. A high-speed tool steel is required when elevated-temperature spinning is performed. The surface of the rollers is often chromium plated for durability and corrosion resistance. The diameter of the rollers in spinning is selected on the basis of the diameter of the part to be formed; the roller diameter should be approximately half the smallest diameter of the part.

Mandrels for room-temperature spinning can be made of wood or plastic for production runs of 25 parts or less. For greater production the mandrels may be made of ductile cast iron or tool steel. For elevated-temperature spinning the mandrels are made of ductile cast iron or high-speed tool steels. For short-run production of titanium a wood form covered with aluminum and steel has been used at temperatures to 1300 F (Ref. 86). This mandrel is shown in Figure 61.

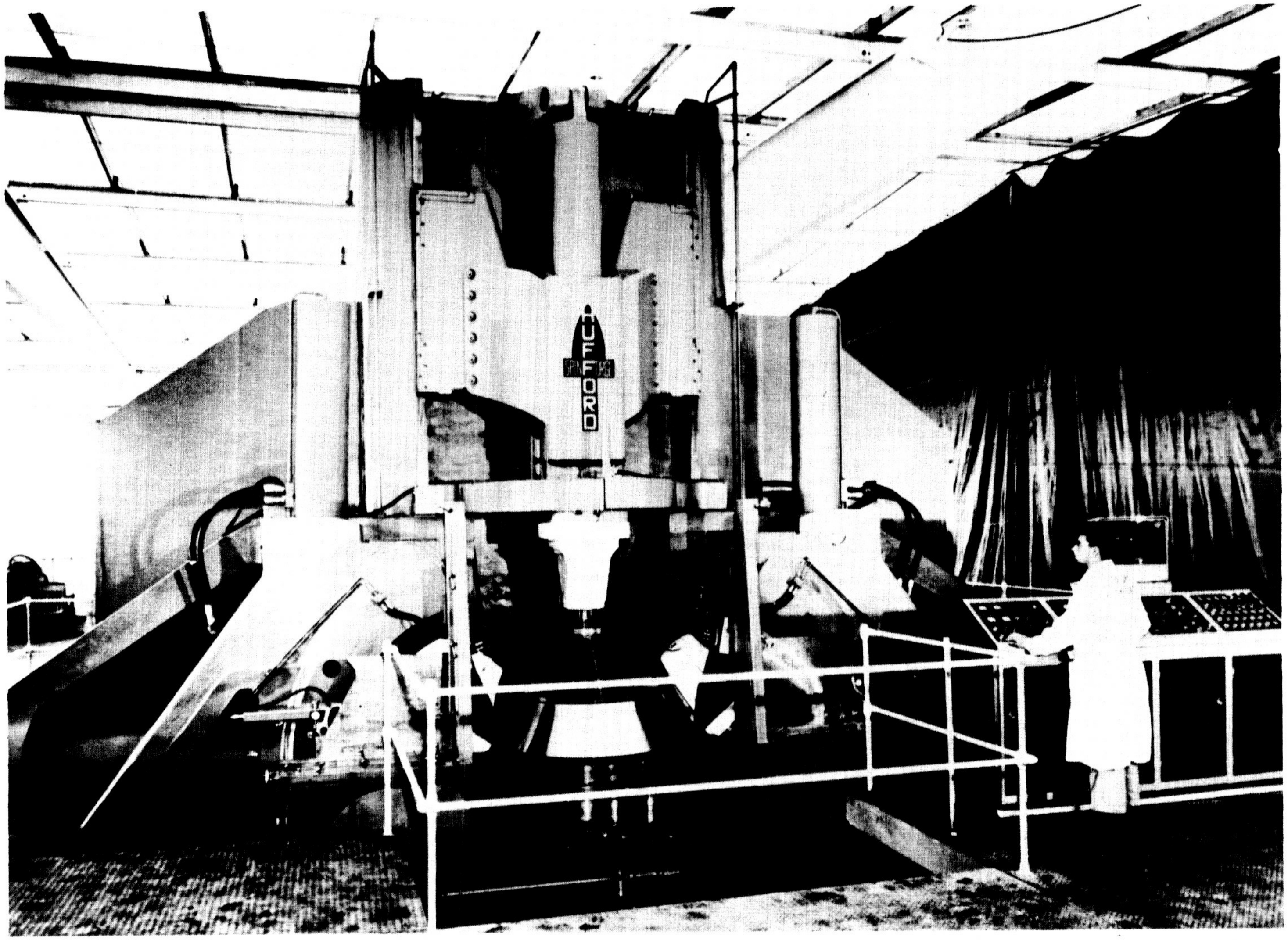


FIGURE 58. HUFFORD 60-INCH SPIN-FORGE MACHINE (REF. 85)

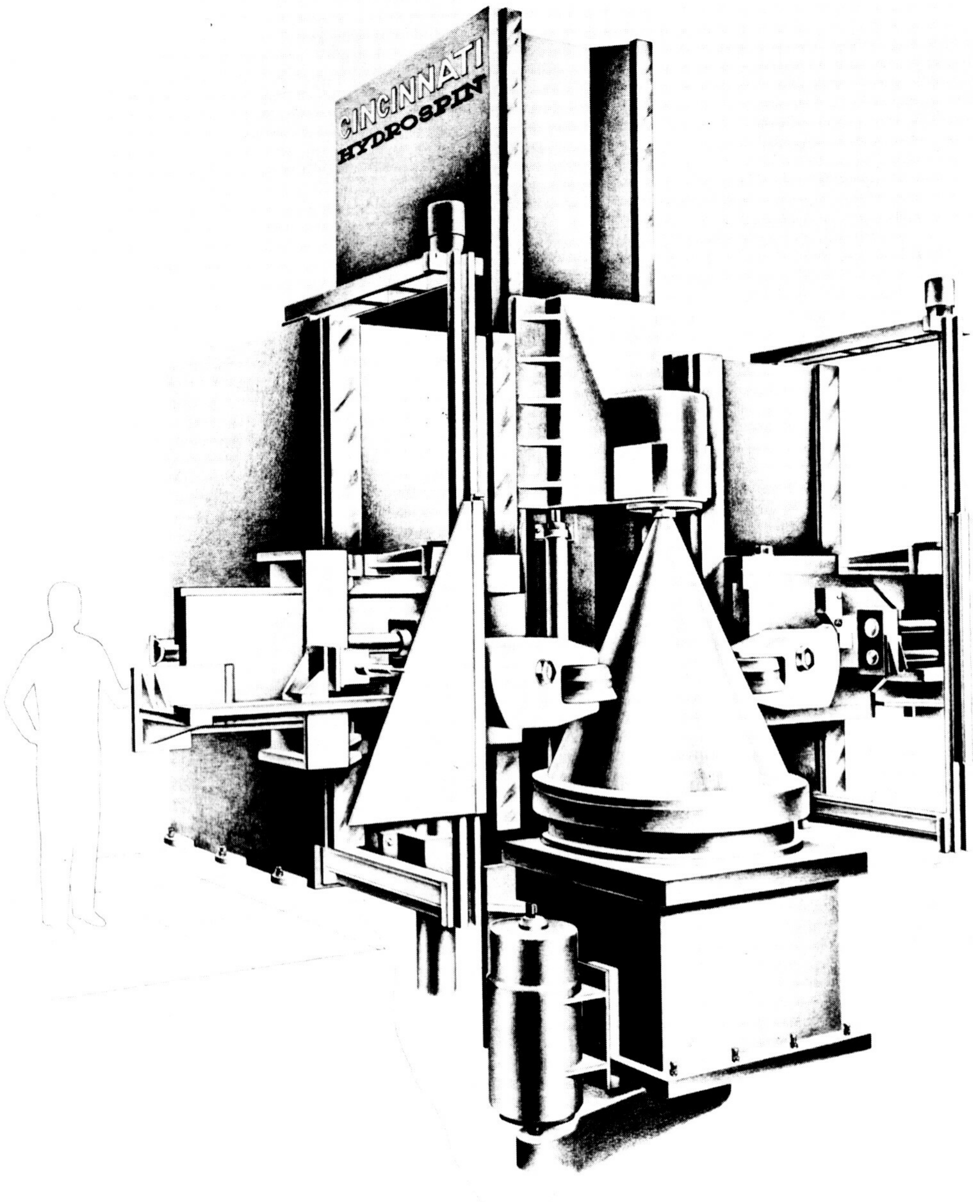


FIGURE 59. CINCINNATI MILLING MACHINE COMPANY 70 X 72-INCH VERTICAL HYDROSPIN MACHINE (REF. 84)

TABLE XXI. TYPICAL AVAILABLE SPINNING AND SHEAR-FORMING-MACHINE SIZES (REFS. 75, 84, 85)

Manufacturer	Port Diameter, inches	Port Length, inches	Spindle, hp	Forces Roller, lb	Forces Carriage, lb	Forces Tailstock, lb	Production Rate, piece/hr	Machine Weight, lb	Number of Rolls	Type
Lodge & Shipley, (Floturn)	12	15	15	4,000	5,000	2,000	75-100	8,750	1	Horizontal
	12	15	40	14,000	12,000	3,000	90-125	26,000	2	Vertical
	24	30	75	32,000	54,000	8,000	30- 80	52,000	2	Vertical
	40	50	20	15,000	--	7,500	8- 30	41,000	1	Horizontal
	60	70	90	40,000	--	15,000	1- 15	100,000	1	Horizontal
	70	84	150	70,000	70,000	35,000	1- 15	195,000	2	Horizontal
Cincinnati Milling Machine Company, (Hydrospin)	42	50	20	50,000	50,000	35,000	--	53,970	1	Horizontal
	42	50	20	50,000	50,000	35,000	--	78,970	2	Horizontal
	62	50	20	50,000	50,000	35,000	--	145,500	2	Horizontal
	70	72	30	70,000	70,000	50,000	--	235,000	2	Vertical
Hufford, (Spin Forge)	60	60	200	225,000	225,000	200,000	--	--	2	Vertical
	60	120	200	225,000	225,000	200,000	--	425,000	2	Vertical

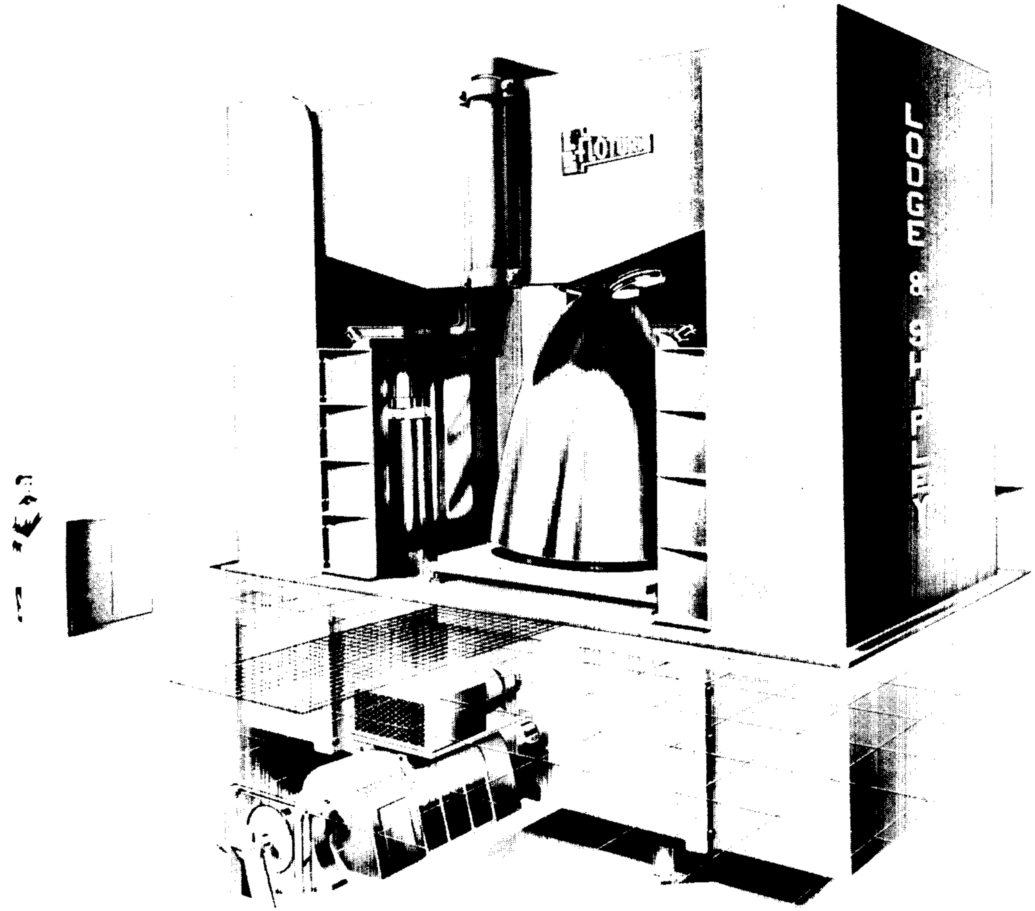


FIGURE 60. LODGE & SHIPLEY 60-INCH X 10-FOOT VERTICAL FLOTURN MACHINE (REF. 75)

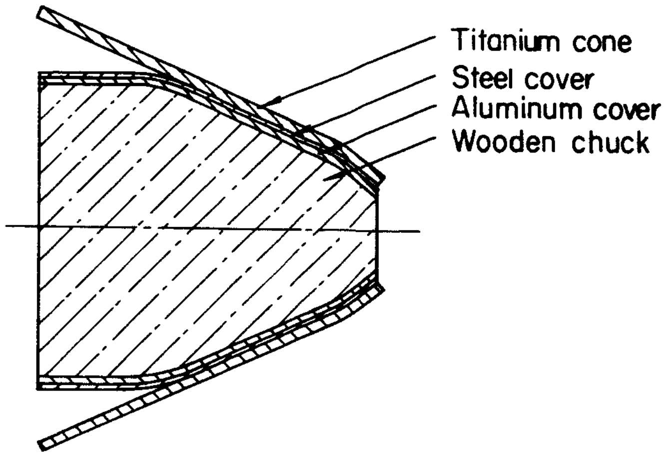


FIGURE 61. ELEVATED-TEMPERATURE SPINNING OVER A WOOD MANDREL (REF. 86)

Tooling for Shear Forming. Shear forming requires stronger tooling than spinning due to the greater forces characteristic of the process. Rollers are used for applying the forming force to the blank. The diameter of the rolls is generally kept to a minimum consistent with the force it is required to transmit. A smaller roller has less contact area with the blank and consequently less friction and power loss. The shape of the roller depends on the amount of reduction to be taken with each pass. A typical roller configuration is shown in Figure 62, and the surfaces, which are important in the process, are indicated. The contact angle determines the length of contact surface for any given reduction. The greater the contact length the greater the frictional forces between the roller and the metal. The approach surface and contact angle are required to prevent the material from burring ahead of the roller. Since the roller step controls the amount of reduction, a different roller is required for each reduction. The burnishing angle and land tend to smooth out the ring marks left on the part due to the axial travel of the tool. Rollers for shear forming are generally made of high-speed tool steel heat treated to R_C 60. The surface is polished and sometimes high-speed tool steels can be chromium plated and used at either room temperature or elevated temperature.

The mandrels for shear forming are made of heat-treated steel because of the high forces involved. A softer material would be locally deformed by the roller pressure. Large mandrels are generally made as shells with supporting internal structure while smaller mandrels are solid.

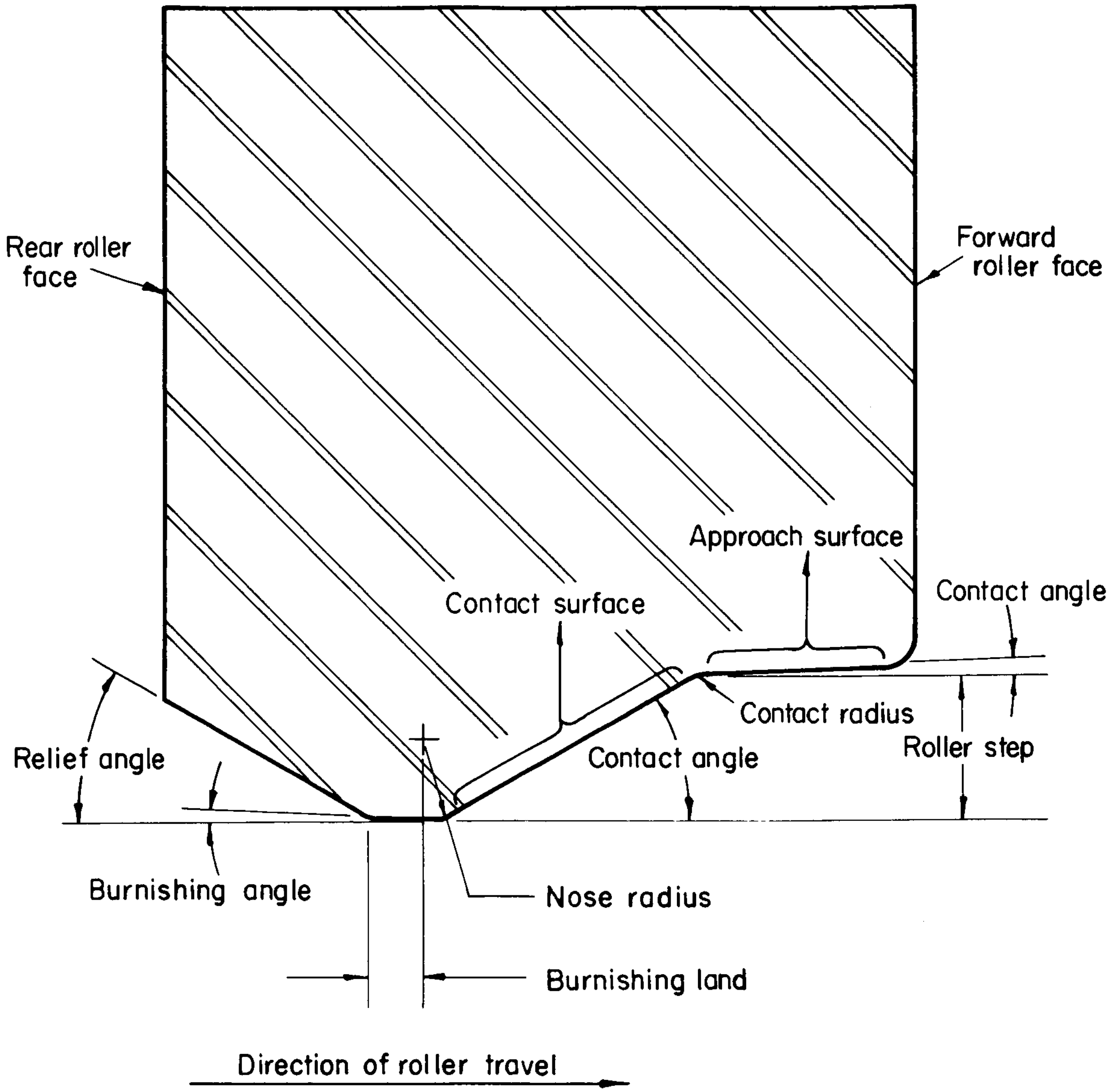


FIGURE 62. ROLLER CONFIGURATION FOR SHEAR FORMING (REF. 87)

Heating Methods. For elevated-temperature spinning or shear forming, the mandrels are generally heated. This can be accomplished by electric-resistance cartridges or by flames. The electric-resistance method may be more expensive to operate but provides less opportunity for contamination of materials that tend to oxidize readily. The rotating contacts transmitting current to the mandrel sometimes limit the amount of power that can be used.

Flame heating of the mandrel can be accomplished with natural gas or bottled gas. With this practice, mandrels are generally hollow so the flame can be played on the inside surface of the mandrel. Localized overheating must be avoided to prevent distortion of the mandrel.

The blanks are generally heated with a torch that applies heat locally to the area where the tooling force is applied. This technique is shown in Figure 63. Very close control must be maintained to prevent overheating of the parts. The size of the proper torch depends on the thickness of material and the speed and feed rate of the operation. Blanks for spinning small parts can be heated in a furnace and then transferred to a lathe for spinning. The limitations of this type of operation are determined by the time required for the spinning operation. Shear-forming operations generally take longer and the blanks cool too rapidly to use this technique. Torch heating is the accepted practice for shear-forming operations. The selection of the proper temperature for shear forming is also influenced by the temperature rise associated with deformation at the tool point.

Blanks can also be heated by radiation from resistance units located around the part. This technique works well on tubing or preforms that are to be shear formed. This practice is difficult to control when processing flat blanks.

The rollers in shear forming are generally cooled to prevent distortion or creep under heavy loads. This is usually accomplished by spraying a lubricant on the roller surface; internal circulating cooling systems are not very practical.

Blank Preparation for Titanium Alloys. The requirements for edge preparation on titanium-alloy blanks are similar to most other materials. The edges should be smooth and free of notches or scratches. The surface of the blank should also be free of scratches. Any surface contamination should be removed before spinning or shear forming.

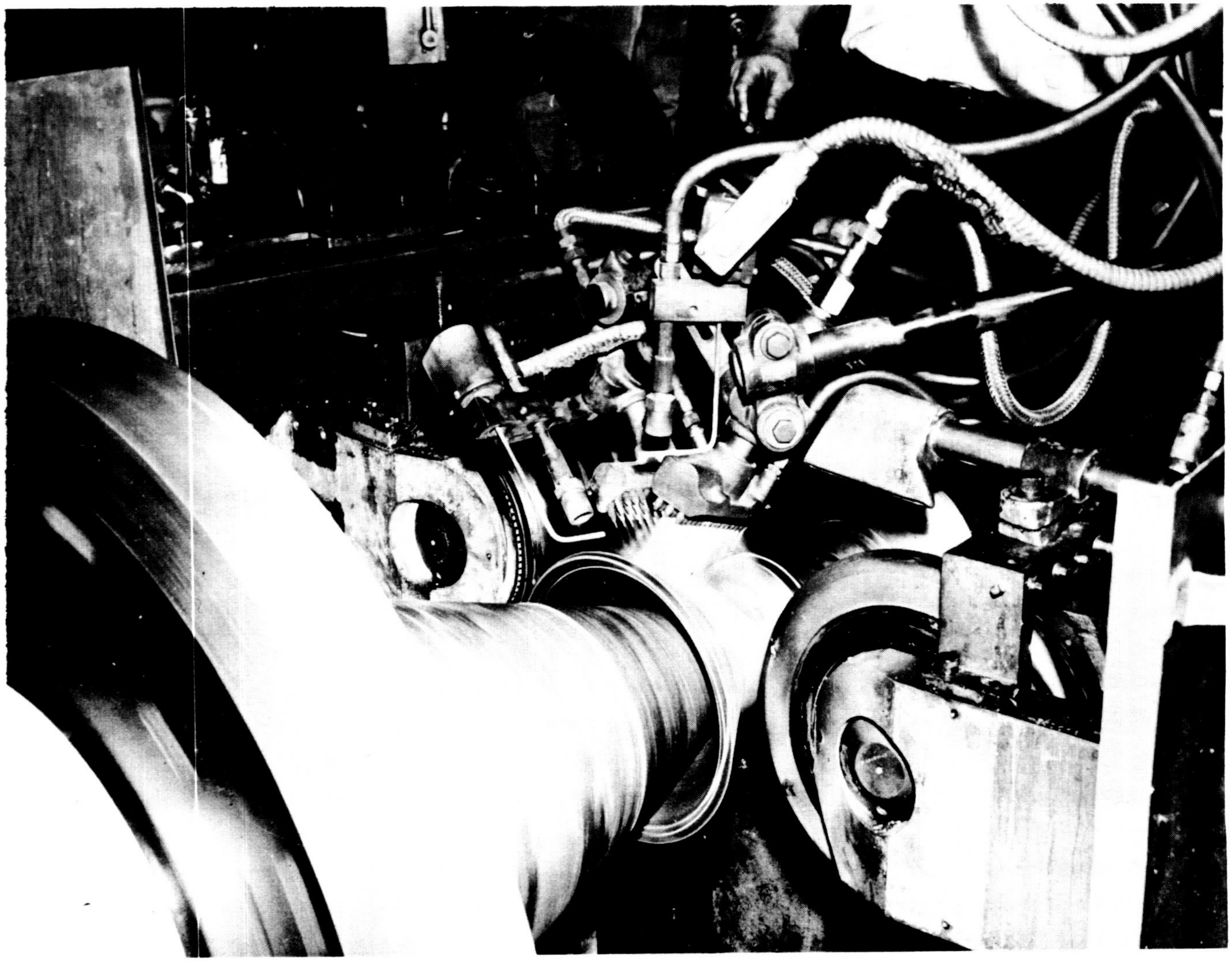


FIGURE 63. TORCH HEATING OF A BLANK DURING CONE SHEAR FORMING (REF. 88)

Lubricants. Very little has been published on lubricants specifically for spinning or shear-forming operations. Due to the localized forming forces the requirements for a lubricant are somewhat more stringent than for other forming operations. In general the lubricant used should be of a nonchlorinated type to prevent contamination of the metal surface during elevated-temperature forming or subsequent thermal treatments. Since the choice of lubricant depends principally on the temperature of forming, some suggestions are given in Table XXII.

TABLE XXII. LUBRICANTS FOR USE IN FORMING TITANIUM

Titanium Material	Operating Temperature	Lubricant (Ref. 89)
Commercially pure	Room temperature	Colloidal graphite Copper plate + methyl borate Molybdenum disulfide Lanolin Phosphate-fluoride coating
Commercially pure	Up to 400 F	Silicone oils Heavy drawing oils (petroleum base) Graphited tallow Yellow laundry soap
Commercially pure and alloys	400 to 800 F	Colloidal graphite Graphite-powdered mica Colloidal molybdenum disulfide Bentone greases with graphite, Grade 0 or 1
Commercially pure and alloys	800 to 1000 F	Certain types of porcelain enameled frits - sprayed on blanks and fired Metallic coatings Graphite-powdered mica Bentone greases with graphite

For room-temperature forming of sheet-metal components of titanium, by methods other than spinning, colloidal graphite, and copper plate with methyl borate give equally good results (Ref. 89). Conversion coatings of the phosphate or fluoride type have little or no lubricity but act as hosts for the adsorption of lubricants (Ref. 90). They have been used successfully on an experimental basis for deep drawing. The conversion coatings should not be used at high temperatures because of reactions that occur at the coating base-metal interface. They have been used experimentally up to 800 F on titanium.

The most common lubricants used on titanium at elevated temperatures are the solid-film types such as graphite, molybdenum disulfide, and mica. Although they can be applied as a powder in most metal-forming operations, they should be suspended in a suitable vehicle for spinning or shear forming. Silicone oils, heavy petroleum-base drawing oils, and synthetics have been commonly used in other forming operations and might be considered for spinning.

Most grease-solid mixtures are compounded as relatively heavy greases that must be applied by swabbing. If used in spinning a heavy buildup on the tools might be expected. A reduction in the viscosity of the grease should help if this occurs.

Specific lubricants that have been used on shear forming of titanium alloys are Esso's Nebula No. 2 and colloidal graphite in a petroleum-naphtha vehicle (Refs. 88,91). These have been used at forming temperatures to 1300 F.

Tests to evaluate the coefficient of friction of steel rubbing on titanium materials at room temperature have indicated that there is very little benefit from the use of lubricants (Ref. 92). The unlubricated surface had a coefficient of friction of 0.49. The most successful lubricants were the synthetic long-chain compounds like polyethylene glycol (0.26), polypropylene glycol (0.33) and sugar solutions, molasses (0.32), honey (0.32), maple syrup (0.32). It is doubtful if any of these lubricants could be used at elevated temperatures (Ref. 92).

Spinning and Shear Forming of Titanium Alloys. The information available on spinning of titanium alloys is meager because more attention has been devoted to shear forming. Wood and associates (Ref. 59), however, published some studies on the subject. As shown earlier in Figure 47, the buckling limits are set by the ratios of the moduli to strengths of the workpiece. Increasing the deformation temperature improves formability because it has more effect on strength than on the moduli of titanium.

Table XXIII gives some formability limits for manual spinning at room temperature. They are expected to hold for relatively small forces and limited amounts of thinning. The data show that spinnability is favored by smaller ratios of blank diameter to sheet thickness. Neither material will withstand very severe deformation at room temperature. For example, the limit for a 3-1/8-inch-diameter, 1/8-inch-thick blank of 6Al-4V alloy appears to be a flat cup 2.4 inches in diameter, 0.53 inch high.

TABLE XXIII. FORMABILITY LIMITS FOR MANUAL SPINNING OF FLAT-BOTTOM CYLINDRICAL CUPS AT ROOM TEMPERATURE (REF. 59)

Thickness, inch	Blank Diameter/ Sheet Thickness	Limiting Ratio for Alloys Indicated[a] Blank Diameter/ Cup Diameter AMS 4911	Blank Diameter/ Cup Diameter AMS 4917	Cup Height/ Cup Diameter AMS 4911	Cup Height/ Cup Diameter AMS 4917
0.020	25	1.3	1.2	0.22	0.14
	50	1.3	1.2	0.22	0.14
	100	1.2	1.2	0.14	0.14
	150	1.2	1.1	0.14	0.07
	200	1.1	--	0.07	--
0.063	25	1.3	1.2	0.22	0.14
	50	1.2	1.2	0.14	0.14
0.125	25	1.2	1.2	0.14	0.14
	50	1.1	--	0.07	--

(a) Alloys AMS 4911 and AMS 4917 contain, respectively, 6Al-4V and 3Al-13V-11Cr.
The term cup diameter refers to the inside diameter; the cup height is based on the outside dimension.

Spinning at elevated temperatures increases the amount of deformation that can be taken before buckling occurs. Figures 64 and 65 show that a deformation temperature postpones elastic buckling to higher strains without affecting the onset of plastic buckling. A higher temperature is necessary to extend the limits for plastic buckling. This analysis indicates that moderately elevated forming temperatures permit spinning cups from thinner blanks, but do not permit larger cup-height/cup-diameter ratios. Comparatively high temperatures are necessary to achieve large ratios of cup height to blank or cup diameters.

Figure 66 shows the effect of temperature on the parameter (compression modulus/compression yield strength) that controls elastic buckling. For both alloys the change toward better formability starts around 1000 F and increases rapidly around 1400 F. The latter temperature is approximately the highest temperature that can be used without degrading the properties of the alloys. The total time required for forming may also influence the choice of spinning temperature.

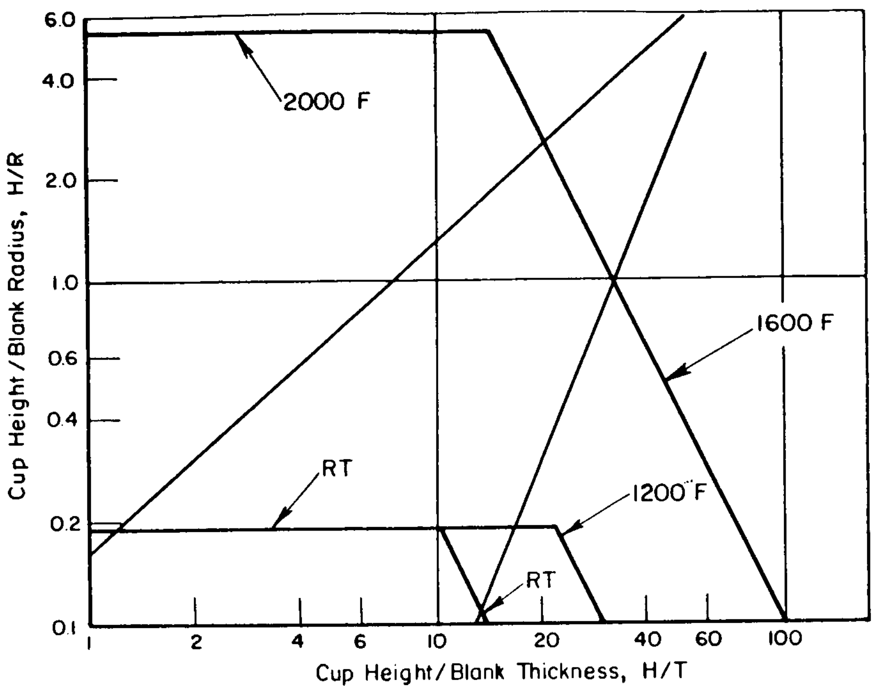


FIGURE 64. ANALYTICAL EXTENSION OF SPINNING-LIMIT CURVE FOR Ti-8Al-1Mo-1V ALLOY (REF. 52)

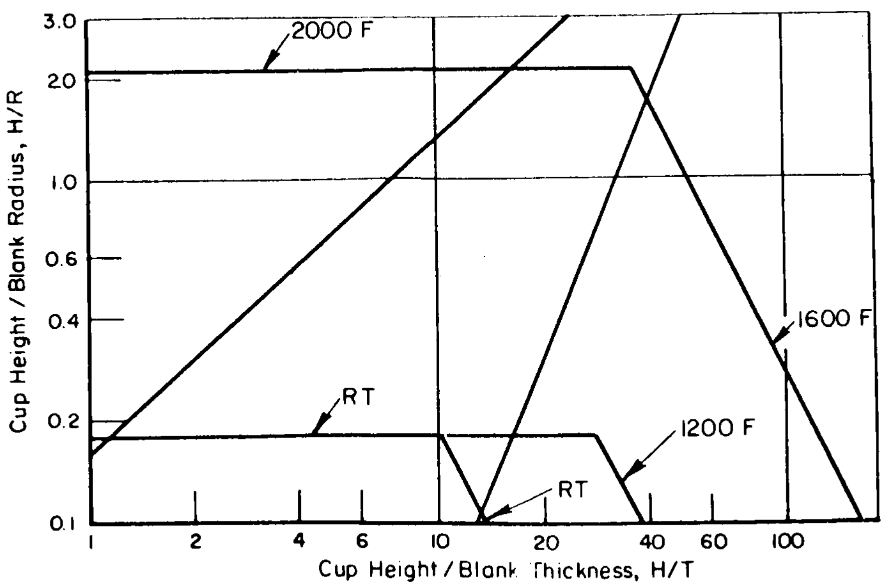


FIGURE 65. ANALYTICAL EXTENSION OF SPINNING-LIMIT CURVE FOR Ti-13V-11Cr-3Al ALLOY (REF. 52)

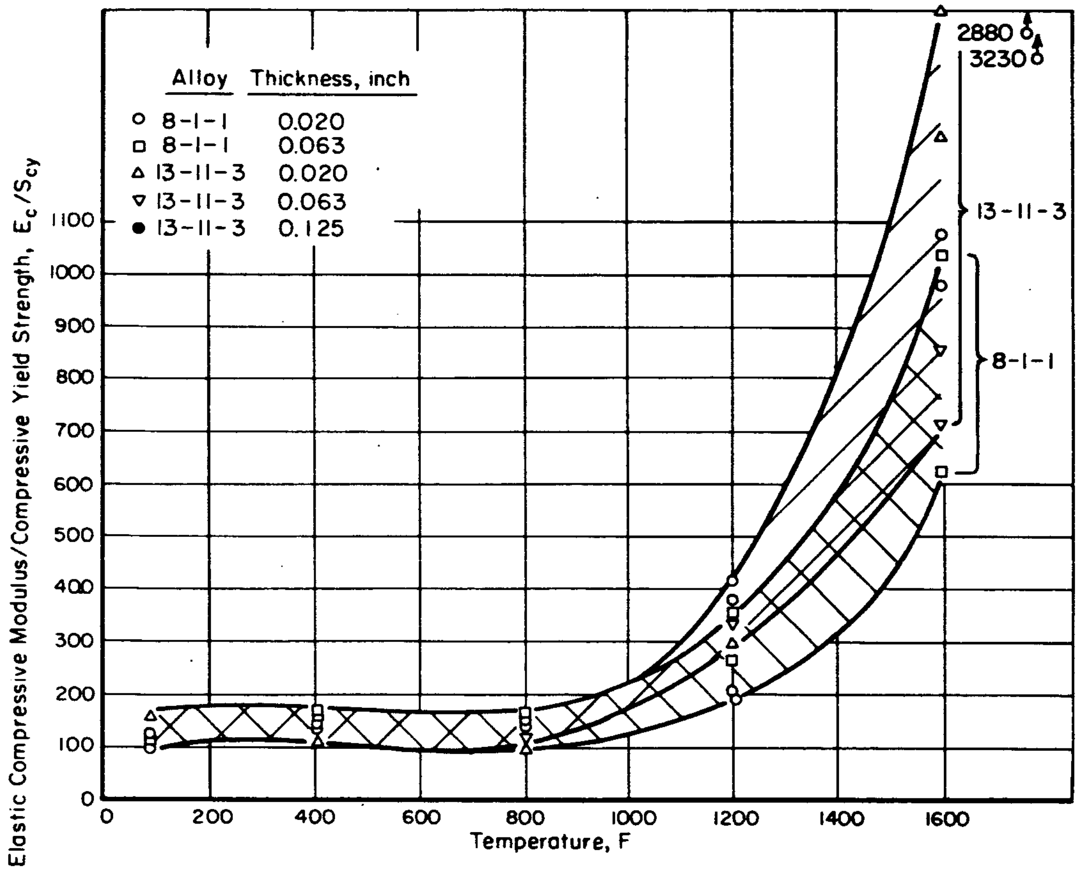


FIGURE 66. EFFECT OF TEMPERATURE ON ELASTIC-BUCKLING LIMIT IN SPINNING (REF. 52)

Based on very little data, it is believed that the parameter controlling plastic buckling (elastic modulus/ultimate strength) does not change in titanium alloys at temperatures below 1000 F.

Shear-Forming Conditions for Typical Parts. Commercially pure and alloy titanium has been shear formed at room temperature and at elevated temperature. For reductions greater than 15 per cent for cones and 50 per cent for cylindrical sections elevated temperatures are desirable. In shear forming titanium, the ratio between the strength of the material being formed and the applied shear-forming stresses is critical. The strength of titanium changes significantly with relatively small changes in temperature within the elevated-temperature working range so that it is necessary to control the temperature within 35 F or less.

Elevated-temperature shear-forming operations have been conducted at temperatures from 400 to 1600 F depending on the alloy being formed. Typical forming temperatures for several alloys are given as follows (Refs. 55,91,93):

Material	Shear-Forming Temperature, F
Commercially pure	800 to 1000
Ti-5Al-2.5Sn	1200 to 1400
Ti-6Al-4V	1100 to 1200
Ti-11Cr-13V-3Al	1600 to 1800

A number of examples of cone and tube shear forming have been tabulated in Table XXIV. Although only a limited amount of titanium shear forming has been conducted, the feasibility of using this process has been amply demonstrated.

Titanium Alloys and Conditions for Spinning or Shear Forming. Titanium alloys are normally spun or shear formed in the annealed or solution-treated condition. The forming of the material in the heat-treated condition is not advisable due to limited ductility. Forming at elevated temperature may lower the properties of materials below those of the heat-treated condition by over aging. If high strengths are desired it is best to form the material in the solution-treated condition and to form at a temperature that will constitute the aging treatment.

Properties After Spinning or Shear Forming. Spinning or shear-forming operations should be expected to increase the yield

TABLE XXIV. DATA COMPILATION ON

Company	Material	Starting Material Condition	Preform Blank Size	Type of Shear Forming	Final Part Configuration	Proces Temperatu Blank	N
Convair	CP-AMS 4901	Stress relieved	35-in.-diam. circle x 0.050 in.	Cone	Hemisphere, 30-in. diam. x 0.030-in. wall	Gas torch	
Convair	CP-AMS 4901	Stress relieved	9.25-in.-diam. hydroformed cup, original blank thickness 0.063 in.	Cone	Parabolic cone, 9.25-in. diam. x 14 in. deep x 0.025-in. wall	RT	F
North American Aviation	Ti-4Al-3Mo-1V	Annealed	8 x 8 x 0.125-in. sheet	Cone	Cone, 6-in. diam x 0.040-0.050-in. wall	RT	F
		Solution treated	8 x 8 x 0.125 in. sheet	Cone	Cone, 6-in. diam x 0.056-in. wall	RT	F
Watertown Arsenal	Ti-6Al-6V-2Sn	Annealed	Tube blank, details not available	Forward	Closed-end cylinder, 3.13 in. OD x 2.99-in. ID x 7 in. long	RT	F
Curtiss-Wright	Ti-6Al-4V	Annealed	Tube blank 4 in. ID x 0.10 to 0.20-in. wall	Forward and backward	Thin-walled cylinders	RT and 600	F
Lear Seigler	Ti-6Al-4V	Solution treated (1550 F brine quench and aged 6 hr at 1000 F; air cooled)	Ring-rolled forging 43.8 in. ID x 0.50-in. wall x 13 in. long	Backward	Missile motor case, 43.89-in. ID x 0.110-in. wall x 43-3/8 in. long	1150 min	1
Douglas	Ti-13V-11Cr-3Al	Annealed	Ring-rolled forgings 6-in. ID x 0.057-in. wall	NA	Thin-walled cylinders, 0.025-in. wall	RT	R
			11-in. diam. circle x 0.134 in.	Cone	Cone	RT	R
Pratt & Whitney	Ti-13V-11Cr-3Al	Solution treated (1800 F, 15 min water quenched)	Ring-rolled forgings 39.6-in. ID x 0.300-in. wall	NA	Rocket cases, 39.6-in. ID x 0.140-in. wall	RT	R
			39.62-in. ID x 0.153-in. wall		39.65-in. ID x 0.072-in. wall	RT	R
			14.13-in. ID x 0.130-in. wall		14.13-in. ID x 0.067-in. wall	RT	R

(a) Maximum values indicate limit of formability without cracking.
(b) NA = not available.

	Forming Data							Total		
			Roller							
es, F landrel	Mandrel Speed, rpm	Feed, ipm	Diameter, in.	Radius, in.	Roller Setting, deg	Roller Pitch	Lubricant	No. of Forming Passes	Total Reduction, per cent[(a)]	Remarks
	75	1	10	1/4	90	NA[(b)]	SAE 30 oil	1	40	
T	175	1-1/2	12	3/16	90	NA	SAE 30 oil	1	60	100 rms surface finish
T	400	1/2 and 1-1/2	NA	1/8 and 1/4	NA	NA	NA	1	60	
T	400	1/2 and 1-1/2	NA	1/8 and 1/4	NA	NA	NA	1	50 max	
T	NA	NA	NA	NA	NA	NA	NA	1	40	Surface finish of 125-microinch on OD; honed quality on ID
		(0.005-in. variation in wall thickness over 7-inch length)								
T	188-260	0.004/ 0.020 in./rev	NA	0.075	30	NA	Nebula No. 2 Grease	1	~16 max	
150-1200	60	4	NA	NA	NA	NA	NA	3	80	Cooled to 800 F on mandrel before removal
T	200	4-1/2-6	NA	1/4	NA	0.225-0.030	NA	4	58	Parts tended to barrel surface finish only fair
T	200	2	NA	1/4	NA	NA	NA	1	63-39	Considerable wall-thickness variation
T	52.5	1.05	NA	0.062	NA	NA	NA	1	53.5	
T	55	1	NA	0.062	NA	NA	NA	1	53.3	
T	150	3	NA	0.062	NA	NA	NA	1	48.2	

146

2

strength and decrease the ductility due to cold working. Even in elevated-temperature operations the material is generally below the recrystallization temperature so that cold-working conditions prevail. When the materials are formed in the solution-treated condition and permitted to age at elevated temperatures during forming, an increase in strength with about the same ductility as heat-treated material can be expected.

Some mechanical properties of Ti-6Al-6V-2Sn alloy after shear forming at room temperature are given in Table XXV (Ref. 94).

TABLE XXV. MECHANICAL PROPERTIES OF Ti-6Al-6V-2Sn ALLOY AFTER SHEAR FORMING (REF. 94)

Material Condition	Yield Strength, 10^3 psi		Tensile Strength, 10^3 psi	Elongation, per cent	Reduction in Area, per cent[a]
	0.1 Per Cent	0.2 Per Cent			
As shear formed	144.7	154.0	165.5	10.0	22.1
	138.4	149.0	159.6	4.0	11.1
Aged 1100 F 1/2 hour	159.2	161.8	166.0	14.0	40.0
	165.3	170.8	172.6	10.0	25.0
Heated 1625 F 1/2 hour; water quenched; aged 1100 F 4 hours	169.7	171.1	176.3	3.0	8.4

(a) All material given a 40 per cent reduction in one pass to a thickness of 0.073 inch.

Post-Forming Operations.

Sizing. Most spinning or shear-forming operations produce titanium parts to final size without any subsequent sizing operations. For operations at room temperature, a springback allowance should be considered in designing the mandrel. A hot-sizing step after spinning may be advisable after forming at room temperature since it is difficult to predict the amount of springback.

Thermal Treatment. Titanium parts spun or shear formed at room temperature should be stress relieved within 24 hours. This treatment is not necessary for parts that are hot sized or worked above the stress-relieving temperature.

Trimming. Parts are normally trimmed to size after forming by machining or sawing. If sawing is used the edges are deburred. After a final cleaning operation the part should be wrapped in paper or plastic to protect its surface from scratches until required for the next assembly. Where surface scratches have occurred they can be removed by hand sanding with a No. 180 grit paper or finer. Etching is also used to remove light scratches although care must be exercised to prevent the removal of too much material so that the final part is not reduced below the permissible thickness.

DROP-HAMMER FORMING

Introduction. Drop-hammer forming is a progressive deformation process for producing shapes from sheet metal in matched dies with repetitive blows. The process offers advantages for a variety of parts that are difficult or uneconomical to produce by rubber- and contour-forming techniques. Typical applications include beaded panels and curved sections with irregular contours. Drop hammers are often used for details such as half sections of tees or elbows that can be joined together later. The process is best suited to shallow-recessed parts because it is difficult to control wrinkling without a blank holder. Nevertheless, many deeply recessed parts, especially those with sloping walls, are made on drop hammers.

In drop-hammer forming the energy delivered per stroke depends on the mass of the ram and tooling attached to it, and the velocity at which it strikes the workpiece. The striking velocity is controlled by the operator. Since the energy delivered is related to the square of the velocity, precise control must be exercised by the operator. Relatively large changes in the mass of the moving tool or punch can also have a considerable effect on the hammer operation. The operator must be skilled in judging the effects of changes in punch mass and velocity to insure successful and reproducible results.

The impact loading characteristic of drop hammers is not well suited to forming some strain-rate-sensitive materials. To work such metals, the operator must limit the maximum velocity of the ram.

Drop-Hammer Presses. The gravity drop hammer is equipped with a weight or ram that is lifted by means of some device such as a rope or a board, and then permitted to drop unrestricted. The pneumatic hammer, shown in Figure 67, and the steam hammer are equipped with a pressure cylinder that lifts the ram and also adds energy to that of the falling ram (Ref. 62). The drop hammer is fundamentally a single-action press. It can be used, however, to perform the work of a press equipped with double-action dies through the use of rubber blankets, beads in the die surfaces, draw-rings, and other auxiliary measures.

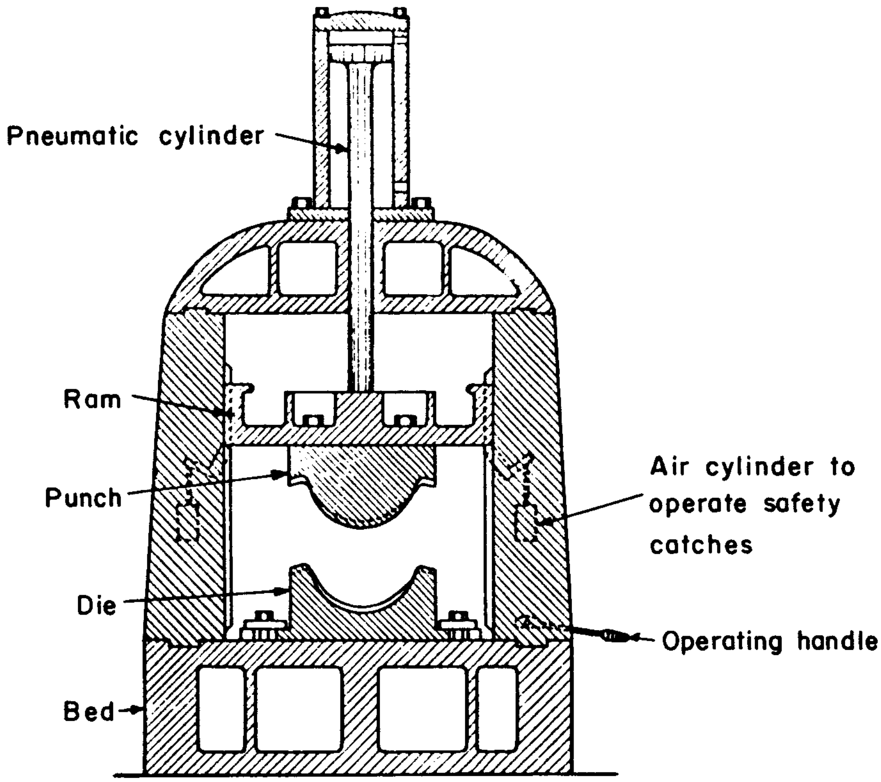
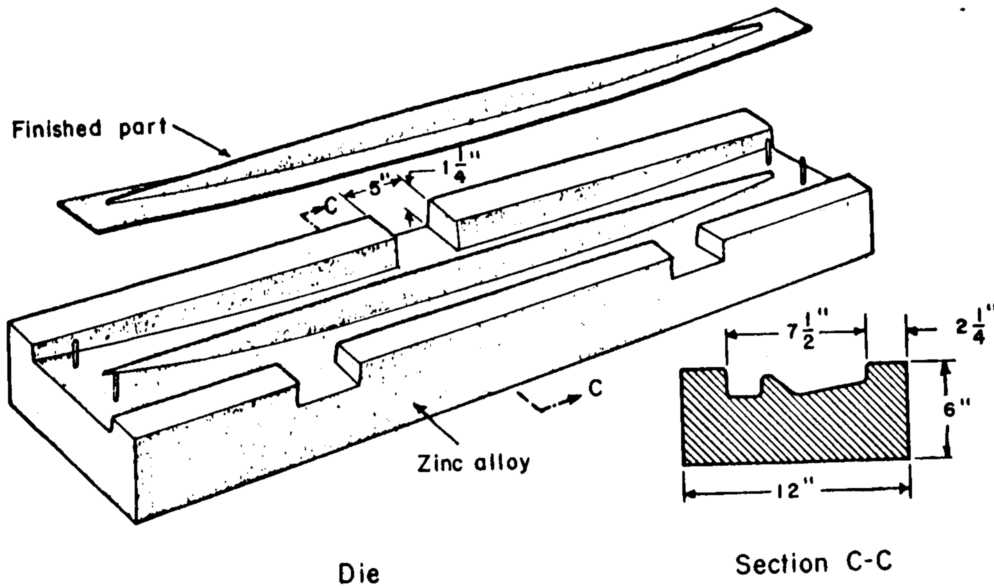


FIGURE 67. PNEUMATIC HAMMER (REF. 95)

The platen sizes of commercially available drop hammers vary from 21 x 18 in. to 120 x 96 in. The smaller machine has a ram weight of 600 pounds and a maximum die weight of 600 pounds, which gives a possible energy level in free fall of 2900 ft-lb. The larger drop hammer has a ram weight of 33,000 pounds and a maximum die weight of 47,000 pounds, which gives a possible energy level in free fall of 90,000 ft-lb (Ref. 95).

Tooling. The basic tool materials for drop-hammer forming are Kirksite and lead. Lead is preferred for the punches (see Figure 67) since it will deform during service and conform to the female die. For room-temperature forming of titanium an uncapped lead punch may have a useful life of about five parts. The wide use of Kirksite as a die material stems from the ease of casting it close to the final configuration desired. Most companies doing a large amount of drop-hammer work prepare the tooling in their own foundry. Beryllium copper dies have been used for drop-hammer forming, but



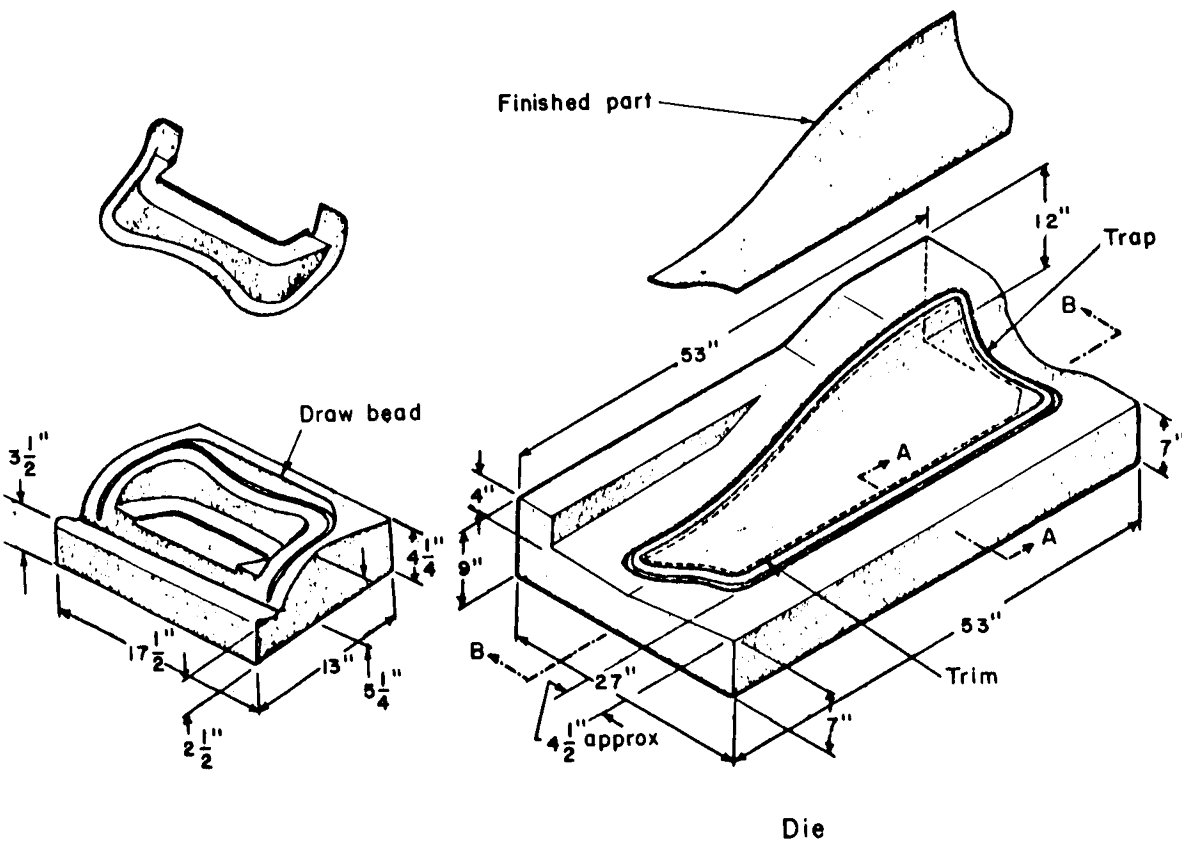


FIGURE 68. TYPICAL DROP-HAMMER DIES AND FORMED PARTS (REF. 62)

generally the additional cost is not warranted. Ductile iron and steel dies are used where the tooling must be heated above 400 F.

Contact between titanium and low-melting tooling materials such as lead or Kirksite should be avoided. This is especially true when the titanium is formed at elevated temperatures or must receive a thermal treatment after forming. The low-melting die material, which rubs off on the titanium surface during forming, will contaminate the material and render it structurally unsatisfactory. Several techniques have been used to overcome this difficulty. The die and punch may be capped with sheet steel, stainless steel, or Inconel to prevent pickup on the titanium. The choice of capping material depends on the punch life desired. Inconel gives the best life in sheet thicknesses of 0.025 to 0.032 inch. It may also be necessary to cap the female die for elevated-temperature work on titanium. This can be accomplished by forming a thin metal part in the die so that it will be retained in the die during the forming of the titanium parts.

Several typical drop-hammer dies are shown in Figure 68 with the finished parts made on them. Sometimes two punches are used: a working or roughing punch and a coining or finishing punch. When the working punch becomes excessively worn, it is replaced by the coining punch, and a new coining punch is prepared. Another method of achieving the same results with one punch is to use rubber pads. Rubber suitable for this purpose should have a Shore Durometer hardness of 80 to 90. Figure 69 indicates the positioning of pads for a particular part. The maximum thickness of rubber is situated where the greatest amount of pressure is to be applied in the initial forming. As the forming progresses, the thickness of rubber is reduced by removing some of the pads after each impact. Rubber pads are not very satisfactory for elevated-temperature forming because of rapid deterioration at the temperatures required for forming titanium (1000 F).

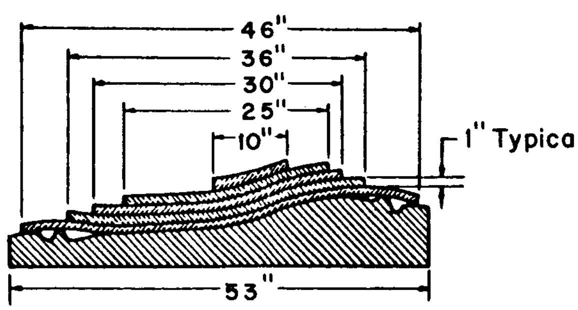


FIGURE 69. POSITIONING OF RUBBER BLANKETS (REF. 62)

The blank would be placed between the die and the first pad.

For room-temperature forming of smoothly contoured parts, Kirksite dies suitably shielded with steel or stainless steel can be used. Steel inserts should be used in sharply radiused corners of the dies. For complicated parts, cast steel or high-silicon cast-iron dies give better die life.

Mating surfaces of the die set must make contact uniformly. Areas of no contact can cause canning and warping, which are difficult to remove in subsequent forming. Hence, male and female dies should be carefully blued in with allowance for the sheet to be formed.

After a set of tooling has been constructed, the tools are proved out by forming either aluminum or stainless steel parts. Stainless steel is the best trial material since it has similar characteristics with regard to springback as titanium.

Buckling is difficult to control in drop-hammer forming because hold-down rings are not normally used. To minimize buckling, most of the deformation should result from stretching rather than shrinking. When shrinking is necessary, as in producing deeply recessed parts, a draw bead (Figure 68) will help to prevent buckling. The draw bead becomes effective only near the end of the stroke. Parts made in dies with draw beads require more material because the beaded sections have to be removed by trimming.

Difficult titanium parts are formed at elevated temperatures (800 to 1000 F). For hot operations, the thermal expansion of the blank and tooling must be considered. If the tooling is not heated, the amount it expands will depend on the length of time it is in contact with the blank. The thermal expansion value used in the design of tooling for titanium is 0.006 in./in. for temperatures between 70 and 1000 F. The allowance for expansion of circular or elliptically shaped parts should be made radially, not peripherally. When a hot-sizing operation is to be performed after forming, the drop-hammer tooling is generally made to net dimensions without consideration of thermal expansion.

If the blanks are to be heated in a furnace and then transferred to the drop-hammer tools, stops should be located in the tooling for rapid and precise location of the blank. Resistance heating may be used in drop-hammer forming but generally requires more time for forming each part due to the electrical connections necessary. Clearance relief for the electrical leads is necessary if the blank is shorter than the die. The dies must be insulated from the bed of the press to prevent short circuiting. Insulation materials such as Transite or high-temperature rubber have been used satisfactorily for this application. A typical arrangement for resistance heating on the drop hammer is shown in Figure 70. This heating technique is generally applied to long slim parts with the current passing through the long dimension of the blank.

When titanium parts cannot be readily formed with one blow in one die set, better results can sometimes be obtained by introducing two-stage tools, each of which permits one-blow forming, rather than using multiple blows in one set of tools. In such cases, good results can be obtained by making the part slightly oversized in the first-stage tools and obtaining the final shape by a coining operation in the second set of tools.

Furnaces used to heat blanks should be controlled within 15 F to prevent possible damage to the titanium. The temperature to be used depends on the titanium alloy being formed. Care must be exercised to assure that the parts are not overheated, and the parts should be shielded so that no hot spots occur. As soon as the blank reaches the required temperature, it should be removed from the furnace and formed. The furnace should be located beside the hammer. The total time for the sequence of transfer, forming, and return to the furnace should not exceed 8 seconds (Ref. 50). After the final strike on the hammer, the dies should remain closed for about 30 seconds so that the part will cool slightly in the die. Care should be exercised in elevated-temperature forming of titanium that the total time at temperature does not exceed that permitted for the alloy. The use of an inert furnace atmosphere increases the permissible time at temperature but should not be depended on in place of efficient operations.

Resistance-heating methods, as shown in Figure 70, require high-temperature rubber pads attached to the ends of the tool so that the blank is not in contact with the tool during heating. The electrodes are clamped to each end of the blank so that the current must pass through the entire blank. Clamping should be secure so that current leakage at the clamp-blank interface will not result in hot spots and possible melting due to insufficient clamping area for the current being transmitted. The current supplied from a low-voltage, high-amperage source, such as a welding machine, is increased until the desired temperature of the blank is obtained. The temperature of the blank can be checked with a thermocouple. The use of temperature-sensitive crayons is permitted only on the trim areas of the part to avoid possible contamination of the part. As soon as the forming temperature is reached, the blank can be covered with a high-temperature rubber pad at least 1 inch thick; the electrodes are

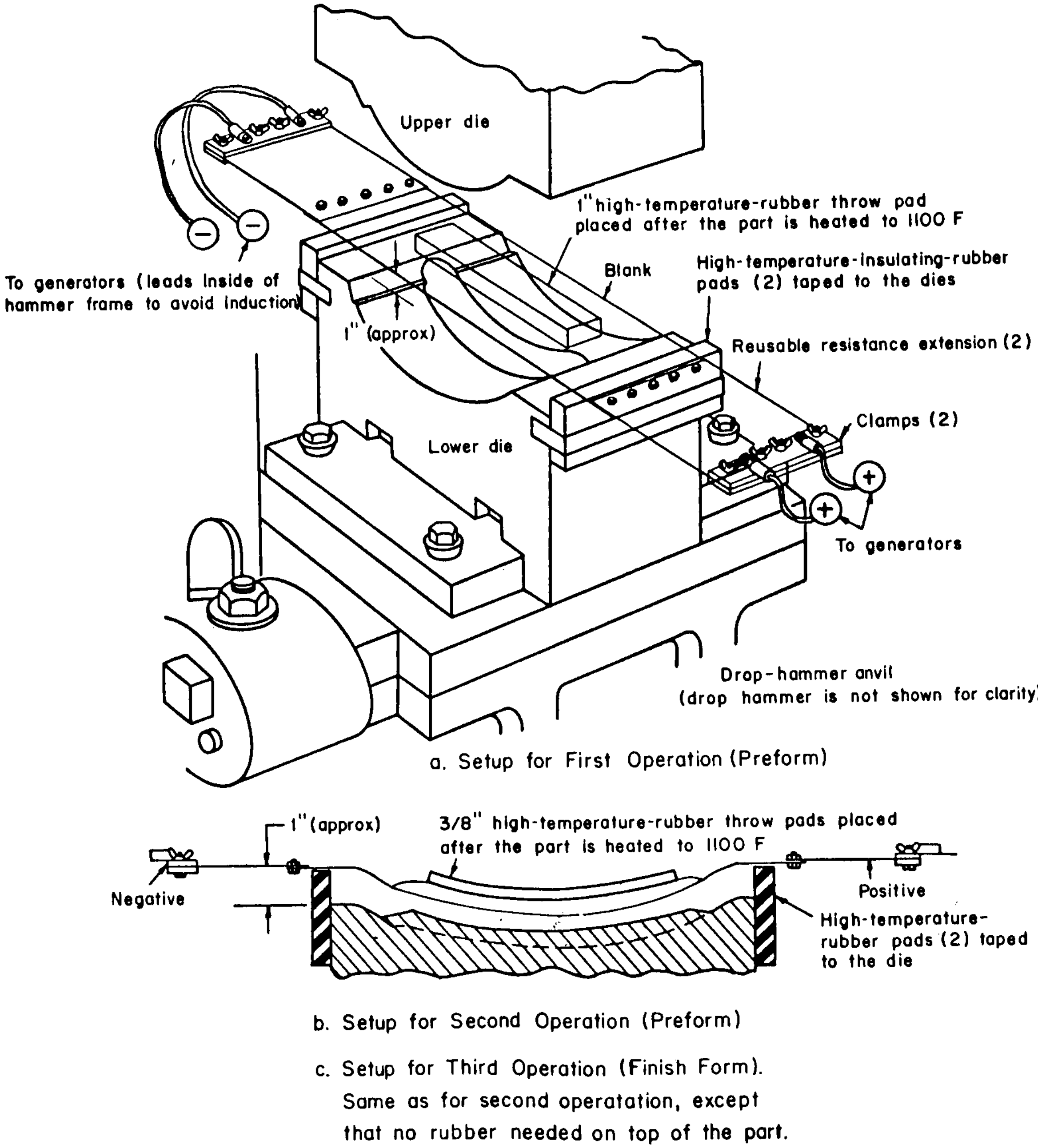


FIGURE 70. TYPICAL SETUP FOR FORMING RESISTANCE-HEATED TITANIUM ON DROP HAMMER (REF. 50)

disconnected and the part is then formed. This process is repeated for each successive blow until the part is formed to final dimensions. In the final stage, no rubber is used over the part and the dies are closed on the part for at least 30 seconds after the final blow.

A third method of heating titanium for drop-hammer forming is with radiant quartz lamps. The lamps are placed close to the blank while the blank is resting on the tooling. The lamps are generally time cycled for the desired temperature. The lamps are then moved out of the way, and the part is formed. This sequence is repeated until the part is completely formed. It sometimes helps if the edges of the blank are supported on an insulating blanket such as asbestos so that the heat loss to the tooling is reduced. Quartz-lamp heating of a flat surface is very effective. After the part has been formed partially, however, it is difficult to control the amount of heat the surface of the part receives. After initial heating it may be necessary to use furnaces to obtain the desired results.

Techniques of Drop-Hammer Forming. The procedures for forming titanium at room temperature in drop hammers resemble those used for stainless steel. The process offers the advantages of flexibility, low die costs, and short delay times between design and production. A number of individual forming operations can be combined on the drop hammer, such as drawing, beading, joggling, and bending. Two parts that incorporate these shapes are shown in Figure 71. There are some limits to the process that should be observed for satisfactory production. The minimum draft angle should be at least 3 degrees. This minimum draft angle should be used only for the wall adjacent to the part outline where sufficient material is available for the draw. The bend radii should be as large as possible. Undercuts should be avoided, and transitions should be made as gradually as possible. Internal contours or recesses may be formed by stretching alone. Hemispherical indentations can be designed into the tooling in trim areas adjacent to stretched recesses to absorb excess material and to prevent wrinkling. Considerable hand work and expense may be saved by allowing some wrinkling in noncritical areas. Regions where wrinkles are not objectionable should be marked on the drawings.

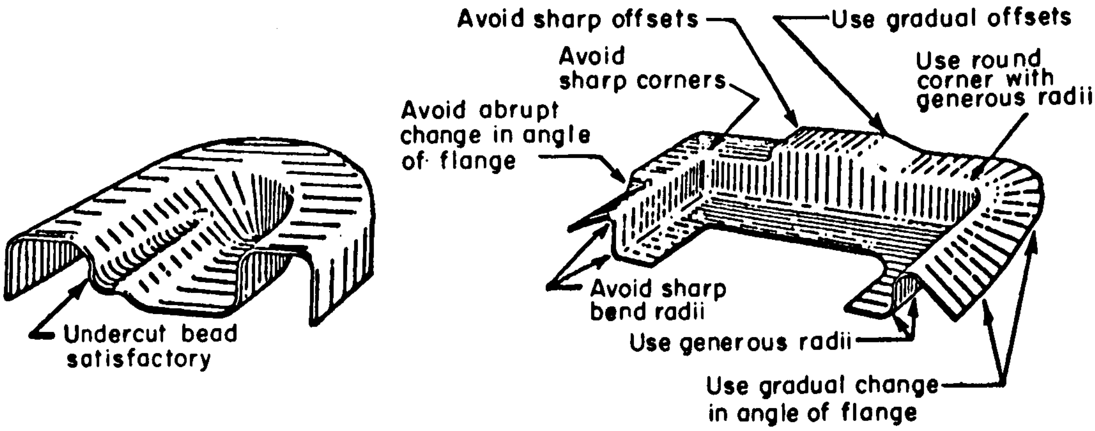
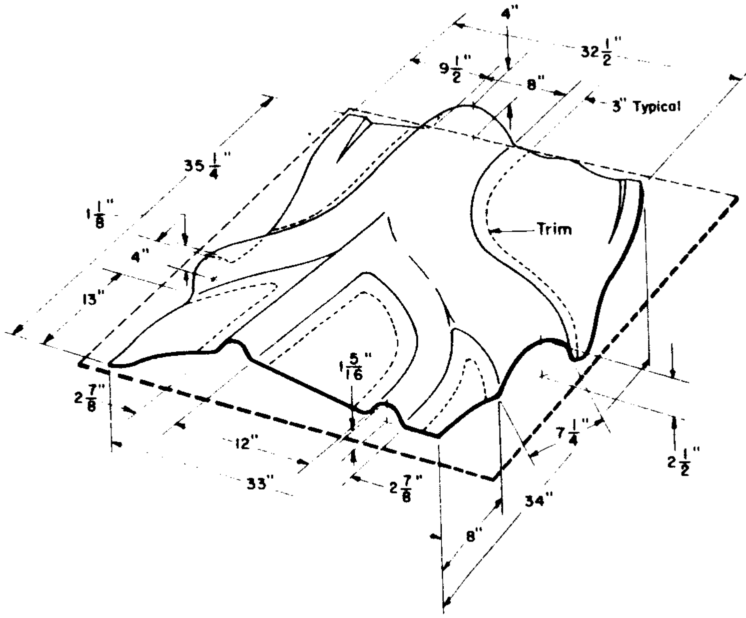


FIGURE 71. TYPICAL PARTS FORMED FROM TITANIUM ON A DROP HAMMER (REF. 97)

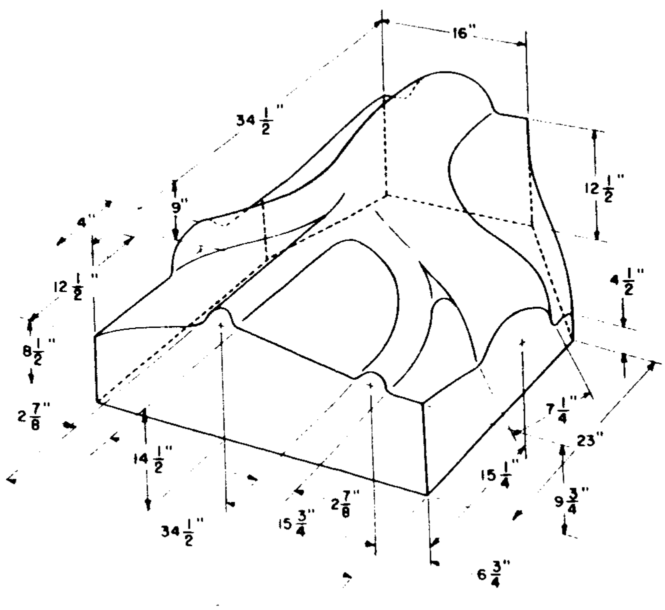
Drop hammers are often used for forming semitubular parts of complex design. Two halves formed in this manner are then welded to form a complete tubing assembly. In forming a semitubular part with a number of branches, the major limiting design factor is the radius, within the hold-down surface, at the apex of a fork, between two branches meeting at an acute angle. The radius at this point should not be smaller than one half of the depth of the draw. A complex semitubular part and die for drop-hammer forming is shown in Figure 72. The starting blank size and the trim areas of the part after forming are indicated. This particular part required several stages for forming and was not made from titanium.

Drop-hammer forming of titanium at room temperature is generally limited to slightly-contoured parts that are usually easier to make by stretch forming. Elevated temperatures are employed to take better advantage of the drop-hammer process. The ductility of titanium improves and the amount of springback decreases as the forming temperature rises.

Drop-hammer forming at elevated temperatures is similar to room-temperature forming except that greater care must be taken in handling the part. Forming the part at the right temperature will require precise movements of the operator if consistent results are to be obtained. If the part chills too much before forming, cracking of the part can be expected. The methods used in elevated-temperature drop-hammer forming varies among different manufacturers. Where furnaces are available close to the machines, furnace



a. Formed Part Before Trimming



b. Punch

FIGURE 72. DROP-HAMMER FORMING OF SEMITUBULAR PART MADE FROM 301 STAINLESS STEEL (REF. 62)

heating appears to be the most accepted and adaptable method of blank-heating. The other methods of radiant heating and resistance heating require different procedures each time the size of the blank changes.

To minimize blank chilling dies are often heated to 300 to 400 F. These temperatures can be used on Kirksite dies without deterioration of the tooling material. The heat can be obtained from steam lines already in most plants without the addition of electric heating. Where higher die temperatures are required, the tools must be made of ductile iron or steel that will withstand temperatures up to 1000 F.

Lubricants used in drop-hammer forming of titanium should be of the nonchlorinated types. Extreme pressure oils, pigmented drawing compounds, and nonpigmented drawing compounds are used in most operations. Some of the specific lubricants which have been used in drop-hammer forming of titanium are Dag-41 and Everlube T-50. The lubricants are generally swabbed onto the blank surface prior to forming, but for elevated-temperature forming it is best to place the lubricants on the die surfaces. The lubricants should be removed from the parts surface as quickly as possible after the parts are formed. Complete removal is necessary before any subsequent thermal treatment.

Blank Preparation. The blanks for drop-hammer forming are generally rectangular in shape and are prepared by shearing. The blank should be large enough to yield a part with a 2- to 3-inch-wide flange in order to facilitate drawing of the metal during forming. Where multistage forming is used, the part may be trimmed so that only a 1/2-inch-wide flange is left for the final forming stage.

Sheared edges are generally satisfactory for drop-hammer forming since the wide flange permits some cracking in the area without harming the part. The blank should, however, be deburred to reduce possible damage to the tooling.

Forming Limits. The severity of permissible deformations in drop-hammer forming is limited by both geometrical considerations and the properties of the workpiece material. According to Wood (Ref. 59) the forming limits can be predicted by considering parts of interest as variations of beaded panels. For parts characterized in this way, the critical geometrical factors are the bead radius, R, the spacing between beads, L, and the thickness of the workpiece material, T. These parameters are illustrated in Figure 73.

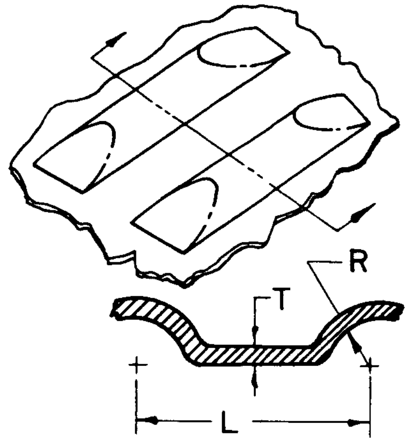


FIGURE 73. PARAMETERS OF DROP-HAMMER BEADED PANELS (REF. 59)

Two of the forming limits depend entirely on geometry and are the same for all materials. The ratio of the bead radius, R, to bead spacing, L, must lie between 0.35 and 0.06. The lower formability limit is controlled by the necessity for producing uniform stretching and avoiding excessive springback. If the R/L ratio is too small there will be a greater tendency for localized stretching at the nose of the punch. Furthermore, the material may deform elastically, not plastically, and springback will be complete when the load is removed.

Within the limits set for all materials by the R/L ratio, success or failure in forming beaded panels depends on the ratio of the bead radius to the sheet thickness, R/T, and on the ductility of the work-piece material. The part will split if the necessary amount of stretching exceeds the ductility available in the material. The splitting limit can be predicted from the elongation value, in a 0.5-inch gage length, in tensile tests at the temperature of interest. The general relationship (Ref. 59) is:

$$\frac{R}{L} = \frac{50\,(e_{0.5})^2}{(R/T)} \quad , \tag{21}$$

where

R = bead radius

L = center to center spacing of beads

$e_{0.5}$ = engineering strain for a 0.5-inch gage length

T = thickness of the blank.

The equation indicates that the permissible R/L ratio decreases as the R/T value increases.

Formability limits constructed in this way for two titanium alloys are shown in Figures 74 and 75. The charts show the marked improvements in formability resulting from better elongation values at elevated temperatures. Although the limits apply to beaded panels they can be used with caution as guides to forming other types of parts with drop hammers.

Earlier, other investigators (Ref. 56) suggested the stretching limits for drop-hammer forming given in Table XXVI. The parts used in that study were more complex than beaded panels. Their limits are more conservative than those indicated in Figures 74 and 75. The minimum thickness for hammer-formed parts of titanium alloys is about 0.025 inch. Heavier stock should be used for more complex shapes. It is difficult to predict proper springback allowances for complex parts. Therefore the general practice is to hot size them after hammer forming. In general, the tolerance for parts formed on drop hammers is about 1/16 inch.

TABLE XXVI. DROP-HAMMER MAXIMUM STRETCH LIMITS FOR VARIOUS TITANIUM ALLOYS

Material	Condition	Maximum Stretch[a] at 900 F
13V-11Cr-3Al	Solution treated	15.8
8Mn	Annealed	15.8
5Al-2.5Sn	Annealed	12.6
6Al-4V	Annealed	12.6
3.25Mn-2.25Al	Annealed	15.8

(a) Per cent stretch = $\frac{L_1 - L_o}{L_o} \times 100$

where
L_1 = stretched length
L_o = original length.

TRAPPED-RUBBER FORMING

Introduction. In trapped-rubber forming, a rubber pad is used as the mating die for a punch or group of punches on the bed of a press. The rubber pad is confined or trapped in a retainer as indicated in Figure 76. Relative motion of the upper and lower platens causes the rubber to fill the space between the retainer and the part and forces the workpiece to assume the shape of the punch. Among

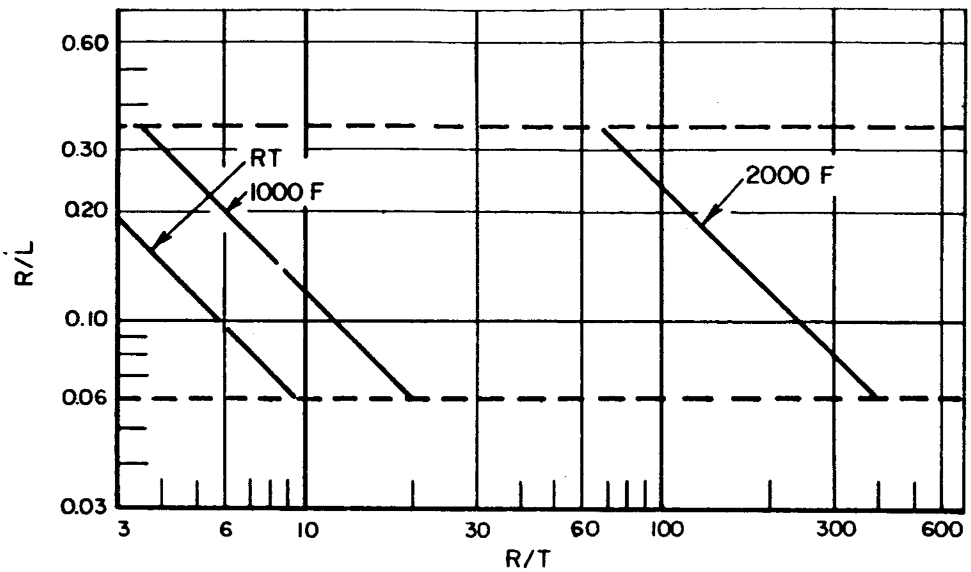


FIGURE 74. LIMITS FOR FORMING BEADED PANELS FROM THE Ti-8Al-1Mo-1V ALLOY WITH A DROP HAMMER (REF. 59)

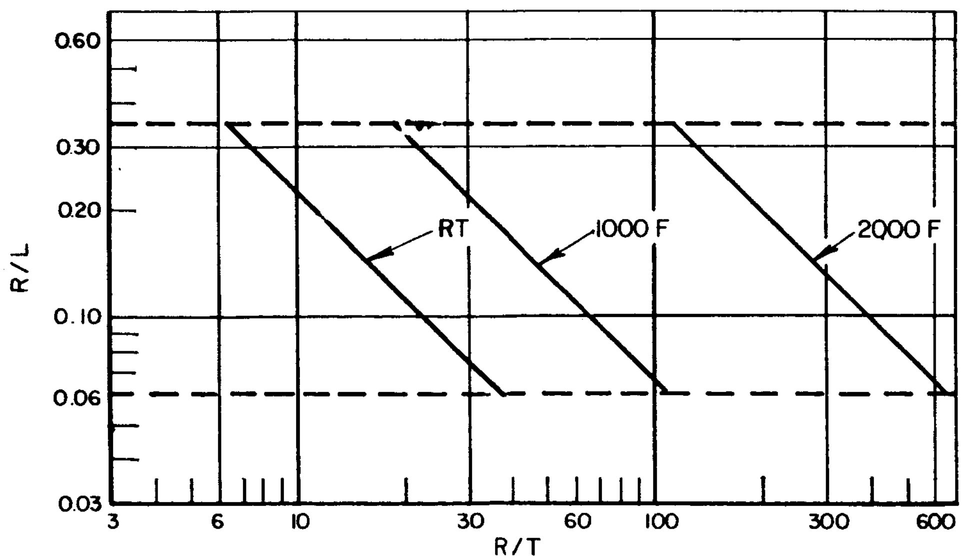


FIGURE 75. LIMITS FOR FORMING BEADED PANELS FROM THE Ti-13V-11Cr-3Al ALLOY WITH A DROP HAMMER (REF. 59)

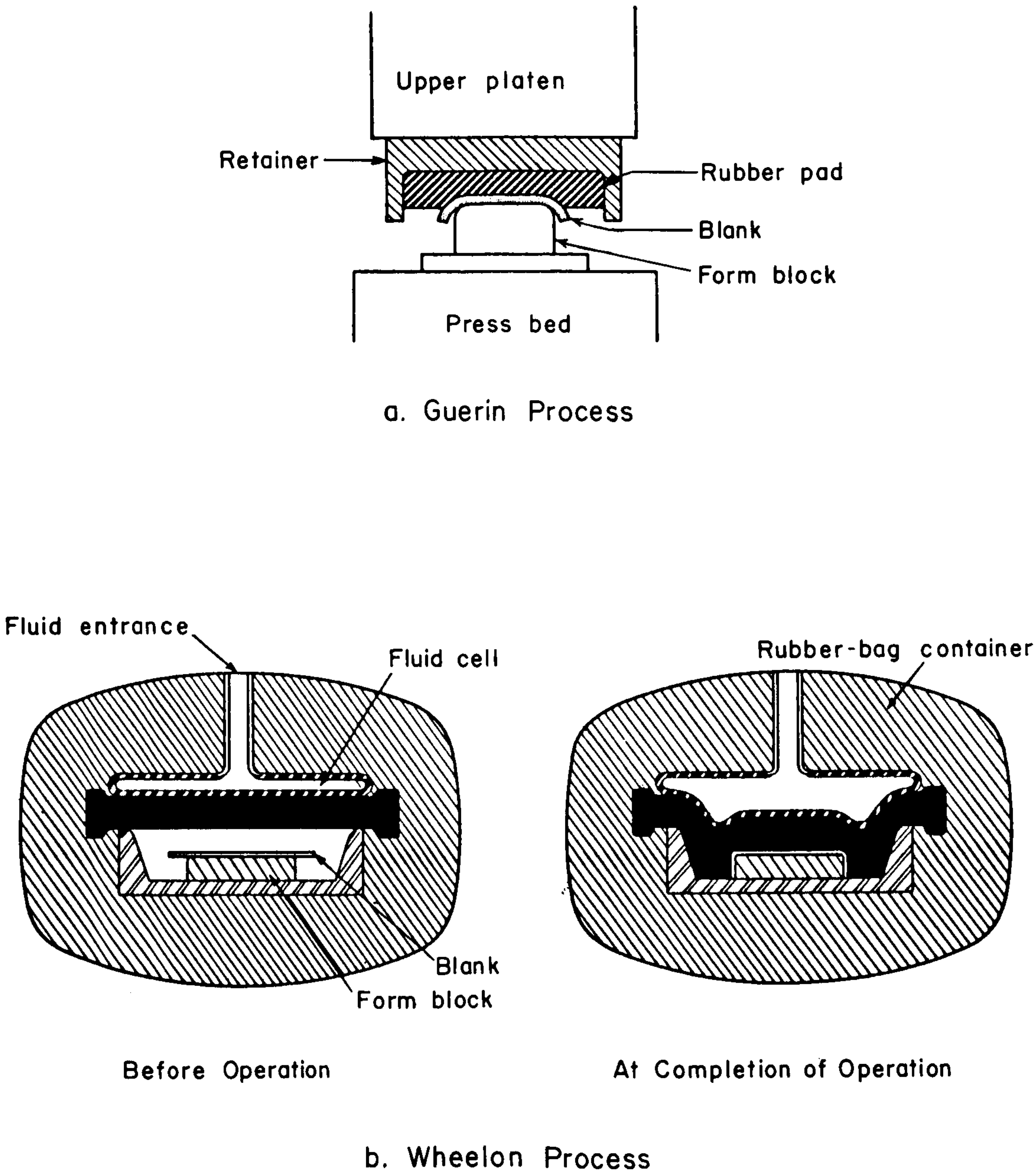


FIGURE 76. METHODS USED FOR TRAPPED-RUBBER FORMING (REFS. 62,98)

other advantages, trapped-rubber forming requires only the simplest half of conventional tooling; the punch and the pad replace the female die. The process is best suited to making small lots of parts with shallow recesses. The original or Guerin approach to trapped-rubber forming and a modification by Wheelon are shown in Figure 76. In the latter process, a rubber bag inflated with a pressurized fluid transfers the pressure from the bag to the part pad. Either process can be used to form several parts simultaneously depending on their size and the area of the press.

The maximum pressure ordinarily developed in trapped-rubber forming is about 10,000 psi. Impact presses are able to produce higher pressures. Parts formed by this process generally require some additional work to correct for springback. Although the process is usually conducted at room temperature, some new high-temperature rubbers have been used to form titanium parts at elevated temperatures.

The trapped-rubber process has been used extensively in the aircraft industry for forming parts with straight and curved flanges. The parts may be formed in one operation or in stages requiring several form blocks depending on the shape of the part. A typical trapped-rubber-formed titanium part made at room temperature from 0.063-inch Ti-13V-11Cr-3Al in the solution-treated condition is shown in Figure 77. The springback on the flanges was removed by subsequent hot sizing.

Trapped-Rubber Presses. Trapped-rubber presses may be of the single- or double-action type. Generally, the smaller presses are single action while the larger presses are of the double-action type. Most of the standard single-action hydraulic presses can be equipped with a trapped-rubber head for forming operations. A small trapped-rubber press might have a loading capacity of 500 tons and a working area of 500 square inches. One of the larger presses, shown in Figure 78, has a load capacity of 7000 tons and a working area of 2200 square inches. The limitations on equipment are generally set by the maximum pressure that can be generated in the rubber and the container strength.

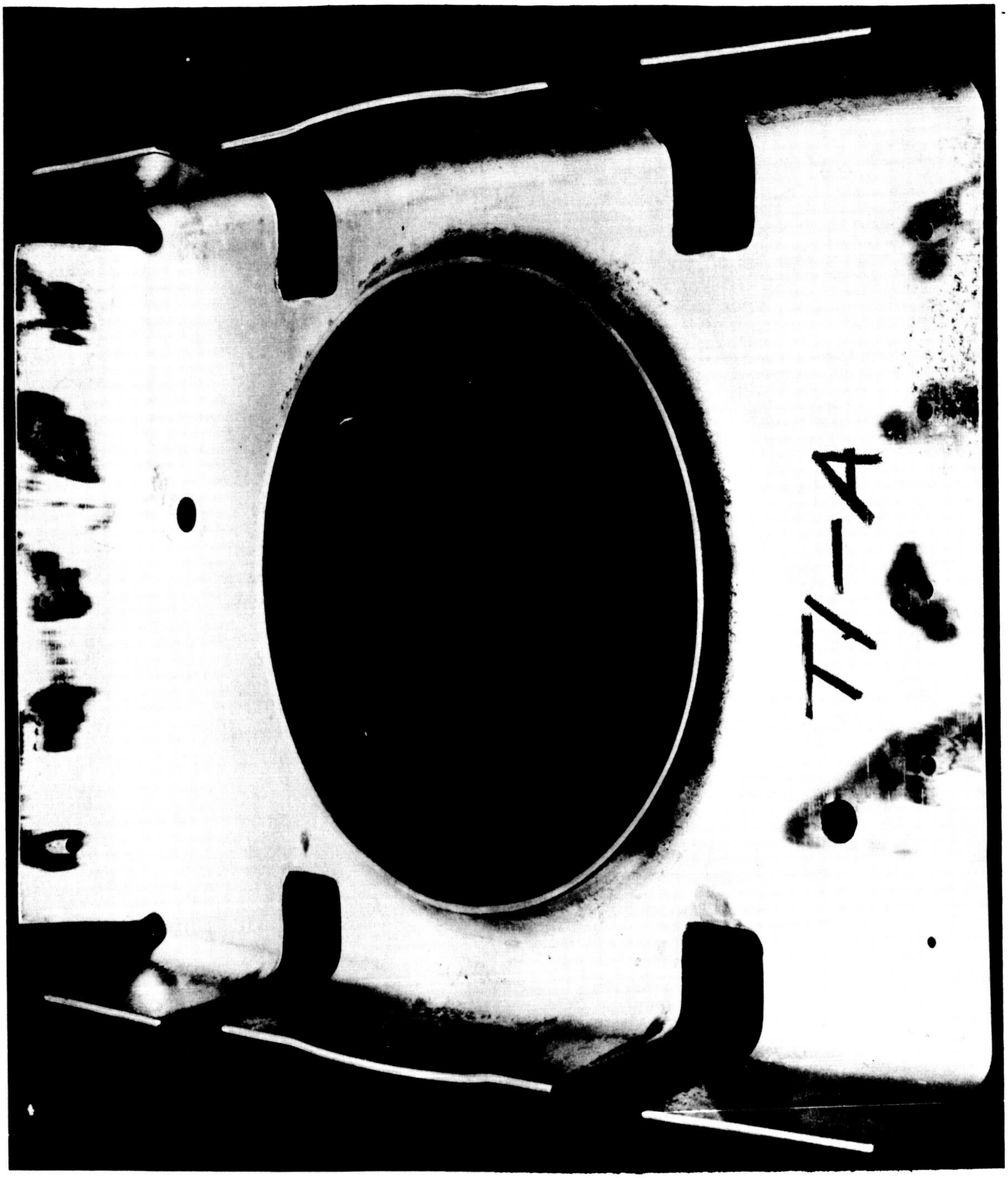


FIGURE 77. TRAPPED-RUBBER-FORMED Ti-13V-11Cr-3Al ALLOY

Courtesy of North American Aviation, Columbus Division.

FIGURE 78. 7000-TON TRAPPED-RUBBER PRESS

Courtesy of Hydraulic Press Manufacturing Co.

New developments in trapped-rubber forming are centered around methods of increasing the pressure that can be applied to the rubber. Heavier containers are being built, and new synthetic-rubber compositions that will withstand the higher pressures are being developed. A partial list of available press equipment and sizes is given in Table XXVII. For specific requirements the manufacturers should be contacted.

TABLE XXVII. SIZES OF TYPICAL TRAPPED-RUBBER PRESSES

Manufacturer	Work Area, in.^{2}	Press Stroke, inches	Forming Pressure, psi	Strokes/Hour
Cincinnati Milling Machine Co.	50	5	5,000	1200
	113	7	10,000	1200
	177	7-9	Up to 15,000	1200
	314	10	Up to 15,000	1200
	490	12	10,000	1200
	531	12	Up to 15,000	90
	804	12	10,000	90
HPM Corporation	Up to 2200	15	Up to 7,000	20

Tooling. The tooling for trapped-rubber forming can be made from a variety of materials depending on the tool life desired and the operating conditions. For room-temperature forming, cold-rolled steel is often used because it is a low-cost material and is fairly easy to machine. Where longer tool life is required, hardened carbon steel or alloy tool steel is used. Where the part shape is more complex, and the punch is difficult to machine, cast iron and ductile iron have been used. Kirksite has been used, but may give a very short life in working titanium materials. If Kirksite is used, the tooling surface should be covered with a thin stainless steel or mild-steel sheet to prevent zinc pickup by the titanium during forming.

Since there is very little rubbing action on the die during forming, very little wear is expected in normal operation. Most of the wear can be attributed to the methods used for removing formed parts from the tools. The pressure exerted by the flexible pad is fairly uniform over the part and die. Any imperfections in the die will be reproduced on the part if the pressure is sufficiently high. This is more troublesome with softer workpiece materials like aluminum than it is with titanium. A good surface finish should be maintained on the die to permit easy movement of the blank as the metal is drawn in, and to prevent scratching or marring of the surface during forming.

Sometimes a pressure plate is used over the punch to assist in keeping the surface of the part flat. The surface plate should also have a good finish and be aligned on the punch by means of tooling pins. Pins also serve to keep the blank in proper position on the punch during forming.

Normally, the tooling is made to net dimensions, and the springback in the part is removed by subsequent forming operations. Sometimes, springback can be minimized on flanges by undercutting the angles by the amount of springback expected. This technique is not very successful when the flange angle is 90 degrees or more. Another technique that can be used to extend forming limits is to place bars of lead over the flange area. Additional pads of rubber may also be placed over those areas where more pressure is required.

Very little forming has been done at elevated temperatures on trapped-rubber equipment because of limitations on the temperature at which the rubber can be operated. With high-speed presses, this becomes practical on forming titanium. The tooling for use at temperatures to 1000 F should be made of a good grade of tool steel. For temperatures above 1000 F, a material like Inconel X or

Hastelloy series should be used for tooling. For elevated-temperature operations, the blank is generally placed on the punch and the assembly is heated in a furnace. The entire assembly is placed on the trapped-rubber press for forming with an insulator material like an asbestos blanket over the heated part. Due to the handling required of the heated punch and blanks, this procedure is generally limited to small parts. A heated platen may be used for larger parts.

Techniques of Trapped-Rubber Forming. The multidirectional pressure in trapped-rubber forming, as compared with unilateral pressure in conventional drawing, results in more uniform stresses in the blank. This permits greater draws and drawing of less uniform shapes with sharply changing contours than with conventional dies. In trapped-rubber forming, the die radius is variable and depends on the pressure applied. As the forming pressure is increased, the radius of the part is decreased until the radius on the tool is reached. The forming pressure can be adjusted during the forming operation with the trapped-rubber process. In practice, the pressure is maintained at a low level until the material has been stretched to the deepest part of the die and then the pressure is increased until the desired radii have been obtained on the part.

With trapped-rubber forming, there is no transmission of stress through the wall of the partially formed part. The material is supported across the die by uniform pressures while the material is unsupported at the forming radius. Since small increments of the blank are stretched into the void and against the punch at one time, there is no thinning of the partially formed section of the part. By proper adjustment of the forming pressure and the speed, the stretching and thinning of the metal during forming can be made to compensate for the increase in flange thickness resulting in a part with fairly uniform wall thickness. Near the completion of the forming stroke, the pressure must be increased to prevent wrinkling of the flange. The reduced gripping area, increased thickening, and work hardening requires an increase in pressure to complete the forming.

The use of an external flange on trapped-rubber parts provides restraint and assists in obtaining closer dimensional tolerances. The extra material can be removed after forming. When blanks are trimmed to final size before forming, lead strips are often used as a substitute for the flange to assist in forming since the lead acts like a mating die.

Elevated-temperature forming with rubber pads should be attempted only on fast presses. Preferably, the rubber should be one of the high-temperature types with a hardness of Shore 80 or 90. Since a number of parts can be made side by side at one time, depending on the area of the part and the working area of the press, it is best to heat the tooling and the blank in a furnace. The male tooling generally is not fastened to the platen of the press so that it is quite easy to move the tooling in and out of the press. The blank and blank holder, if used, should be assembled on the punch before it is heated to save time in transfer from the furnace to the press. The tooling assembly with the blank is covered with a heat-resistant material such as asbestos; the part is then formed. Dwell times must be kept short to prevent heating the rubber.

Lubricants are seldom used in trapped-rubber forming since there is very little sliding-type friction involved in the process. If a lubricant is used, the nonchlorinated types should be used for elevated-temperature forming or when the parts are to receive a subsequent elevated-temperature treatment.

Blank Preparation for Trapped-Rubber Forming. Blank preparation for trapped-rubber forming is the same as for other forming processes. This process, however, generally necessitates the use of tooling holes for maintaining part location on the punch during forming. They must be located accurately within 1/32 inch or difficulty will be experienced in loading the blanks and, possibly, from elongation of the holes during forming. The tooling holes should be deburred the same as with the rest of the blank. When severe stretch flanges must be formed, the edge that is to be stretched should be polished to insure maximum formability.

Titanium Trapped-Rubber-Forming Limits. The trapped-rubber process is commonly used for producing contoured flanged sections and stiffened panels from titanium. Finished parts can be made if the requirements for the bead radius, flange height, bead spacing, or the free-forming radius are not too severe. If the design requirements exceed the capabilities of the material, the process may be used to fabricate preforms that are subsequently hot sized.

Ductility and stiffness are the principal properties influencing the performance of a material in trapped-rubber forming. Wood and associates (Ref. 53) have shown the quantitative relationships between mechanical properties determined in tensile and compressive tests and formability limits. The conventional values for tensile elongation correlate with the maximum permissible amount of stretching without splitting. In stretch flanging, splitting limits are given by the maximum ratio of the flange height to the contour radius. Generally speaking, the contour radius on the forming block, for titanium parts, should be 24 inches or larger for sheet up to 0.080 inch. Buckling, which depends on the ratio of the elastic modulus to the yield strength of the material, affects the maximum height to which flanges can be formed. The tendency for buckling increases with the ratio of the flange height to the thickness of the workpiece material. In shrink flanging, using higher forming pressures minimizes buckling or wrinkling. This expedient is not helpful in stretch flanging. The minimum permissible bend radii in rubber-pad forming of various titanium alloys are the same as those given in the section on brake forming. Higher forming pressures are needed to produce smaller bend radii.

For tight bends, the minimum practical flange length increases with sheet thickness. For forming pressures of 5000 psi or more, the ratio of flange length to sheet thickness should fall in the range from 10 to 18. Higher ratios are necessary for thicker sheet ranging from 0.020 to 0.090 inch.

Some parts made by the trapped-rubber process include beads, shrink flanges, and stretch flanges. If so, failures may occur in various regions depending on the severity of the shape change required at those locations. Therefore, it is convenient to consider, separately, the different criteria limiting formability.

Figure 79 shows the geometrical limits for stretch flanges that can be produced from four titanium alloys by the trapped-rubber process at room temperature. They are based on a theoretical analysis of the mechanics of the operation and knowledge of the tensile properties (Refs. 53,99,100). Experiments at room temperature by the same investigators indicate the formability limits are realistic. Although the limits for various part shapes appear to be close together, the differences are sometimes important. For instance, when the form-block radius is 24 inches, the splitting limits indicate that the maximum thicknesses for the Ti-4Al-3Mo-1V and the Ti-2.5Al-16V alloys are 0.040 and 0.024 inch, respectively. The corresponding flange heights for those thicknesses would be 0.72 and 0.43 inch maximum.

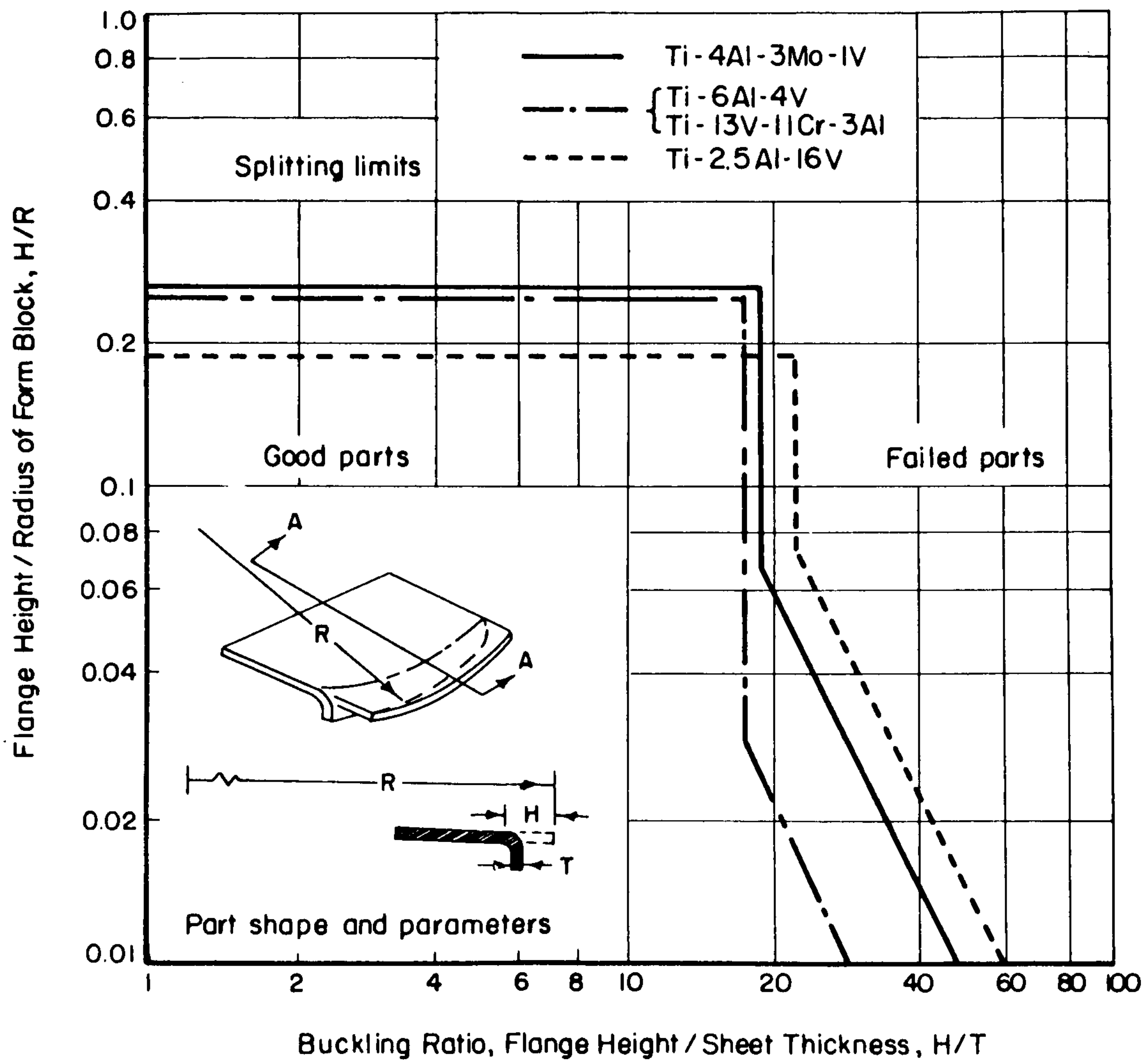


FIGURE 79. CALCULATED FORMABILITY LIMITS OF ANNEALED TITANIUM ALLOYS IN RUBBER-STRETCH-FLANGE FORMING AT ROOM TEMPERATURE (REFS. 53,99,100)

Figure 80 shows the limiting theoretical dimensions for shrink or compression flanges formed from titanium-base materials by the rubber-pad process. From the standpoint of buckling, the Ti-2.5Al-16V alloy has the best formability of the group. For equal flange heights and sheet thicknesses, it can be formed to a smaller contour radius. After constructing the formability boundaries analytically from mechanical-property data Wood and associates (Ref. 53) verified them experimentally.

Tables XXVIII and XXIX describe conditions found to be satisfactory for trapped-rubber forming in other investigations. The studies summarized in Table XXVIII indicate that increasing the pad pressure decreased the springback on shrink flanges but not on stretch flanges. There was also a tendency for springback to be less severe when the die-bend radius was smaller. However, the use of an overlay was far more effective. In some cases, the deviation from the desired flange angle of 90 degrees was probably caused by insufficient forming pressure rather than by springback.

Beading is another common operation in rubber forming. The bead radius is important because the stiffening effect decreases as the radius increases. The minimum radius that can be formed in a titanium sheet is the same as that for brake bending at the same temperature. How closely the minimum bend radius, for either a bead or the die-bend radius of the forming block, can be approached depends on the forming pressure and the stiffness of the metal. Figure 81 shows the effect of pressure on the minimum radii that can be formed in 0.063-inch sheet for two titanium alloys. The graph indicates that increasing the pressure in the range up to 25,000 psi permits forming smaller radii. Increasing the pressure in the higher range has much less effect on the minimum radius that can be produced by rubber-forming process. The practical limit at room temperature appears to be about 5 T.

As discussed under drop-hammer forming, failures in beading operations result from splitting or from buckling. Success or failure depends on the ratio of the bead radius to the thickness of the material, R/T, or on the spacing of the beads, R/L.

Table XXX gives geometrical limits for beaded panels made by the trapped-rubber process. The experiments were made with a relatively low forming pressure, 3000 psi, at both 70 and 1000 F. Increasing the forming pressure increases the limiting R/T ratios. The table indicates that raising the forming temperature permits closer beads in sheets of a particular gage.

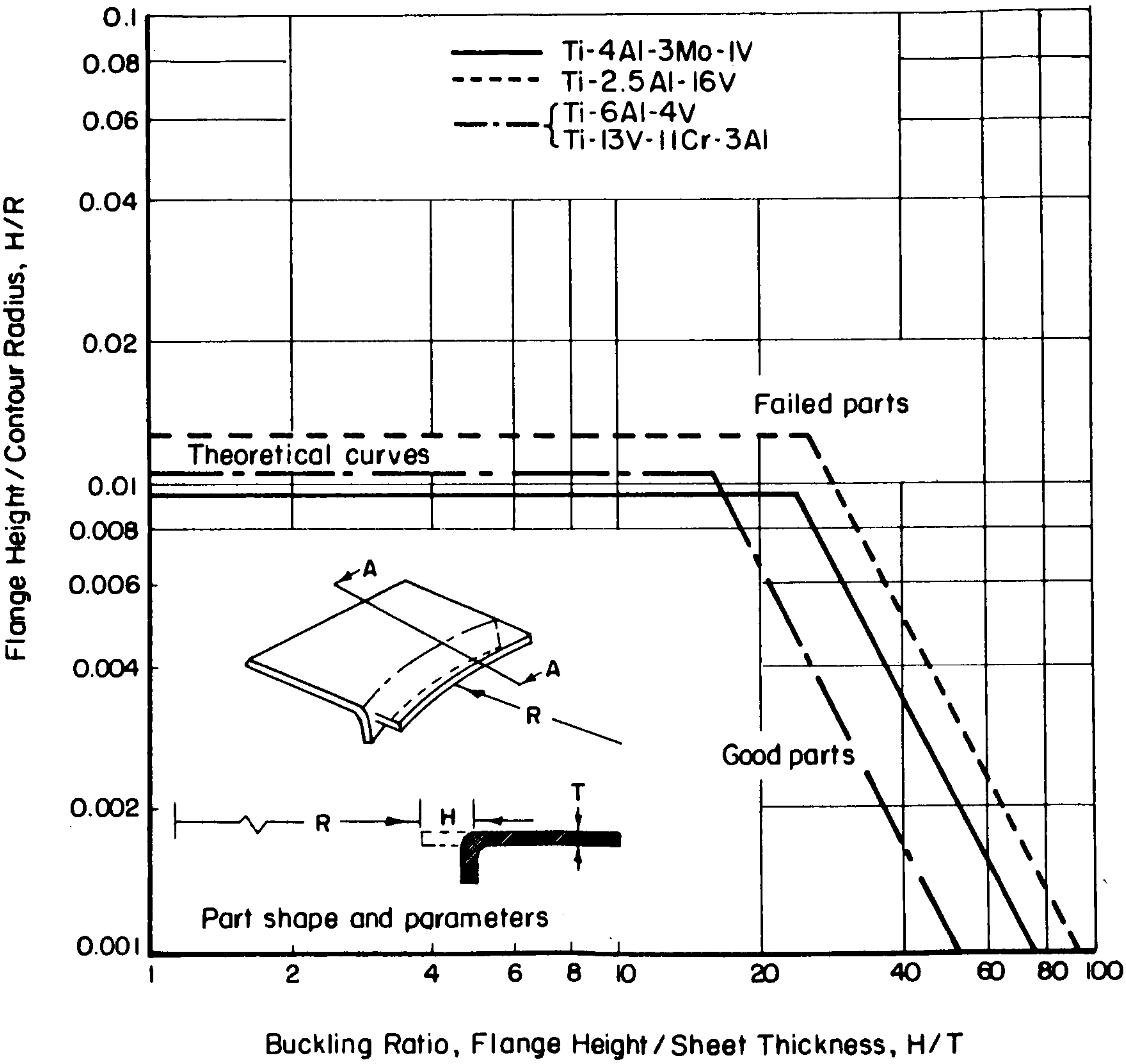


FIGURE 80. CALCULATED FORMABILITY LIMITS OF TITANIUM ALLOYS IN RUBBER-COMPRESSION-FLANGE FORMING AT ROOM TEMPERATURE IN COMPARISON WITH THE THEORETICAL CURVE (REFS. 53,99,100)

TABLE XXVIII. RESULTS OBTAINED IN TRAPPED-RUBBER FORMING OF 0.063-INCH SHEET (REF. 61)

Die-Bend Radius, in.	Die-Contour Radius, in. Stretch	Die-Contour Radius, in. Shrink	Temperature, F	Overlay Used	Rubber Pressure, psi	Springback Stretch, deg	Springback Shrink, deg
			Ti-8Mn				
0.250	2.562	1.937	RT	No	10,000	11-12	12-12.5
					35,000	17-20	12-14
0.250	2.562	1.937	RT	Yes	10,000	11-12	12
					35,000	11-12	10-12
0.250	2.562	1.937	0-30	No	10,000	10.5-11.5	11-12.5
					35,000	10-12.5	10.5-11.5
0.187	2.625	2.031	RT	No	10,000	10-11.5	9
					35,000	13-15	9.5-10
0.187	2.625	2.031	RT	Yes	10,000	8-9	9-9.5
					35,000	6.5-7.5	8-9
0.187	2.625	2.031	0-30	No	10,000	7.5-8	9-9.5
					35,000	7-8	9
			Ti-4Al-3 Mo-1V				
0.250	2.562	1.937	RT	No	10,000	7	13-13.5
					35,000	7-15	13.5-14.5
0.250	2.562	1.937	RT	Yes	10,000	12-13	12.5-13
					35,000	11.5-12.5	10.5-11.5
0.250	2.562	1.937	0-30	No	10,000	12.5	12
					35,000	11	11.5
0.250	2.562	1.937	0-30	Yes	10,000	13.5-16.5	13-16
					35,000	13.5	12.5
0.187	2.625	2.031	RT	No	10,000	8.5-10	10-11.5
					35,000	14.5-15	10.5-11
0.187	2.625	2.031	RT	Yes	10,000	10	10-11.5
					35,000	8-9	8-9
0.187	2.625	2.031	0-30	No	10,000	9.5-10	9-9.5
					35,000	9-10.5	9
0.187	2.625	2.031	0-30	Yes	10,000	11-15	10.5-12
					35,000	9.5	8
0.250	2.562	4.000	RT	No	10,000	10-14	15-16.5
					35,000	7.5-9.5	14-15
0.250	2.562	4.000	0-30	No	10,000	8.5-10	14-15.5
					35,000	7.5-9.5	13.5-14.5
0.250	2.562	4.000	RT	Yes	10,000	10-13	15-16
					35,000	7-9.5	12-14.5
0.250	2.562	4.000	0-30	Yes	10,000	11.5-12.5	13.5-14.5
					35,000	8.5-12	13-14

TABLE XXIX. RESULTS OBTAINED IN TRAPPED-RUBBER, STRETCH FLANGING OF TITANIUM ALLOYS AT ROOM TEMPERATURE (REF. 100)

Thickness, in.	Die-Bend Radius, in.	Forming Radius, in.	Springback, deg	H/T	H/R
		Ti-4Al-3Mo-1V; With Overlay, Forming Pressure 10,000 psi			
0.125	--	5.0	--	8.7	0.220
0.125	--	5.0	--	12.	0.300
0.063	--	5.0	--	17.5	0.220
0.063	0.156	10.0	12 - 19	7.9	0.05
0.063	0.156	8.0	16 - 19	7.9	0.063
0.063	0.156	6.0	14 - 18	7.9	0.083
0.063	0.156	4.0	15 - 26	7.9	0.125
0.063	0.172	10.0	18	7.9	0.05
0.063	0.172	8.0	22 - 28	7.9	0.063
0.063	0.172	6.0	32 - 38	7.9	0.083
0.063	0.172	4.0	32 - 38	7.9	0.125
0.063	0.156	10.0	9 - 11	11.9	0.075
0.063	0.156	8.0	11 - 13	11.9	0.094
0.063	0.156	6.0	13	11.9	0.125
0.063	0.156	4.0	8 - 10	11.9	0.187
0.063	0.172	10.0	10	11.9	0.075
0.063	0.172	8.0	13 - 15	11.9	0.094
0.063	0.172	6.0	8 - 13	11.9	0.125
0.063	0.172	4.0	6 - 16	11.9	0.187
0.063	0.156	10.0	5 - 7	15.9	0.100
0.063	0.156	8.0	5 - 7	15.9	0.125
0.063	0.156	6.0	1 - 7	15.9	0.167
0.063	0.156	4.0	0 - 7	15.9	0.050
0.063	0.172	10.0	--	15.9	0.100
0.063	0.172	8.0	9	15.9	0.125
0.063	0.172	6.0	5 - 6	15.9	0.167
0.063	0.172	4.0	0	15.9	0.250
		Ti-2.5Al-16V; With Overlay, Forming Pressure 10,000 psi			
0.040	0.156	10.0	19 - 22	12.5	0.05
0.040	0.156	8.0	21 - 23	12.5	0.063
0.040	0.156	6.0	24 - 27	12.5	0.083
0.040	0.156	4.0	--	12.5	0.125
0.040	0.172	10.0	21 - 24	12.5	0.05
0.040	0.172	8.0	22 - 24	12.5	0.063
0.040	0.172	6.0	21 - 23	12.5	0.083
0.040	0.172	4.0	--	12.5	0.125

TABLE XXIX. (Continued)

Thickness, in.	Die-Bend Radius, in.	Forming Radius, in.	Springback, deg	H/T	H/R
Ti-2.5Al-16V; With Overlay, Forming Pressure 10,000 psi (Continued)					
0.063	0.156	10.0	16 - 20	7.9	0.05
0.063	0.156	8.0	19 - 21	7.9	0.063
0.063	0.156	6.0	19 - 21	7.9	0.083
0.063	0.156	4.0	18 - 21	7.9	0.125
0.063	0.172	10.0	17 - 21	7.9	0.05
0.063	0.172	8.0	20 - 24	7.9	0.063
0.063	0.172	6.0	19 - 24	7.9	0.083
0.063	0.172	4.0	17 - 25	7.9	0.125
0.040	0.156	10.0	18 - 22	18.9	0.075
0.040	0.156	8.0	20 - 22	18.9	0.094
0.040	0.156	6.0	17 - 20	18.9	0.125
0.040	0.156	4.0	15 - 20	18.9	0.187
0.040	0.172	10.0	19 - 20	18.9	0.075
0.040	0.172	8.0	19 - 22	18.9	0.094
0.040	0.172	6.0	17 - 21	18.9	0.125
0.040	0.172	4.0	14 - 19	18.9	0.187
0.063	0.156	10.0	15 - 18	11.9	0.075
0.063	0.156	8.0	16 - 19	11.9	0.094
0.063	0.156	6.0	14 - 17	11.9	0.125
0.063	0.156	4.0	13 - 17	11.9	0.187
0.063	0.172	10.0	14 - 17	11.9	0.075
0.063	0.172	8.0	15 - 18	11.9	0.094
0.063	0.172	6.0	14 - 19	11.9	0.125
0.063	0.172	4.0	13	11.9	0.187
0.040	0.172	10.0	16 - 20	25.0	0.100
0.040	0.172	8.0	20 - 21	25.0	0.125
0.040	0.172	6.0	18 - 20	25.0	0.167
0.040	0.172	4.0	--	25.0	0.250
0.063	0.172	10.0	--	15.9	0.100
0.063	0.172	8.0	15 - 16	15.9	0.125
0.063	0.172	6.0	--	15.9	0.167
0.063	0.172	4.0	--	15.9	0.250

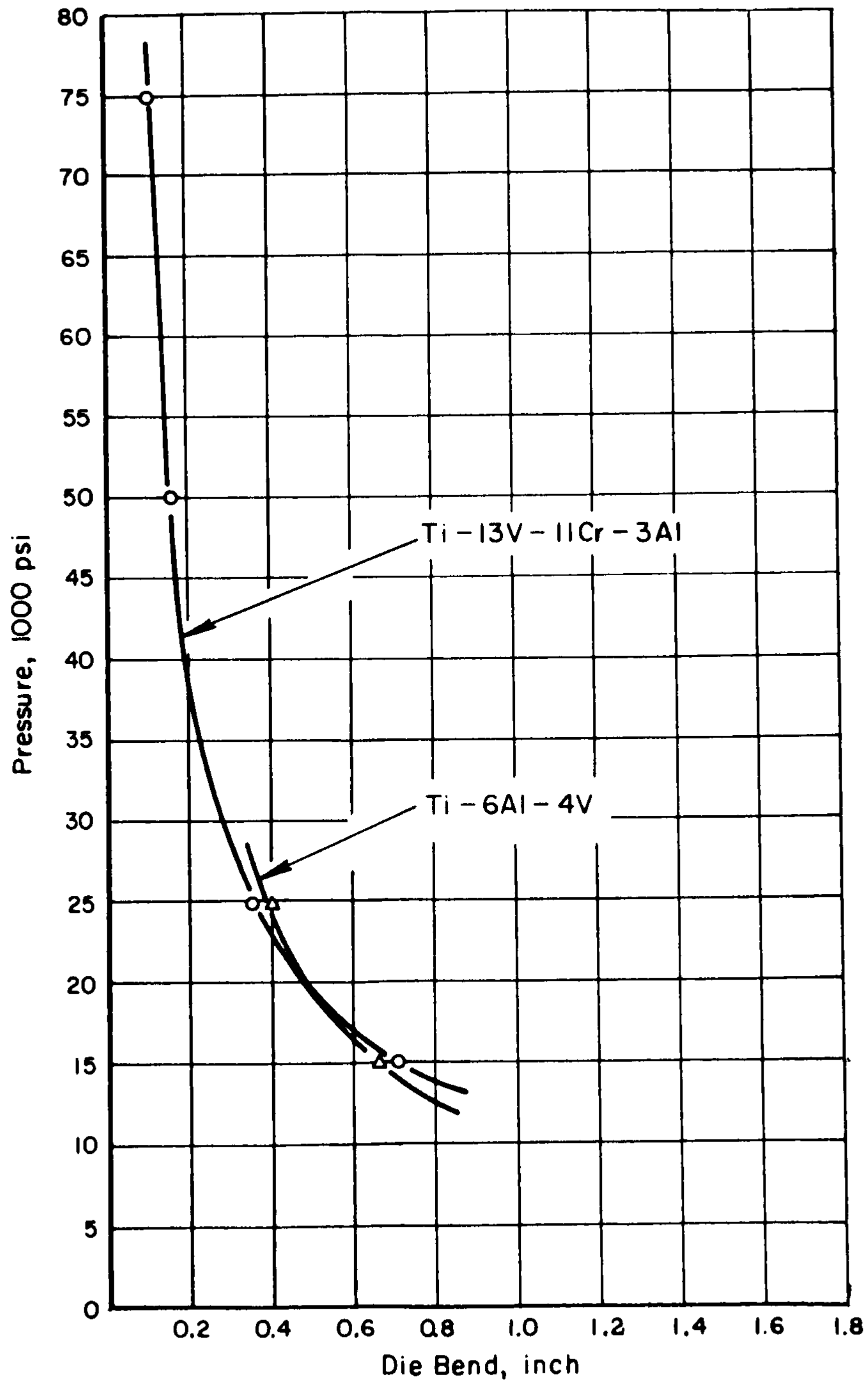


FIGURE 81. EFFECT OF PAD PRESSURE ON RADII THAT CAN BE FORMED AT ROOM TEMPERATURE BY TRAPPED-RUBBER TECHNIQUES IN 0.063-INCH SHEET (REF. 59)

TABLE XXX. LIMITS[a] ON FORMING BEADED PANELS BY THE TRAPPED-RUBBER PROCESS WITH A PRESSURE OF 3000 PSI (REFS. 52, 59)

		Insufficient Pressure Limits, R/L					Splitting Limits, R/T						
	Critical Ratio	Temperature		For R/T Ratios of			Temperature		For R/L Ratios of				
Material	L/T	F		2	5	15	F		0.01	0.03	0.06	0.10	0.15
Ti-8Al-1Mo-1V	147	RT	R/L	0.093	0.123	0.178	RT	R/T	52	47	44	---	---
			L/T	21.5	40.6	84.3		L/T	5200	1568	733	---	---
Ti-8Al-1Mo-1V	121	1000	R/L	0.107	0.140	0.195	RT	R/T	52	47	44	---	---
			L/T	18.7	35.7	77.0		L/T	5200	1568	733	---	---
Ti-13V-11Cr-3Al	107	1000	R/L	0.125	0.165	0.230	500	R/T	60	54	50	---	---
			L/T	16.0	30.3	65.2		L/T	6000	1800	833	---	---
				For R/T Ratios of									
				7	15	30							
Ti-13V-11Cr-3Al	202	RT	R/L	0.12	0.14	0.17	RT	R/T	53	---	47	44	42
			L/T	60	104	173		L/T	5300	---	775	440	277

(a) Parameters:
R = bead radius
T = sheet thickness
L = bead spacing

Post-Forming Treatments. Because of springback, parts made by the trapped-rubber process usually require a subsequent operation to bring the part to final dimension. Normally, a hot-sizing treatment is used (see section on hot sizing). Considerable difficulty is experienced in attempting to hot size parts that have flange angles out of dimension by 20 degrees or more since the pressures available on hot-sizing equipment are generally limited.

Trimming necessary to complete the part should be done after the final sizing and thermal treatment. Residual stresses in the part can seriously affect the dimensions of the part if trim areas are removed before lowering the residual stresses.

STRETCH FORMING

Introduction. In stretch forming, the workpiece, usually of uniform cross section, is subjected to a suitable tension and then wrapped around a die of the desired shape. Deformation occurs mainly by bending at the fulcrum point of the die surface. Compression buckling is avoided by applying enough tensile load to produce approximately 1 per cent elongation in the material. The tensile load shifts the neutral axis of the workpiece toward the forming die.

The terms linear stretch forming and stretch-wrap forming denote operations on preforms such as extrusions or brake-formed parts. Figure 82 illustrates two types of linear stretch forming. The classification is based on the position of the flange in the plane of forming. Depending on its location the flange is stressed in either tension or compression. Although the sketch shows an angle, the same classification is used when forming channels and hat sections. A typical linear stretch-forming operation for making bent "T" sections is shown in Figure 83.

Stretch forming is also used for producing double contours in sheet, as shown in Figure 84. Ordinarily the sheet is stretched and bent around a male die as with convex curvature. In a second double-contouring technique, called Androforming, the sheet is pressed between matched dies after the tensile load has been applied. This type of stretch forming is illustrated by Figure 85.

Equipment Used for Stretch Forming. Presses with a capacity range of 5 to 5000 tons are used for stretch forming sheet and sections. The small-capacity machines are generally used for linear stretch forming of light sections while the large-capacity machines

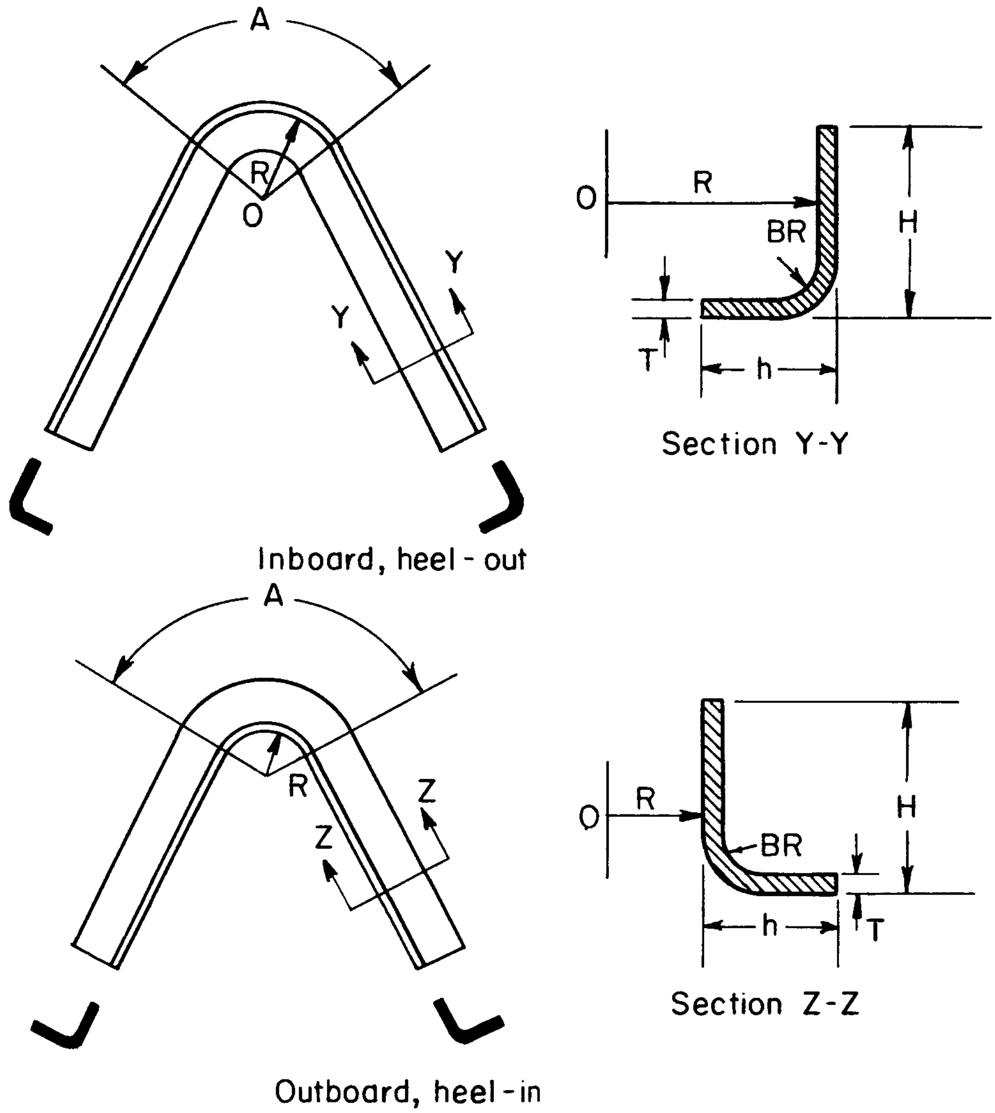


FIGURE 82. PARAMETERS OF HEEL-IN AND HEEL-OUT LINEAR-STRETCH-FORMED ANGLES (REF. 101)

R = stretch-die radius
BR = brake-formed radius
h = flange dimension

H = heel dimension
A = forming radius
T = thickness of material.

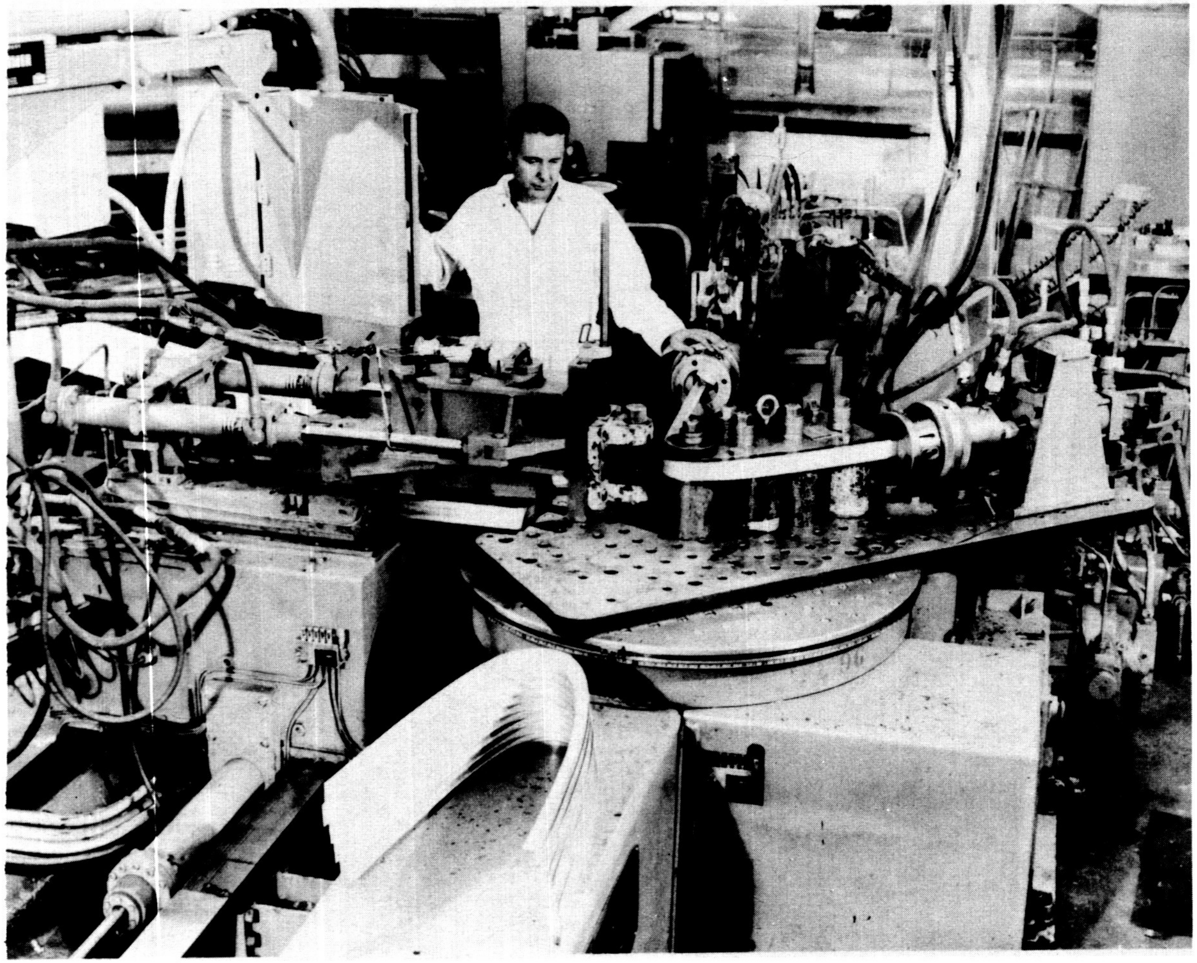


FIGURE 83. STRETCH-FORMING MACHINE FOR SECTIONING

In-board or heel-out "T" sections are being formed. Courtesy of Cyril Bath Company.

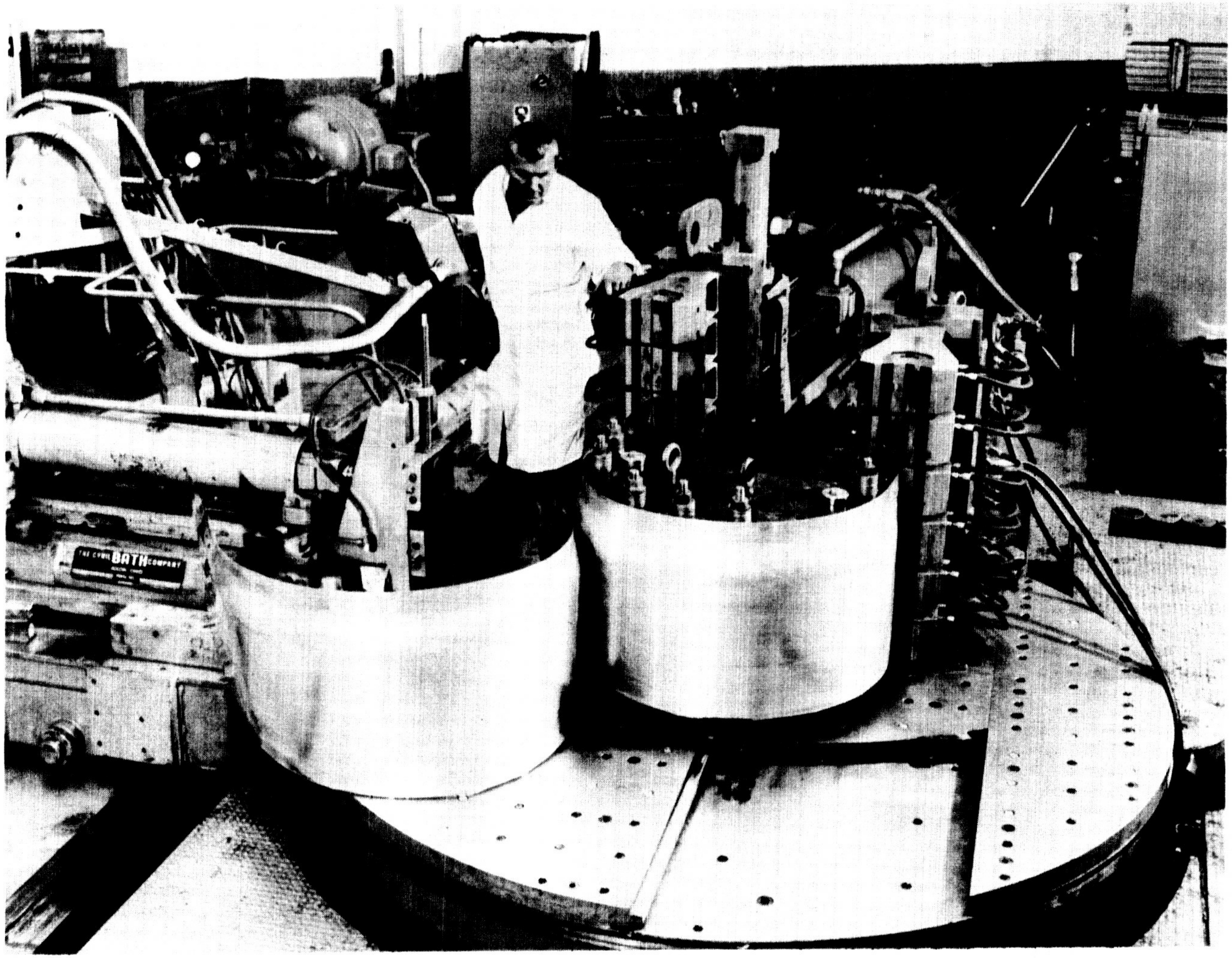
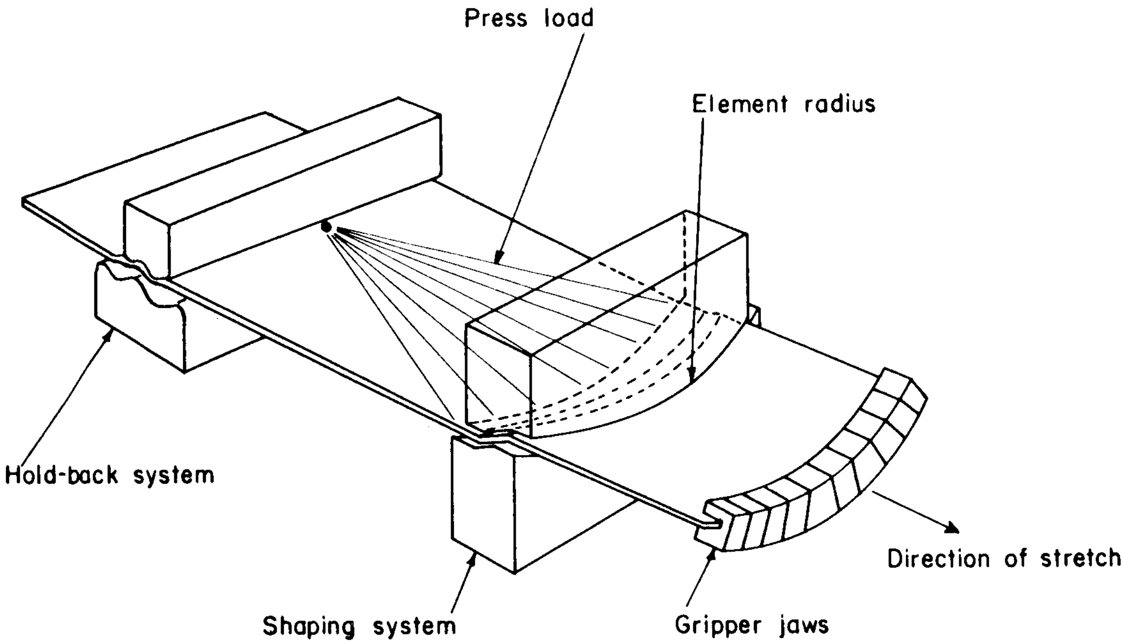
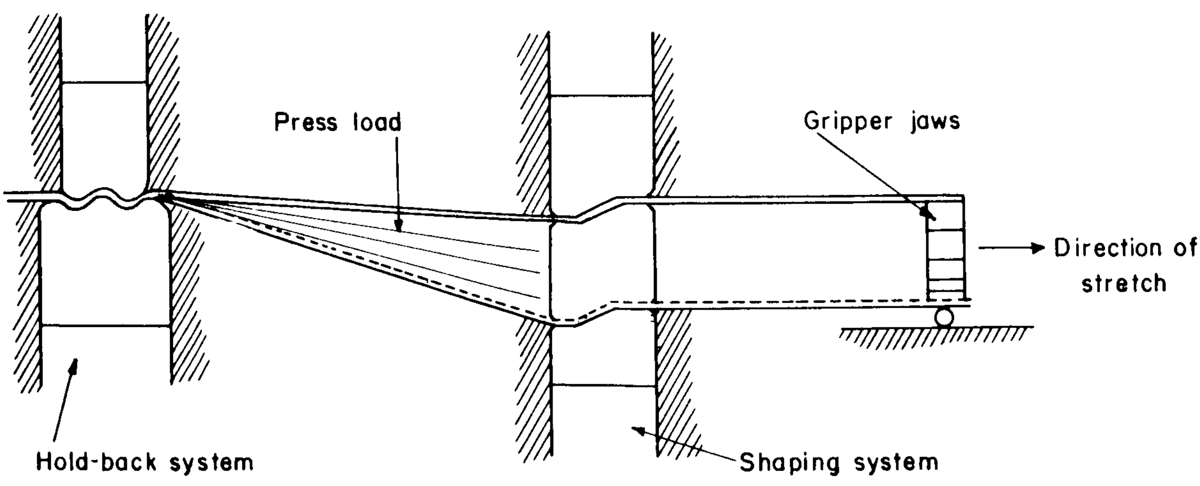


FIGURE 84. STRETCH-FORMING MACHINE FOR SHEET

Courtesy of Cyril Bath Company.





Side View

FIGURE 85. THE ANDROFORM MODIFICATION OF THE STRETCH-FORMING PROCESS (REF. 53)

are used either for sheet and plate or heavy sections. The specifications of some commercially available equipment for stretch forming are given in Table XXXI. Equipment that could be used to stretch form aluminum plate 14 x 20 feet and 1 inch thick with a capacity of 6000 tons has been proposed (Ref. 102).

Equipment for producing double-contoured stretch-formed parts from sheet metal is shown in Figure 84. Figure 86 is a photograph of a stretch former that handles unusually long, wide sheet. The press in Figure 87 employs the stretch-draw principle to form parts with irregular contours. A 250-ton machine of this kind is capable of making parts that would require a 900-ton double-acting deep-draw press. Figure 83 shows a typical setup for stretch forming small sections.

Tooling. The tooling for stretch forming normally consists of a male die made to the contour and dimensions desired in the final part. A number of materials have been used for tooling depending on the number of parts to be made and the temperature at which the forming is to be done. For room-temperature linear stretch forming of sections, a composite steel die with inserts that will accommodate different thicknesses of material is often used. Tooling of this kind is shown in Figure 88. The method of using die inserts to adjust for various thicknesses of materials and angle-leg lengths is shown in Figure 89. By using inserts the number of different-size tooling sets can be significantly reduced.

For room-temperature operations on sheet, the tooling can be made from Kirksite or from concrete faced with plastic. Cast-aluminum tooling faced with a 3/4-inch layer of epoxy resin can be used for larger production quantities. The life of the stretch-forming tooling can be extended by first stretch forming a thin sheet of stainless steel over the tool and then forming over the stainless. This should be done when Kirksite tooling is used in order to prevent the pickup of the low-melting alloy on titanium.

The grips for stretch forming should be made of hardened tool steel with sharp clean serrations. This is particularly important when a number of grips are used as in forming sheet. If the grips are not in good mechanical working condition, the workpiece may slip in some locations and tear at the grips that apply a greater holding force. Relieving the first four teeth near the jaw edges by polishing or grinding helps to prevent premature tearing of the sheet.

TABLE XXXI. CAPABILITIES OF TYPICAL STRETCH-FORMING MACHINES

Tonnage[a]	Rate of Forming, deg/min	Material Size, in.	Type
		Cyril Bath (Ref. 103)	
200-2000	-	84-144 width	Sheet stretch
150	36 max	-	Sheet or section stretch
100	36 max	-	Section stretch
75	36 max	-	Section stretch
50	36 max	-	Sheet or section stretch
25	50 max	-	Section stretch
10	90 max	-	Section stretch
250 pressing, 85 stretching		Bed 138 x 128	Stretch draw sheet
		Sheridan-Gray (Ref. 104)	
5	-	16-96	Section
10	-	16-144	Section
21	-	18-144	Section
54	-	28-216	Section
104	-	40-288	Section
306	-	48-288	Section
59	220 max	20-336	Sheet stretch
120 to 5000 stretching	-	48-240 width	Sheet stretch draw[b]
300 to 1000 pressing	-	96-360 length	Sheet stretch draw[b]

(a) All tonnage for stretch unless otherwise noted.
(b) Presses similar to Androforming.

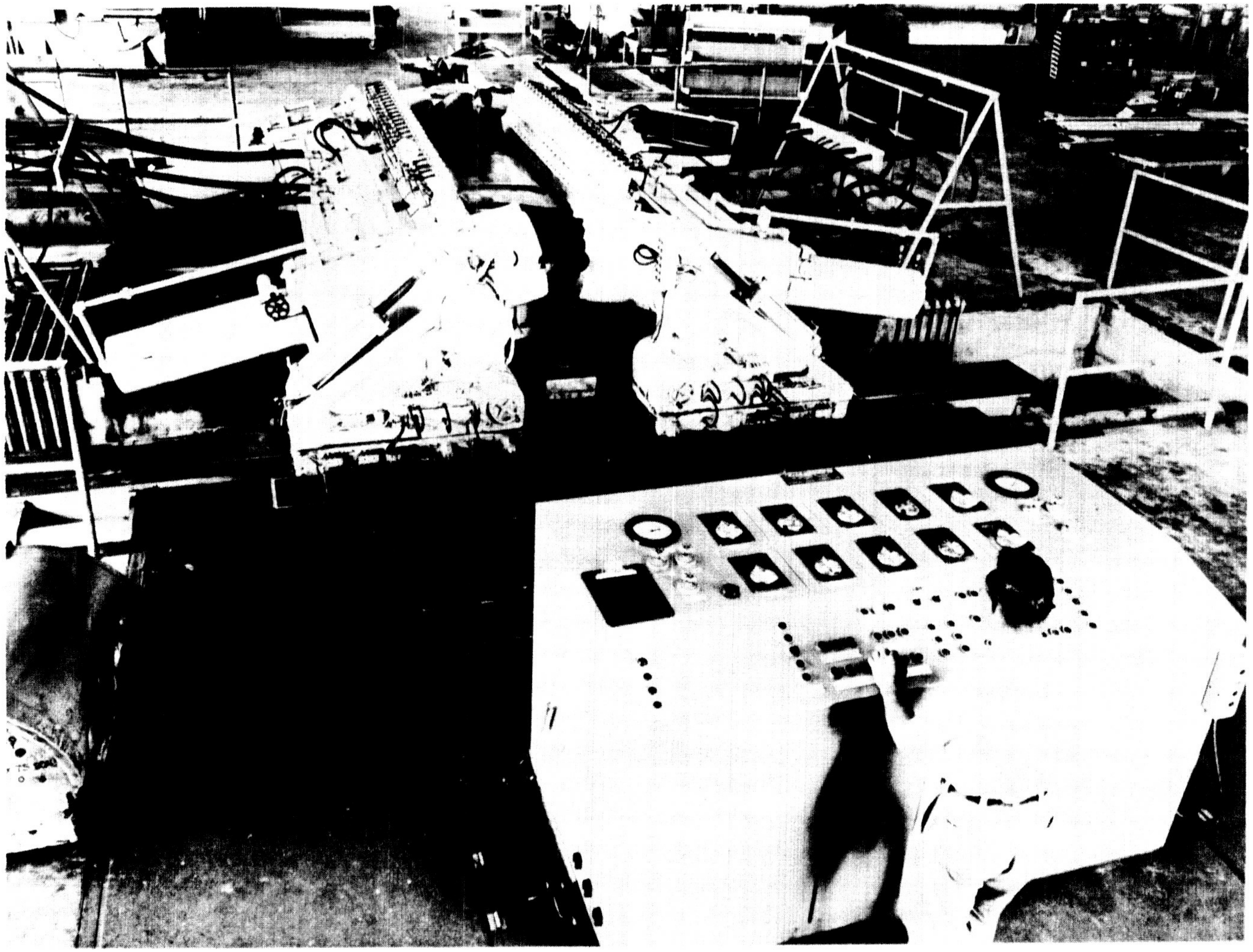


FIGURE 86. STRETCH-FORMING-SHEET EQUIPMENT FOR LARGE-WIDTH SHEETS, 500 TONS ON DIE TABLE, 144-INCH-WIDE JAWS
Courtesy of Sheridan-Gray.

FIGURE 87. STRETCH-DRAW-PROCESS MACHINE FOR SHEET

250-ton press, 85-ton stretch. Courtesy of Cyril Bath Company.

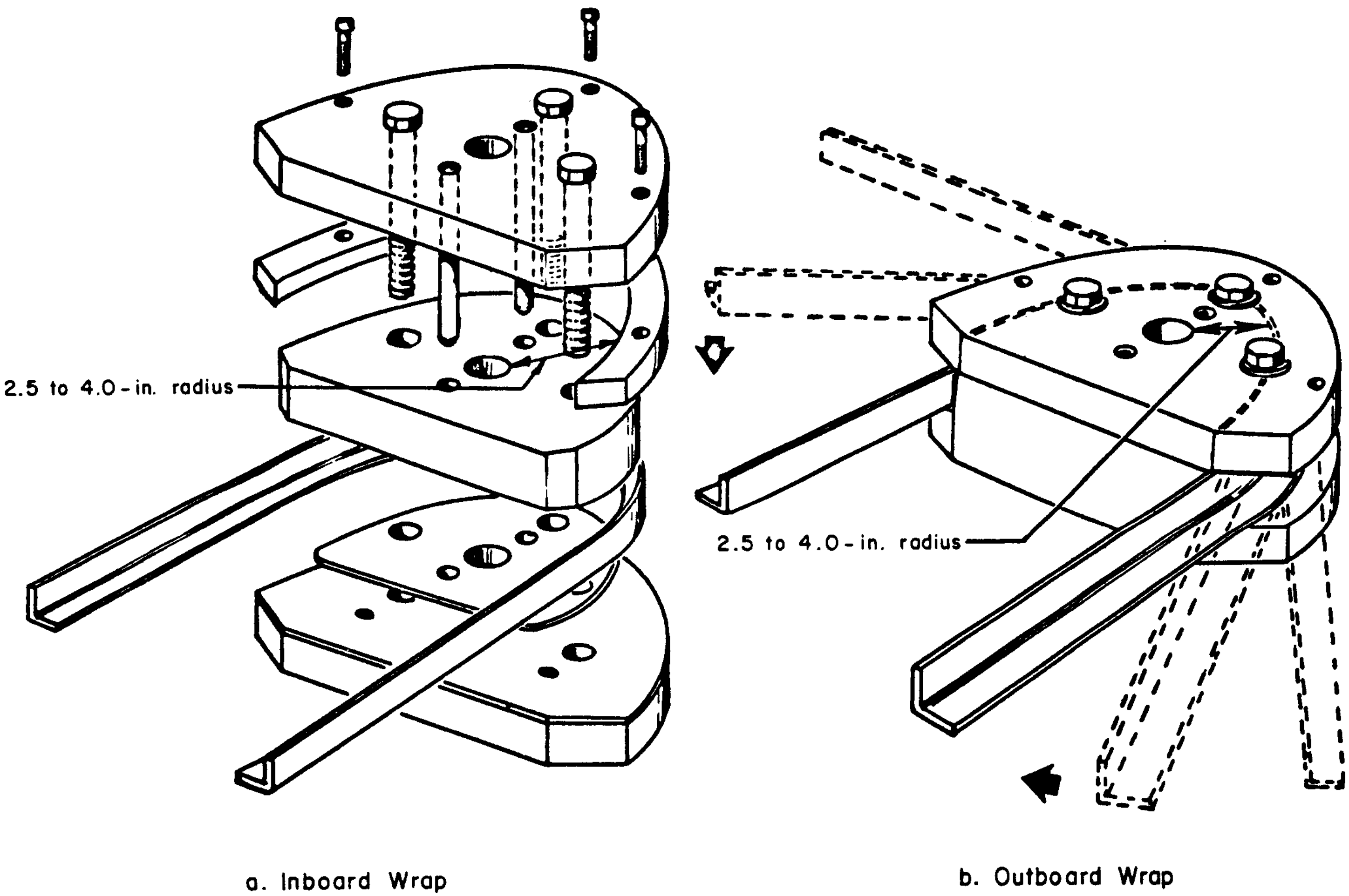


FIGURE 88. STRETCH-MACHINE (ANGLE SECTIONS) TOOLS (REF. 61)

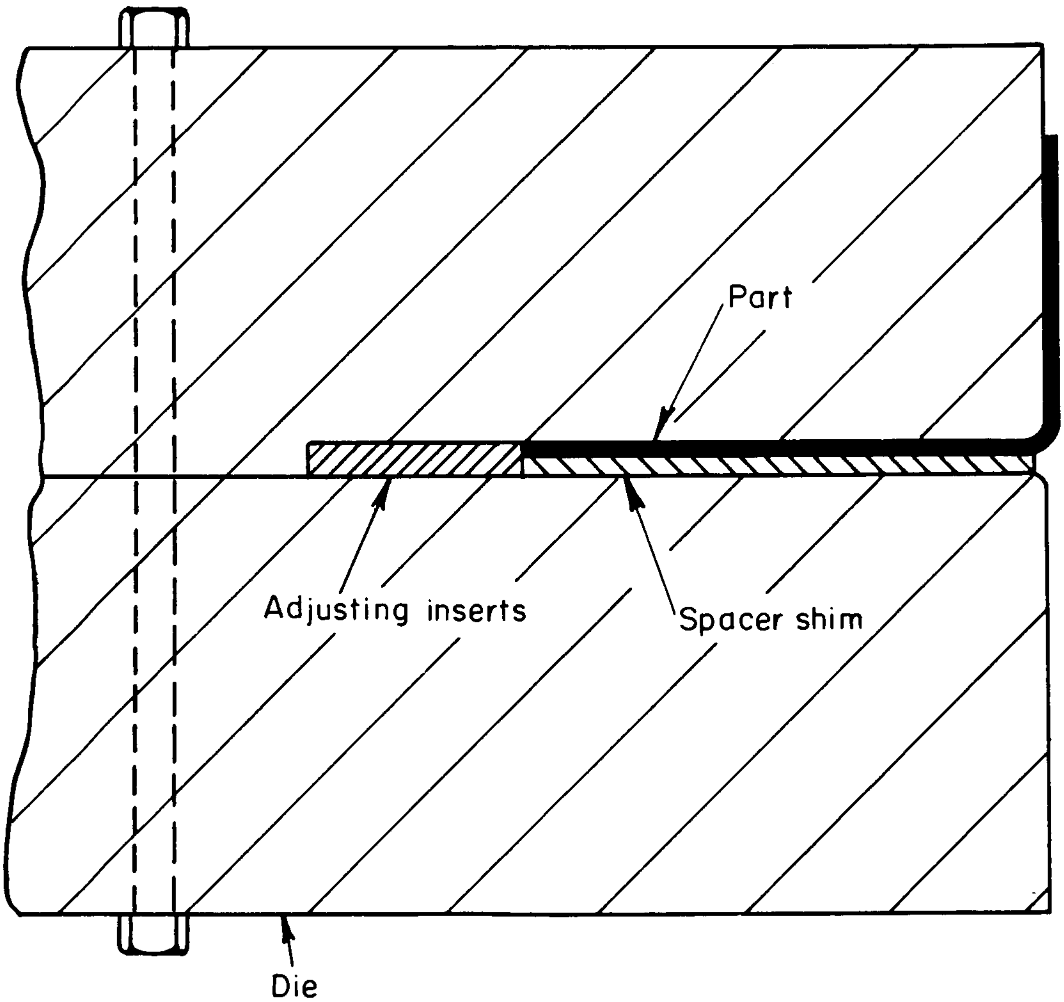


FIGURE 89. SECTIONAL VIEW OF LINEAR STRETCH TOOLING FOR HEEL-OUT ANGLES (REF. 52)

Tooling materials used at elevated temperatures must be able to withstand the pressure and temperature without deforming. A variety of materials such as cast ceramics (Glasrock), high-silicon cast iron, stainless steel, 4130 steel, or H-11 tool steel have been used satisfactory for elevated-temperature stretch forming of titanium (Ref. 21), provided the tool does not exceed 1000 F. Glasrock will function satisfactorily at temperatures above 1000 F.

Cartridge-heated tooling has been used successfully for stretch forming titanium sheets and sections at elevated temperatures (Ref. 55). The Meehanite tooling, which can be heated to 800 F, heats the sheet-metal workpieces by conduction. Figure 90 shows the arrangement used for stretch-forming sections heated to 1000 F. Tooling made from 4340 steel was used for that application. Other methods that have been tried for heating the blank during forming include resistance heating and radiant heating.

These techniques are suitable for titanium, but flame heating with torches should be avoided.

Techniques of Stretch Forming. In stretch forming titanium, skilled operators and careful attention to details are essential for success. Trouble results from exceeding the uniform elongation of the material that is affected by stress raisers on the surface and from nonuniform stretching (Ref. 50). Special care should be exercised to assure a good-quality surface on the workpieces to be stretch formed.

The preformed sections or sheet material, in either the solution treated or annealed condition, are first loaded into the clamping jaws of the stretch press. A load is then applied to the material to produce at least 1 per cent extension at the grips. The grips are then either rotated around the die as in section forming or pulled against the die in sheet forming, and the load is increased slightly to assure that the part conforms with the die. The rate of movement against the die should be low compared with that used for other materials, about 0.75 to 1 degree per minute. After the material is in complete contact with the die over the entire area to be formed, the stretching load is again increased to minimize springback. Since a large amount of springback usually results from room-temperature stretch forming of titanium, the machine is generally adjusted for overforming to compensate for this. In forming sections, a springback from 20 to 30 per cent of the bend angle can be expected.

When titanium is stretch formed, the materials should always be stretched with the rolling direction of the material. For preformed

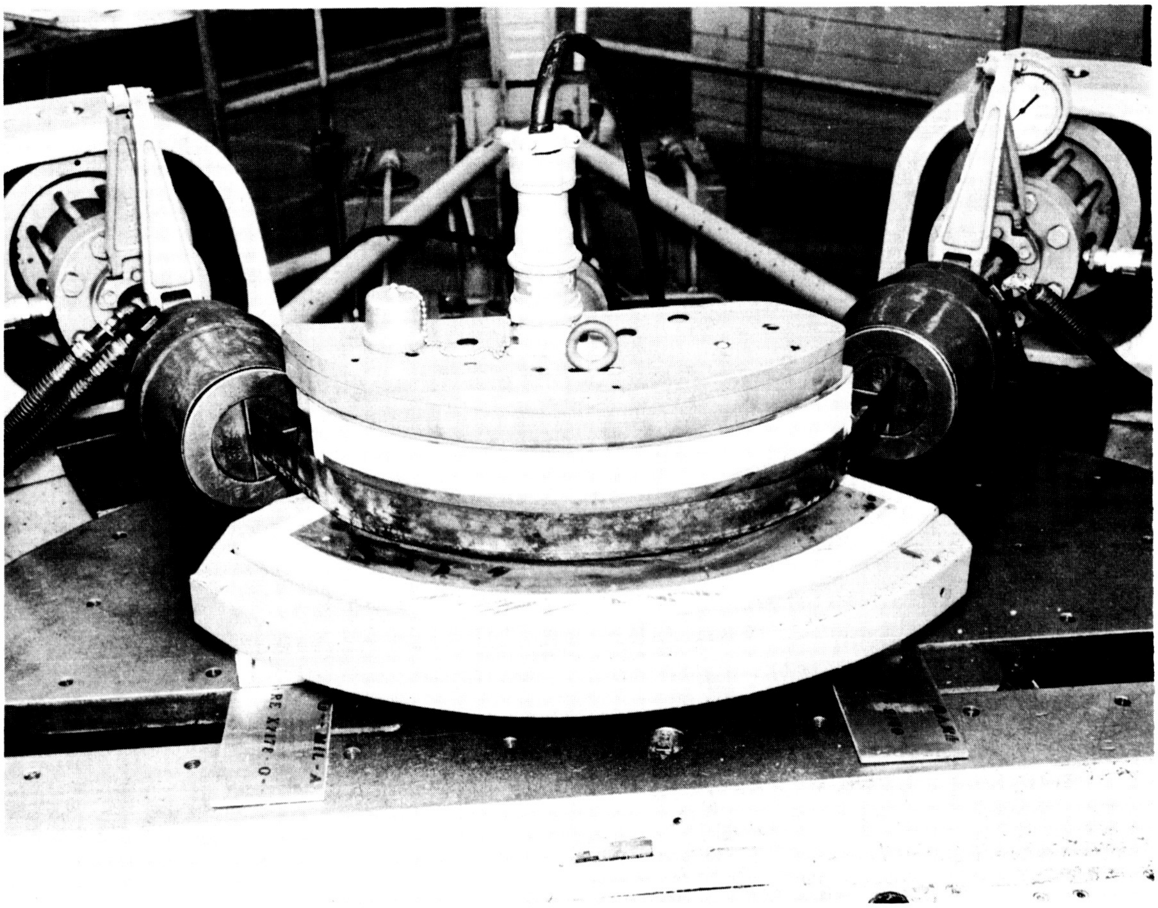


FIGURE 90. ELEVATED-TEMPERATURE ANGLE-STRETCH FORM WITH FORMED PART INTACT (REF. 55)

A-stretch-formed part.

angles, channels, or hat sections, this requires that the prior operation be performed across the rolling direction of the material.

When severe deformation is required, either elevated-temperature forming or multistage forming with intermediate anneals may be used. Elevated-temperature forming is more successful for linear stretch forming than it is for sheet forming because it is easier to control the temperature in the smaller working area. Hot spots, which are more likely to occur in sheets, will deform more than other areas. This is especially true for blanks heated by contact with the tooling since the part of the blank in contact will be hotter and tend to deform more than other areas. A skilled operator can sometimes take advantage of spot-heating areas that require more stretch.

Lubricants have been found to have very little effect in stretch forming of titanium because of the relatively small movement of the material over the die. No increase in uniform elongation was noted in stretch forming titanium with a lubricant at temperatures of 800 F or above (Ref. 57). Electrofilm 22T* has been reported to increase the uniform elongation in stretch forming titanium sections at room temperature (Ref. 57).

Titanium-Blank Preparation. For room-temperature stretch forming, the blanks should have uncontaminated surfaces and the edges to be stretched should be polished. Elevated-temperature forming has been found to be less dependent on surface and edge condition of the blank than room-temperature forming. Blanks with as-sheared edges have exhibited the same amount of ductility in stretch forming of titanium at elevated temperatures as those with ground and polished edges (Ref. 57). Sections to be linear stretch formed should be cleaned after brake forming and stress relieved. Any surface contamination from the brake-forming operation or thermal treatment should be removed by acid etching as described under the section on blank preparation. Where the maximum available sheet size is required to make a part, tabs may be welded onto the sheet for the grip area. A reduction in strength due to the welding may limit the amount of stretching possible by this method.

Titanium-Stretch-Forming Limits. Success or failure in stretch forming a material to a particular shape depends on its mechanical properties at the forming temperature and on the severity of the forming. Failures occur from buckling or from splitting, as illustrated in Figure 91. The geometrical factors controlling the

*Produced by Electrofilm, Inc., North Hollywood, California.

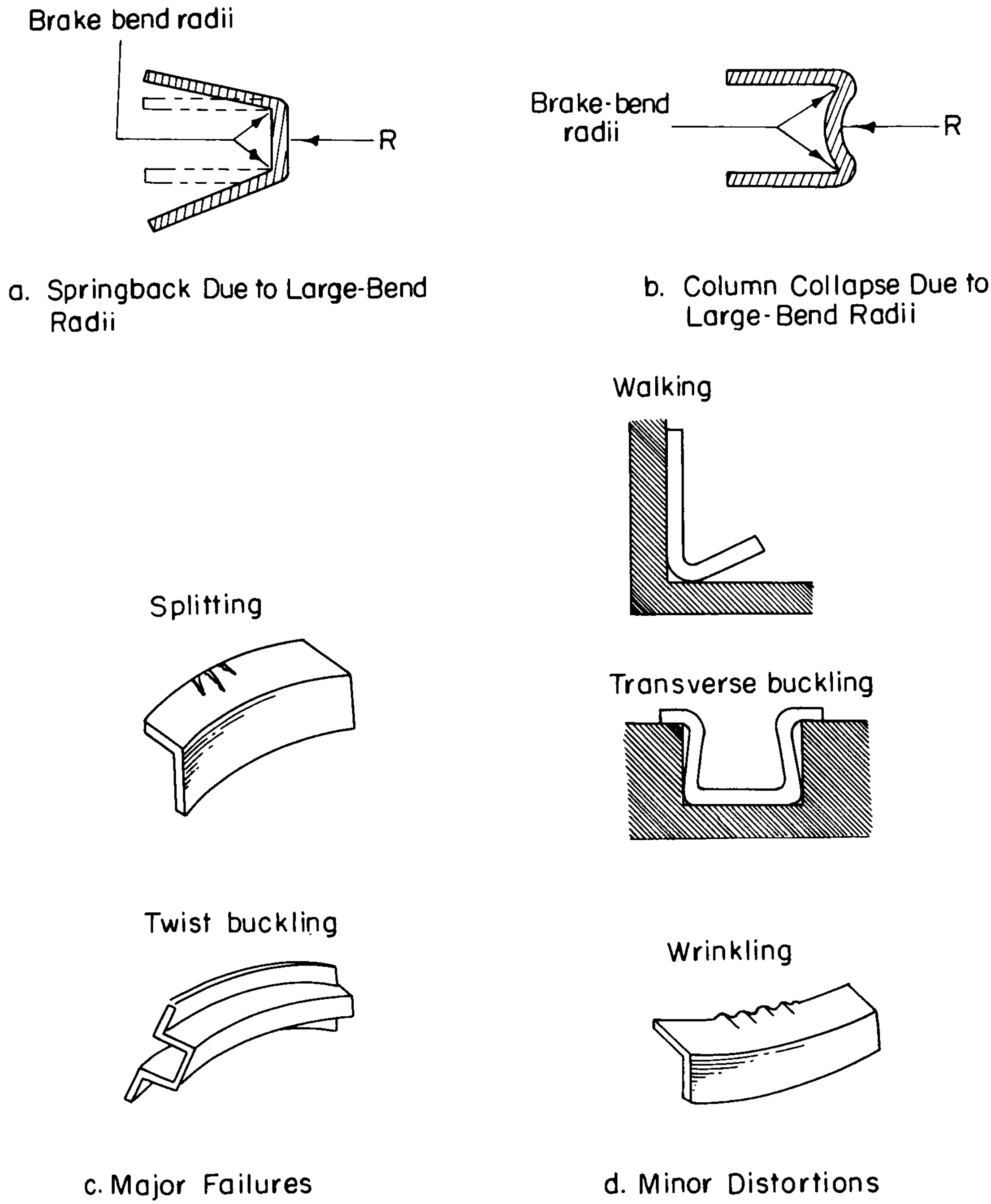


FIGURE 91. TYPES OF FAILURES FOR LINEAR STRETCH FORMING (REF. 59)

difficulty in forming of a section are the thickness, the height of the workpiece in the plane of bending, and the radius of the stretch-forming die. The important characteristics of the workpiece material are its capacity for stretching without rupture and its ratio of elastic modulus to yield strength. These mechanical properties influence splitting and buckling, respectively. Wood (Ref. 59) demonstrated that the amount of stretching a material will withstand before splitting correlates with elongation, in a 2-inch gage length, in tensile tests. The maximum per cent stretch in a particular operation is generally determined by the flange dimensions in the plane of forming of the section divided by the inside radius of the bend times 100. For example, the elongation would amount to 10 per cent for a section with a 1-inch flange formed around a 10-inch radius.

Wood and associates (Refs. 52,53,59) predicted splitting and buckling limits in various titanium alloys stretch formed at several temperatures. The predictions were based on analysis of the mechanics of the operations and a knowledge of mechanical properties exhibited in tensile tests. The formability limits were checked by forming good parts within the limits and failed parts beyond the limits.

Figure 92 shows the forming limits for heel-in or outboard stretch forming of titanium sections. At room temperature, the Ti-6Al-4V alloy can be stretched more, without splitting, than the other two alloys. This is indicated by the relative H/R ratios, which reflect ductility and ability to stretch. On the other hand, the Ti-8Al-1Mo-1V alloy appears to be better than the other two alloys when parts with a wide flange have to be formed at room temperature. For that type of operation, buckling rather than splitting is more likely to control failure.

The chart indicates that raising the forming temperature from 75 to 500 F is expected to have no effect on the deformation limits for the Ti-8Al-1Mo-1V alloy, but helps the Ti-13V-11Cr-3Al alloy. For the latter material, the improvement in the splitting limit is more noticeable. Temperatures above 1400 F would be much more effective because they produce greater improvements in ductility and decreases in stiffness. Temperatures around 2000 F are probably impractical for most operations.

Figure 93 gives the formability limit curves for heel-out, or inboard, stretch forming of angle and channel sections. This change in part orientation causes a shift in the limiting H/R and H/T ratios

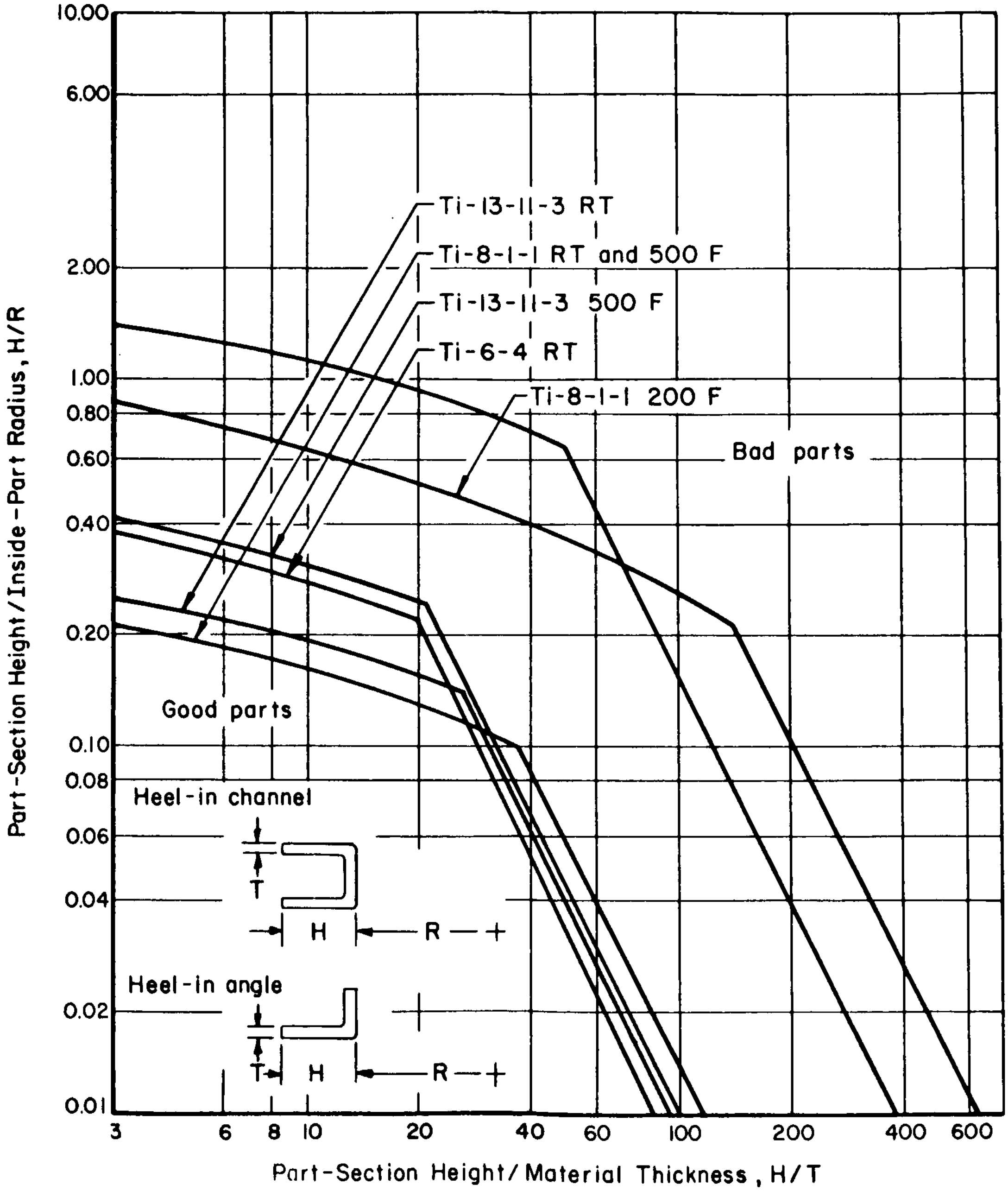


FIGURE 92. COMPOSITE LIMIT CURVES FOR TITANIUM LINEAR-STRETCH HEEL-IN ANGLE AND CHANNEL SECTIONS AT VARIOUS TEMPERATURES (REF. 52)

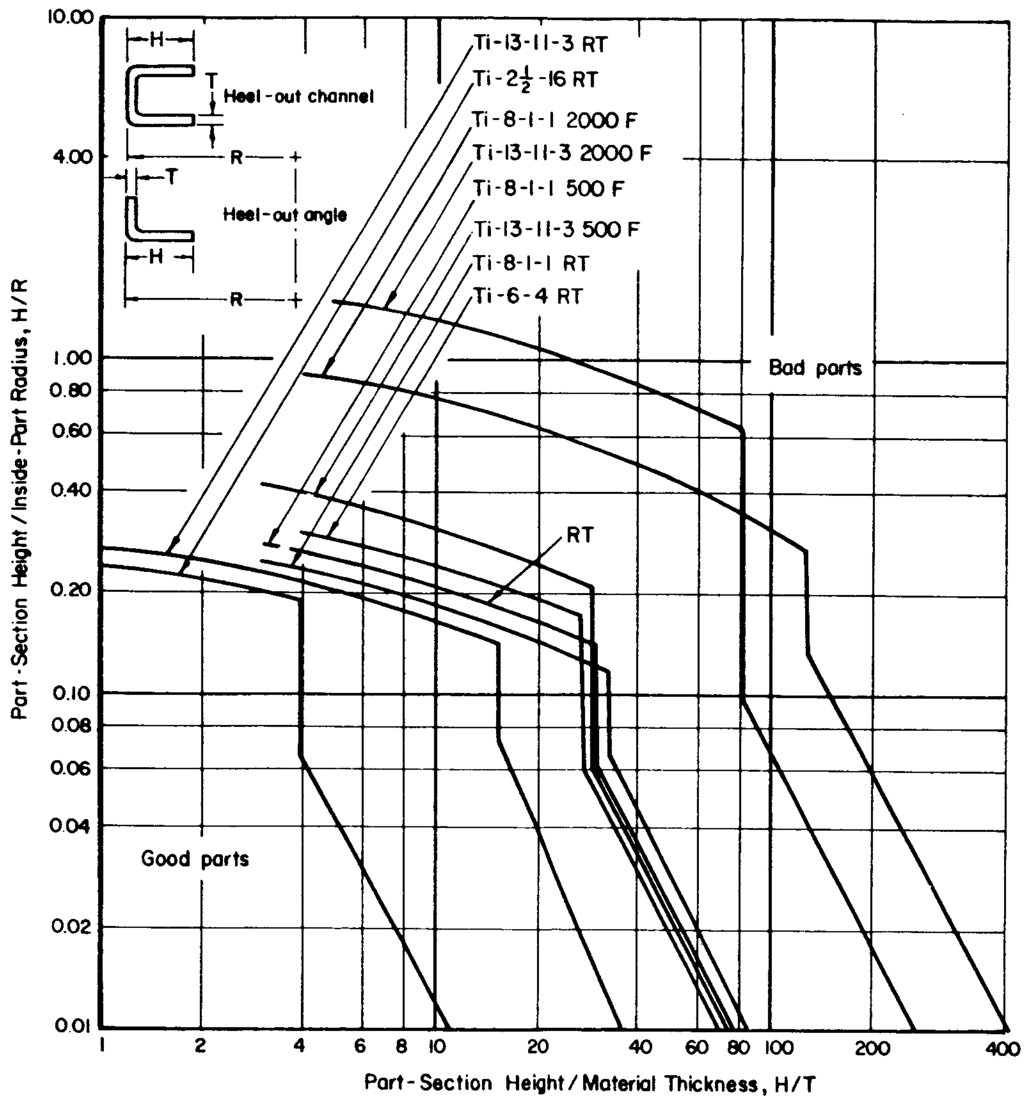


FIGURE 93. LINEAR-STRETCH HEEL-OUT-ANGLE-SECTION TEST RESULTS AT ELEVATED TEMPERATURES (REFS. 52, 100)

because it affects the severity of deformation. The relative order of formability among the materials is not changed because it depends on their mechanical properties.

The formability limits of hot sections in the heel-in position are shown in Figure 94. The buckling limits are a little higher than for angles and channels because the flange on the hot gives some support during forming.

Elongation is the material property affecting success in stretch forming sheet; thickness has little or no effect. In double-contour forming of sheet, the radii of curvature and their chord lengths are the geometrical factors controlling the limits of deformation. The products of the two limiting ratios of the radii to their chords is a constant for a particular material and forming temperature at maximum possible deformation. That is, using the terminology illustrated in Figure 95:

$$\left(\frac{R_L}{L}\right)\left(\frac{R_T}{T}\right) = \text{constant} \quad .$$

The tensile load should be applied in the direction necessary to stretch the sheet over the smaller radius because this requires more elongation. In many titanium flat-rolled products, the ductility varies significantly in different directions. Therefore, the blank should be oriented so the pull is applied in the direction in which the sheet is more ductile. Usually, this is parallel to the major direction of extension in rolling.

Figure 95 also shows the stretch-forming limits for two titanium alloys. The limits, expressed in ratios of die radii to chord lengths, are based on elongation values in room-temperature tensile tests. Although the difference is small, the Ti-6Al-4V alloy is expected to show better forming properties. Forming limits can be extended to some extent by using higher forming temperatures, lower forming rates, and smoother dies and sheets.

In Androforming sheets between matched dies, shaping-system elements (Figure 83) permit the forming of smaller contour radii. Unlike simple stretch forming, thickness, as well as ductility, is important because failure can result from either buckling or splitting. Therefore, the parameters used to define forming limits in Figure 96 include an allowance for sheet thickness. The terms for longitudinal and transverse radii, R_L and R_T, respectively, indicated in those figures correspond to the sketch in Figure 95. It is important to note,

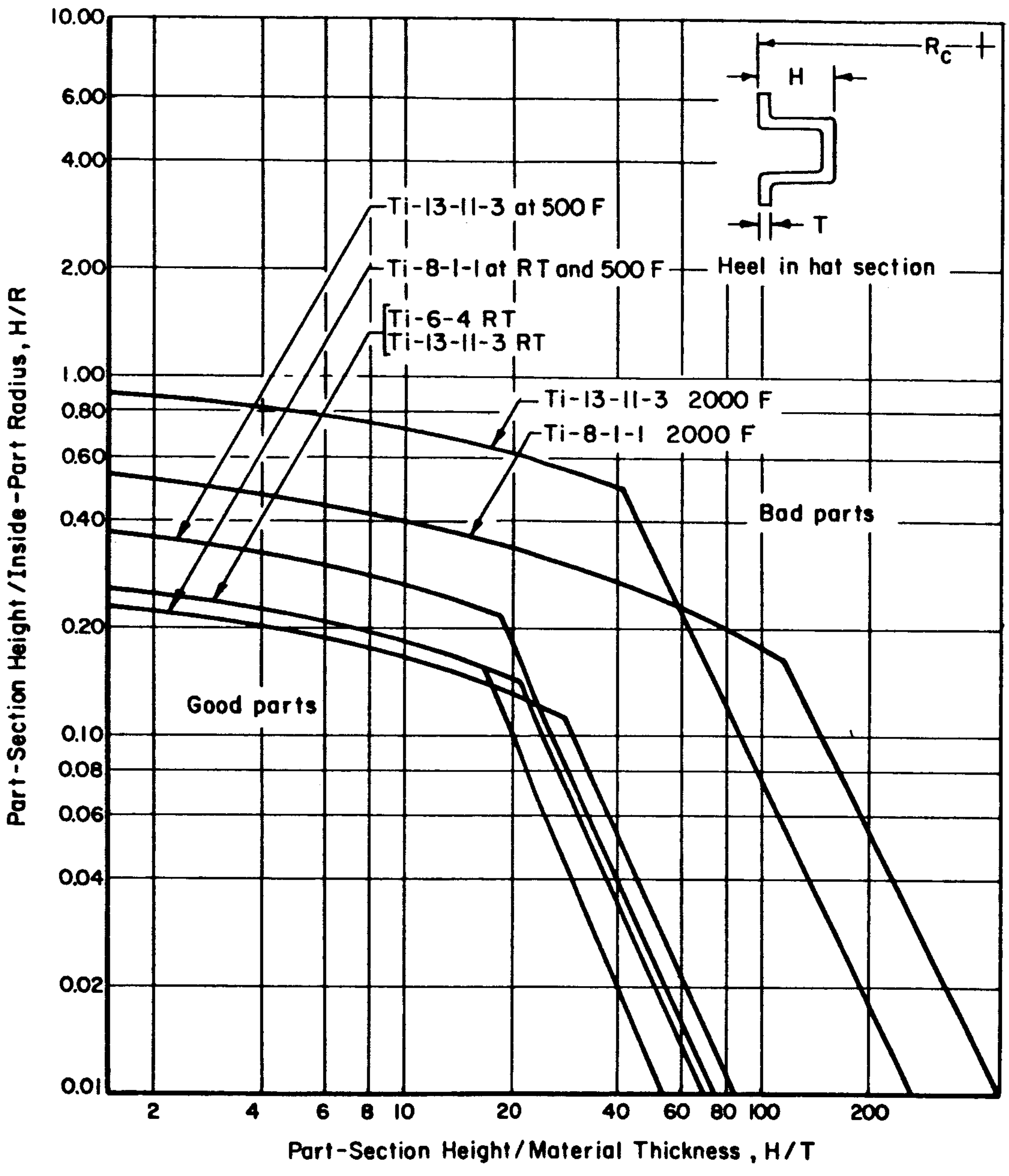


FIGURE 94. COMPOSITE OF OPTIMUM TITANIUM LINEAR-STRETCH HEEL-IN HAT-SECTION-LIMIT CURVES IN THE ROOM-TEMPERATURE TO 2000 F RANGE (REF. 52)

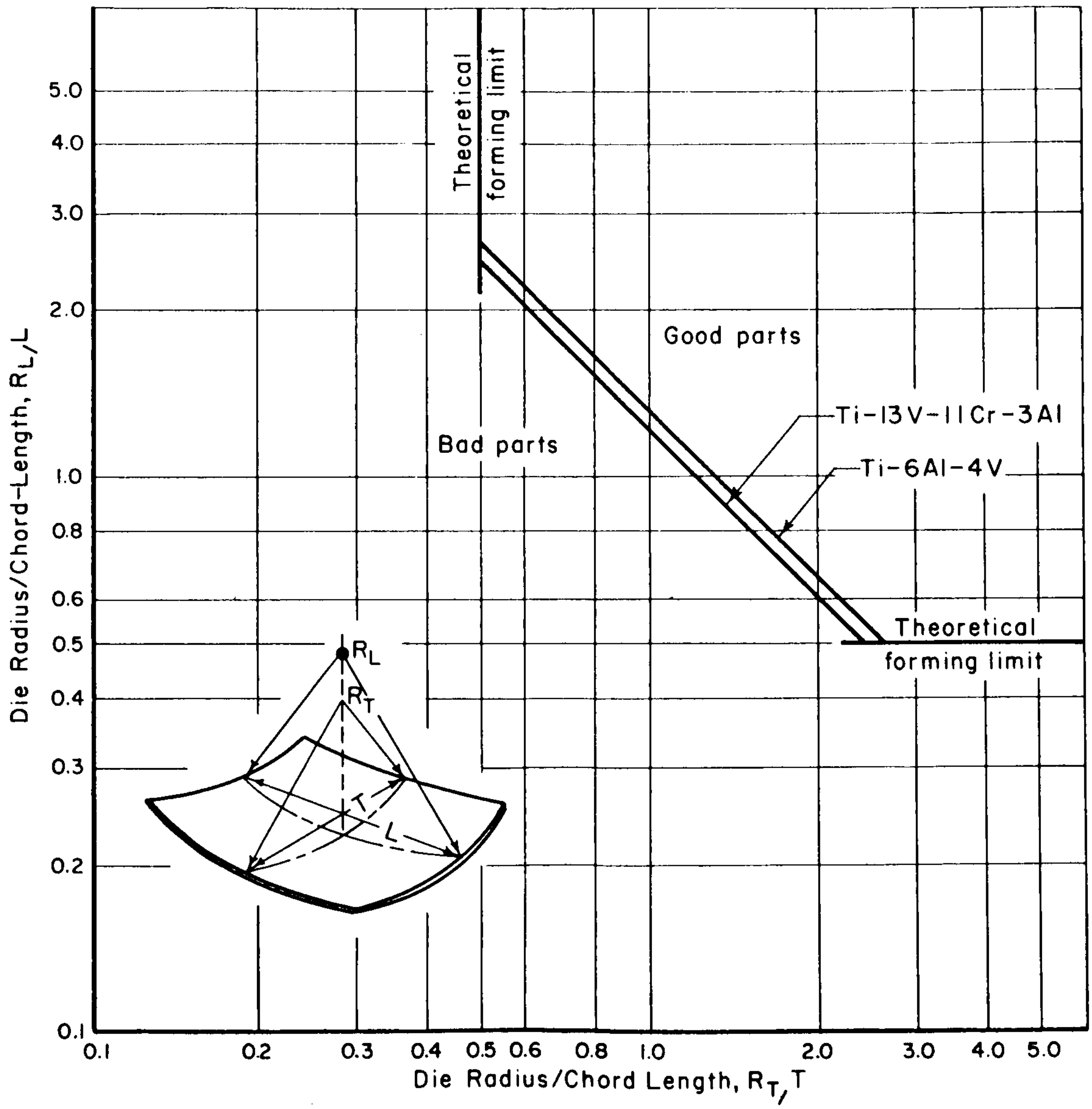


FIGURE 95. LIMITS FOR STRETCH FORMING TITANIUM SHEET (REF. 53)

however, that the direction of pull, L_R, is perpendicular to that shown in the sketch; changing from a 50-inch to a 20-inch forming element lowers the limiting parametric ratios. The room-temperature-limit curves in Figures 96 and 97 indicate that the Ti-6Al-4V alloy is more likely to buckle and less likely to split in Androforming than the Ti-13V-11Cr-3Al alloy.

Post-Forming Treatments. Stretch forming of titanium at room temperature is usually followed by a hot-sizing treatment to attain the desired shape and dimensions as described in the hot-sizing section. Parts should be hot sized before the final trimming operation. Parts that do not require hot sizing, for instance formed sections, should be stress relieved within 24 hours after forming to prevent possible cracking from residual stresses.

The parts should be cleaned after the final trimming operation and protected from contamination during handling or storage. This is generally done by wrapping the parts in plastic or paper. The parts are then stored until required for the next assembly.

Properties of Stretch-Formed Titanium. Some limited studies on the properties of stretch-formed titanium alloys have been conducted. The greatest effect is the loss of compressive properties due to the Bauschinger effect. The test data shown in Table XXXII were obtained from tensile and compressive specimens removed from angle sections that had been stretch formed 7.7 per cent. Forming at elevated temperatures is shown to have a beneficial effect on the final-material properties. In some cases the material properties after forming as well as formability should be considered when selecting the forming temperature.

The cumulative time at temperature may be even more important than the temperature itself in affecting mechanical properties of cold-worked titanium. Too long a time at temperature can reduce the mechanical properties.

Table XXXIII gives some information on this subject for the Ti-4Al-3Mo-1V alloy. The data show that the tensile strength and both the compressive and tensile yield strengths of the specimens decreased with increasing exposure time at 1100 F. The changes were most marked during the first 5 minutes, but apparently continued for periods up to 16 minutes. The data suggest that the room-temperature elongation values were relatively independent of the time the specimens had been heated at 1100 F.

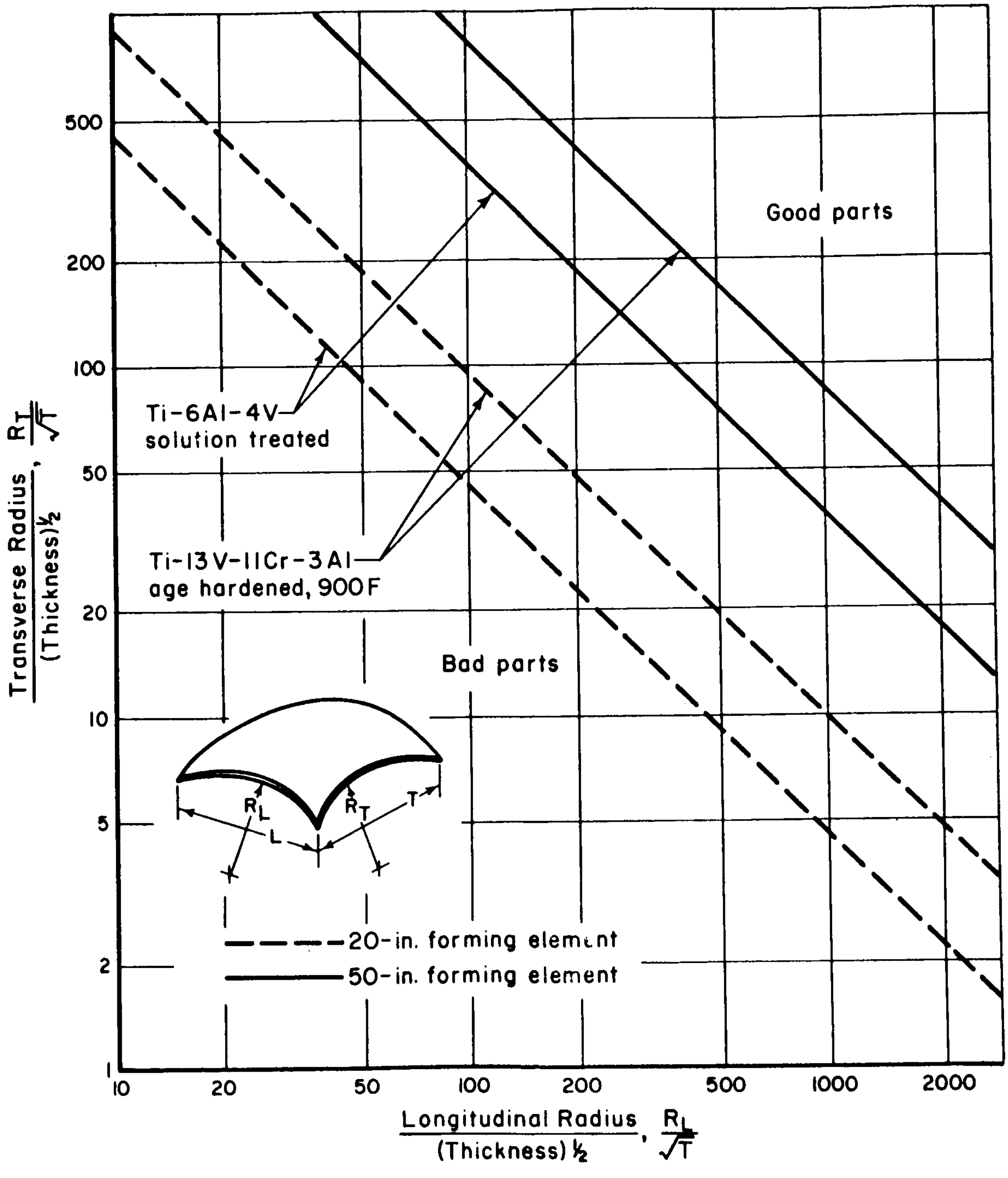


FIGURE 96. ANDROFORM-SPLITTING LIMITS, STRETCH IN LONGITUDINAL DIRECTION (REF. 53)

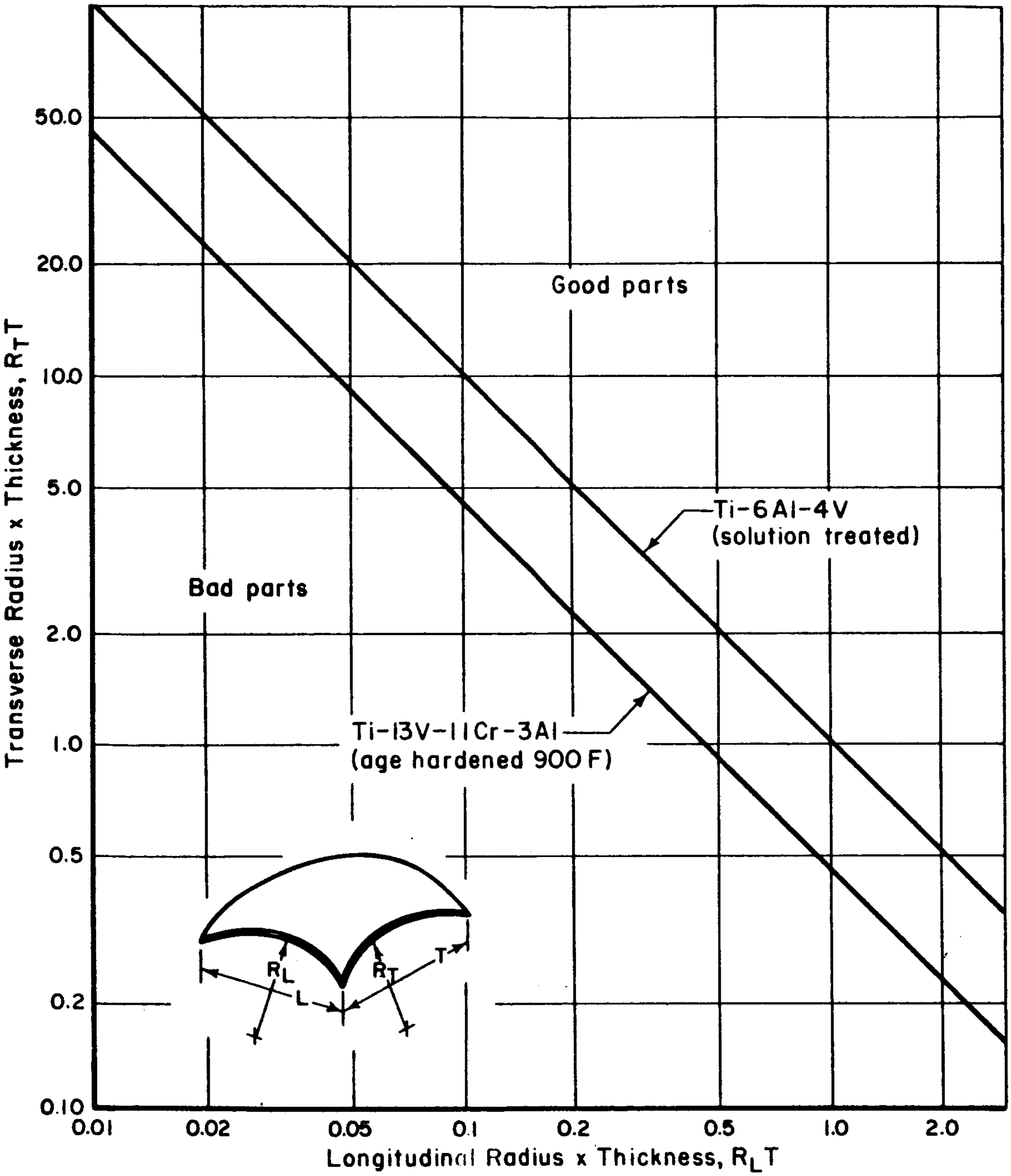


FIGURE 97. ANDROFORM-BUCKLING LIMITS FOR 50-INCH FORMING ELEMENT (REF. 53)

Stretch in longitudinal direction.

TABLE XXXII. MECHANICAL PROPERTIES OF STRETCH-FORMED TITANIUM ALLOYS (REF. 105)

Specimen[a]	Forming Temperature, F	Tensile Strength, 10^3 psi	Tensile Yield Strength, 10^3 psi	Compressive Yield Strength, 10^3 psi	Elongation, per cent	Loss in Compressive Yield Strength From Forming, per cent
			Ti-5Al-5Zr-5Sn			
PT1 and CP1	Not formed	120.9	113.8	131.1	14.2	--
PT2 and CP2	Not formed	121.0	113.3	127.1	14.7	--
PT3 and CP3	Not formed	120.6	113.0	128.2	14.7	--
1T1 and 1C1	RT	129.1	124.0	81.8	12.5	35.5
6T1 and 6C1	RT	131.2	127.4	86.6	11.5	35.5
5T1 and 5C1	RT	129.1	124.3	81.0	11.5	35.5
11T1 and 11C1	900	138.8	134.4	110.2	9.0	16.3
12T1 and 12C1	900	140.0	134.7	105.3	13.0	16.3
17C1 and 17C2	1200	126.1	118.8	119.1	12.0	7.5
23T1 and 23C1	1300	123.0	112.4	113.5	9.0	11.9
			Ti-7Al-12Zr			
PT1 and CP1	Not formed	137.3	125.8	154.2	12.5	--
PT2 and CP2	Not formed	136.5	125.8	148.8	11.3	--
PT3 and CP3	Not formed	138.0	129.5	147.5	12.0	--
2T1 and 2C1	RT	147.5	143.8	89.5	8.0	41.1
7T1 and 7C1	RT	146.9	142.9	89.5	9.0	41.1
8T1 and 8C1	RT	145.1	149.9	86.3	9.0	41.1
13T1 and 13C1	900	139.2	133.1	111.6	9.0	28.8
14T1 and 14C1	900	143.4	138.9	102.0	4.0	28.8
19T1 and 19C1	1200	135.4	122.1	133.3	6.5	11.2
25T1 and 25C1	1300	138.7	124.5	135.2	5.5	9.7
26T1 and 26C1	1300	140.4	126.0	135.9	13.0	9.7

(a) Specimens identified by letters PT are parent material tension tests
Specimens identified by letters CP are parent material compression tests.
All other specimens: T = tension; C = compression.

Specimens for Table XXXII are taken from stretch-formed angles as shown below:

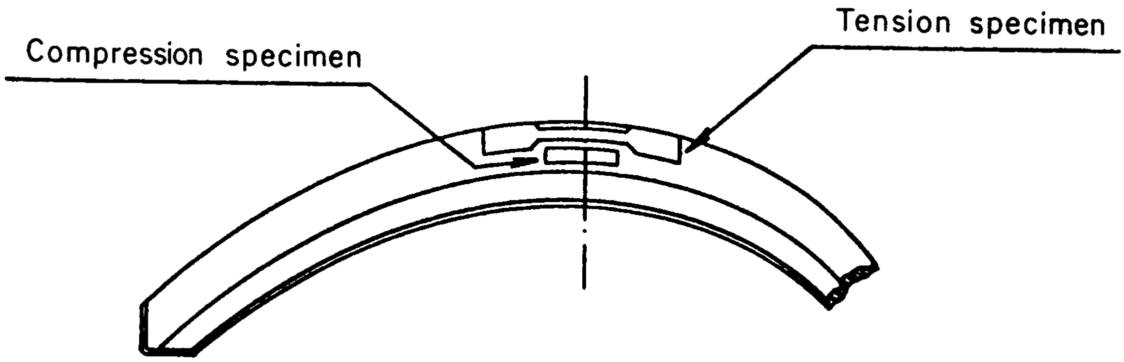


TABLE XXXIII. ROOM-TEMPERATURE MECHANICAL PROPERTIES OF Ti-4Al-3Mo-V ALLOY AFTER STRETCH FORMING 10 PER CENT AT 1100 F IN THE SOLUTION-HEAT-TREATED CONDITION AND AGING (REF. 55)

Cumulative Time at 1100 F, min	Tensile Ultimate, 10^3 psi	Tensile Yield, 10^3 psi	Compression Yield, 1000 psi	Elongation, 2-Inch Gage, per cent
4.7	162	147	158	0.07
5.0	164	147	--	0.07
7.4	158	135	148	0.08
7.7	160	148	157	0.07
9.0	162	147	158	0.07
10.0	155	139	139	0.06
11.0	151	135	140	0.08
12.0	150	136	146	0.08
12.4	158	142	150	0.08
16.0	150	139	144	0.09
Unstretched or aged	190	159	167	0.06

TUBE FORMING

Because of their high strength to weight ratios, tubular parts of titanium are being used for the air-duct system in jet airplanes. There are about 650 feet of Grade A-40 (commercially pure) titanium-welded thin-walled ducting in the Boeing Model 727 commercial jet liner (Refs. 106,107). Since the air ducts are one of the last items to be installed, they must weave around the structural components. Consequently there are many elbows and few straight runs. The normal bend radius is twice the tube diameter (2D), but some elbows must be bent on 1-1/2-D radii. The rather difficult problem of bending thin-walled titanium tubing is described in this section along with methods of bulging cylindrical bodies of various shapes.

Tube Bending (Refs. 106,107). The four major methods in general use for bending tubes are: (1) ram or press bending, (2) roll bending, (3) compression bending, and (4) draw bending. Ram or press bending is accomplished by placing the tube between two supports, thus forcing the tube to bend around the ram. Roll bending consists of passing the tube through a suitable series of grooved, power-driven rolls to accomplish the bending. In compression bending, both the tube and the die are stationary, and a wiper die is utilized to wrap the tube around the stationary bend die. Only the first three methods are used for heavy-wall tubing; they are likely to cause thin-wall titanium tubing to wrinkle, fracture, or even collapse.

The fourth method, draw bending, is used to bend thin-walled titanium tubing. The tube is confined in the bend; wiper and clamp dies are illustrated in Figure 98. Internal support is provided by a multiball mandrel to prevent collapse of the tubing. Prior to bending, a clamp plug is inserted in one end of the tube. The tube then is placed in the die cavities and the other end of the tube is pushed over the mandrel. As the clamp die is closed, a cleat on the die is pressed into the tube and clamp plug, crimping the tube and preventing it from slipping during forming. The mandrel is forced through the tube so that its nose is in line with the tangent of the bend die. Then the pressure die is closed.

During draw forming, the bend and clamp dies are rotated drawing the tube over the stationary mandrel into the bend area. The stationary wiper die, and the bend die confine the inside of the bend and permit the mandrel balls to iron out wrinkles as they occur. The pressure die travels with the tube and provides the reaction force necessary for bending.

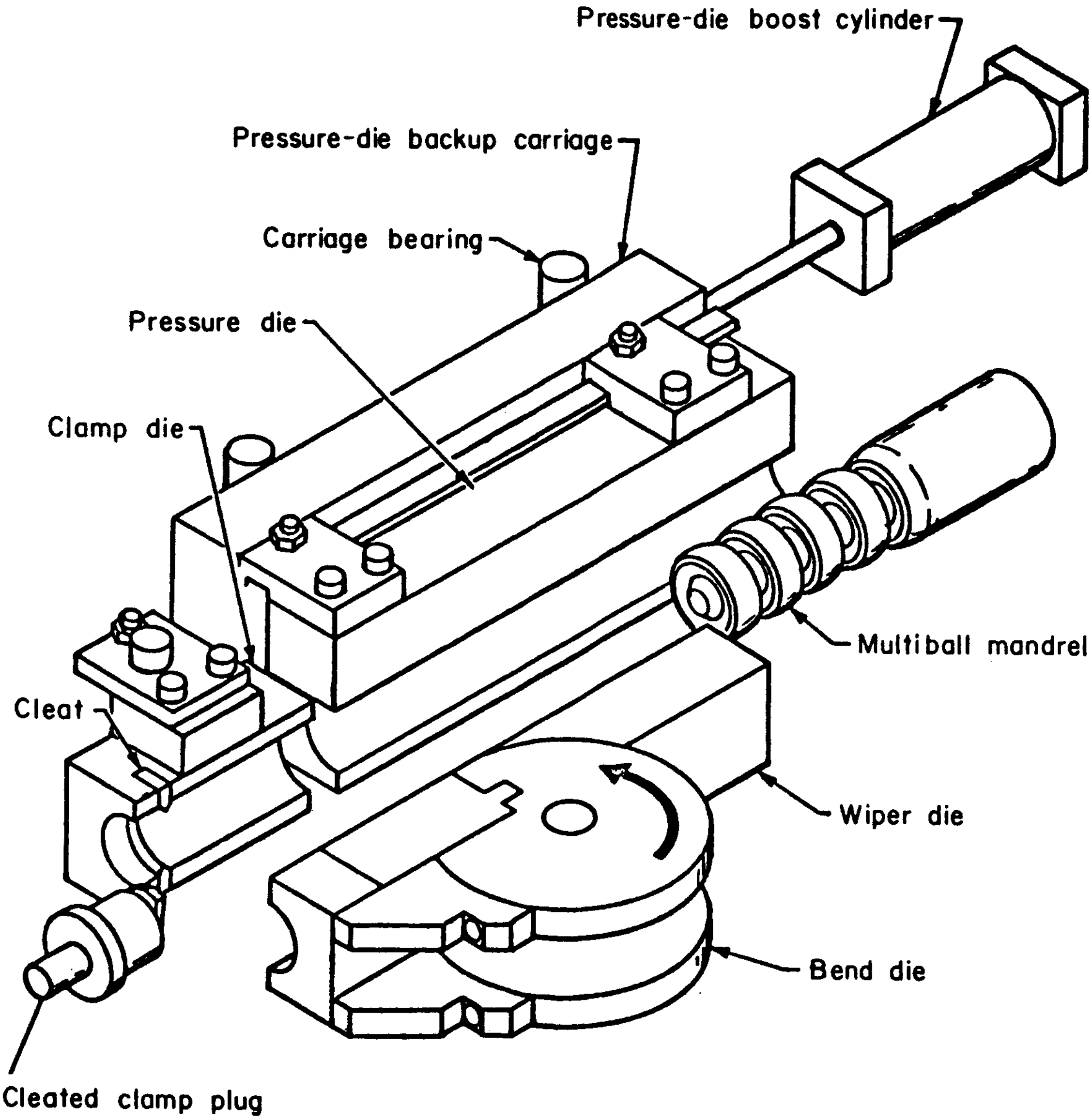


FIGURE 98. TYPICAL TUBE-BENDING TOOLS (REF. 107)

Courtesy of American Society for Tool and Manufacturing Engineers.

The pressure-die boost cylinder is a special attachment considered necessary for bending titanium tube. It applies a load to the end of the pressure die, which reduces the tension stress on the outside of the elbow and moves the neutral axis outward so that only 50 per cent of the tube is in tension. Thus, only about 33 per cent elongation is required to produce a 1-1/2-D bend (centerline radius) with this system. This amount of elongation is well within the elevated-temperature properties of the commercially pure titanium. The speed of the pressure-die boost system must be coordinated with bending speed to avoid sliding friction between the pressure die and the tube. Figure 99 shows 4-1/2-inch-diameter elbows produced by this bending technique on a 6-3/4-inch bend radius. It can be seen that the tubes are free of wrinkles.

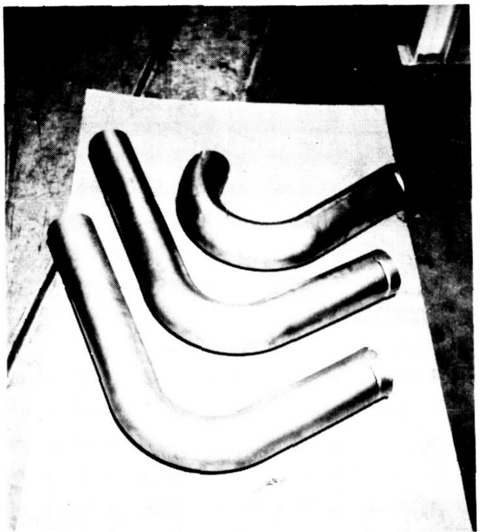


FIGURE 99. 4-1/2-INCH-DIAMETER BY 0.020-INCH WALL-THICKNESS TITANIUM ELBOWS (REF. 107)

Centerline-bend radius is 6.75 inches.

Courtesy of American Society for Tool and Manufacturing Engineers.

A number of refinements to the conventional process are required when bending Grade A-40 (commercially pure) titanium, thin-walled tubing. Elevated temperatures are generally required for tube sizes above about 2-1/2 inches in diameter as is shown in Table XXXIV. The available data and experience indicate that the best ductility for bending commercially pure titanium is obtained between 350 and 400 F. As can be seen in Figure 100, a maximum in the elongation curve exists at about 400 F. The ductility also is high and the strength even

TABLE XXXIV. BENDING LIMITATIONS FOR GRADE A-40 TITANIUM TUBING (REF. 106)

Courtesy of American Society for Tool and Manufacturing Engineers.

Tube Diameter, inch	Wall Thickness, inch	Minimum Bend Radius, inch	Preferred Bend Radius, inch	Maximum Bend Angle[a], deg	
				Minimum Bend Radius	Preferred Bend Radius
		Room-Temperature Bending			
1-1/2	0.016	2-1/4	3	90	120
	0.020	2-1/4	3	100	160
2	0.016	3	4	80	110
	0.016	3	4	100	150
2-1/2	0.016	3-3/4	5	70	100
	0.020	3-3/4	5	90	140
	0.035	3-3/4	5	110	180
		Elevated-Temperature Bending			
3	0.016	4-1/2	6	90	120
	0.020	4-1/2	6	110	160
	0.035	4-1/2	6	130	180
3-1/2	0.016	5-1/4	7	90	120
	0.020	5-1/4	7	110	160
	0.035	5-1/4	7	130	180
4	0.020	6	8	110	160
	0.035	6	8	120	180
4-1/2	0.020	6-3/4	9	130	140
	0.035	6-3/4	9	140	140
5	0.020	10	10	--	110
6	0.020	12	12	--	100

(a) Bend angle is predicated on a clamp section 3 times as long as the tube diameter and on maximum-mandrel-ball support.

lower at temperatures above 1000 F; at these higher temperatures the problems of heating the dies without damaging the bending equipment and providing adequate lubrication are greatly compounded.

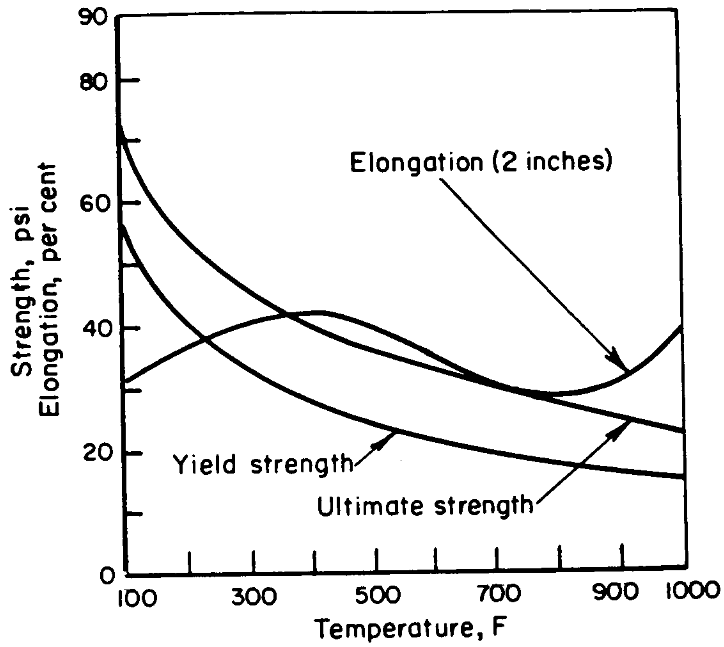


FIGURE 100. ELEVATED-TEMPERATURE MECHANICAL PROPERTIES OF COMMERCIALLY PURE TITANIUM (AMS 4902) (REF. 107)

Elongation is at a maximum at about 400 F. After decreasing, the elongation again becomes larger at about 1000 F where the strength is lower than at 400 F.

Courtesy of American Society for Tool and Manufacturing Engineers.

Equipment. Titanium tube is bent in commercially available equipment that has been modified to accept heated tooling. The diameter of the tube dictates the equipment size; one equipment manufacturer* supplies aircraft tube-bending equipment in the following sizes:

*Pines Engineering Company, Inc., Aurora, Illinois.

Bender Model No. (Ref. 107)	Maximum Tube Diameter, in.
3A	2-1/2
4	3 to 4
8A	4-1/2 to 6

Other producers of aircraft tube-bending equipment produce machines with similar capacities.

Tooling. Most tooling materials have a great chemical affinity for titanium and gall under the high loads produced in tube bending. The situation is not greatly alleviated by the conventional lubricants normally used for tube bending.

SAE 4340 steel heat treated to Rockwell C 45 to 48 is adequate for the pressure die because it does not slide against the tube. The wiping die and mandrel that are subjected to sliding friction should be made from aluminum bronze (AMPCO 21).

Heating Methods. The Grade A-40 titanium tubes that must be bent at elevated temperature normally are not preheated. Experience has shown that the tube rapidly attains the proper temperature when placed over a preheated mandrel and confined in a preheated pressure die.

The tools used for elevated-temperature tube bending are usually heated by electric cartridge-type heaters. Electric cartridge heaters have a coiled resistance wire wound on a threaded refractory core (Ref. 108). The core and wire are embedded in a mass of magnesium oxide or similar refractory cements and encased in an Inconel sheath. The units are designed to operate at relatively high temperatures and watt densities (Ref. 108). This method of heating is reliable, inexpensive, requires little maintenance, and gives the desired control of temperature.

To handle the heated tubes, the tube bender must be suitably insulated to prevent excessive temperatures at the bearings and also supplied with electrical leads to supply power to the electric cartridge heaters. The heated pressure dies may be insulated with Transite to prevent excessive heat transfer to the pressure-die backup carriage bearings. Such an installation is shown in Figure 101. Electrical leads run directly from bus bars on the pressure die, which supply power to the cartridge heaters, to the powerstat carts.

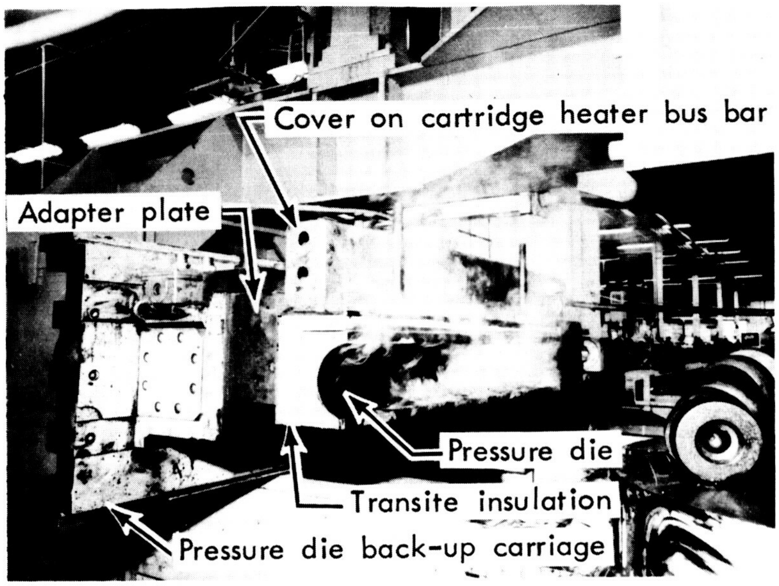


FIGURE 101. FACILITIES FOR HEATING PRESSURE DIES IN TUBE BENDERS (REF. 107)

Courtesy of American Society for Tool and Manufacturing Engineers.

The powerstat cart consists of two controllers and two variable transformers, one each for the mandrel and pressure die. The temperature is monitored by thermocouples. The powerstats are supplied with 440-volt, 30-amp electrical power.

Only the mandrel bodies are heated. The mandrel balls are not heated because forming is essentially completed by the time the balls come into contact with the tube.

Tube Preparation for Bending. Tubes straight within 0.030 inch per foot give good bending results and are normally purchased to that specification. Straightening tubes prior to bending can reduce the elongation limits of the material by as much as 20 per cent. Annealing after straightening or welding would not solve the problem since the tube again would warp during the annealing operation and additional straightening or sizing would be required.

The diameters of the tubes to be bent must be held within +0.0025 to 0.007 inch, and the ovality should be within 6 per cent of the nominal tube diameter. These rather close tolerances are necessary to insure proper confinement of the tubes by the bending tools.

Lubricants. Many conventional lubricants do not provide the continuous film needed to separate the tools from the workpieces under high bending loads involved. Ineffective lubrication causes galling of titanium tubes. Experiments indicate that greases with high graphite contents should be suitable for bending titanium at elevated temperatures. In production operations, however, such lubricants have not been completely satisfactory and minor galling frequently occurs. A phosphate conversion coating is, therefore, used on tubes to supplement graphite-grease lubricants. This coating is applied as indicated in the section on surface preparation.

Tube-Bending Precautions. The commercially pure Grade A-40 titanium tends to deform locally under tensile loads, especially if they are not applied uniformly. For this reason, tube-bending speeds must be kept low; speeds of 1/4 to 4 rpm have been used to produce satisfactory parts. It should be kept in mind that after the bending speed is set, the pressure-die boost system also must be adjusted to provide a uniform thrust and to insure that satisfactory bends will be formed.

Bend quality can also be adversely affected by excessive wear of the mandrel and wiper die. If the mandrel body and balls and the wiper die are allowed to wear down more than 0.005 to 0.008 inch, the tools will not confine the tubes adequately. Thus, large pressure-die forces must be used, and the amount of elongation required to form the parts will be increased. This results in high failure rates.

Removal of Lubricants After Bending. After bending, the elbows should be cleaned using the following seven-step procedure:

(1) Emulsion clean with a stiff brush to remove gross particles of lubricants from the tube

(2) Dip in aliphatic naphtha-type solvent

(3) Alkaline clean

(4) Water rinse

(5) Pickle in nitric-hydrofluoric acid mixture

(6) Water rinse

(7) Air dry.

Tube Bulging.

Introduction. In bulging an internal pressure is applied to form a cup or tube to the desired shape. The internal pressure can be delivered by expanding a segmented punch or through a fluid, rubber, or other elastomer. The process, characterized by the use of simple and low-cost tooling, is adaptable to fast operations and is capable of forming an acceptable part in one step. For titanium and its alloys the process is normally limited to forming in the annealed condition.

The two types of bulge forming can be classified as die forming and free forming. As the names imply, the die-formed component is made in a die that controls the final shape, while the free formed part takes the shape that will contain the internal pressure. Either type of operation can be carried out by a variety of processes.

Equipment Setup and Tooling. Conventional processes for bulge forming apply internal pressure to the tubing at a low rate by the motion of mechanical and hydraulic presses. A liquid or semiplastic filler material is normally used inside the tube as indicated in Figure 102, so that a hydrostatic pressure is approached.

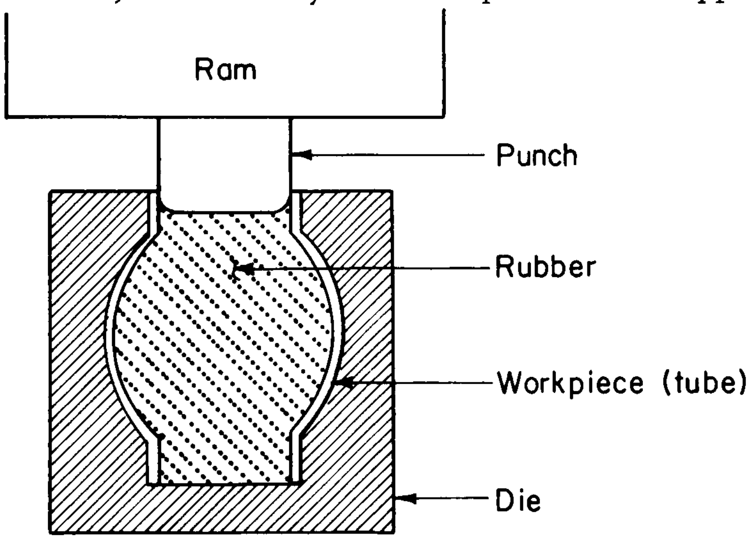


FIGURE 102. RUBBER-BULGING SETUP (REF. 59)

The behavior of the filler material will control how closely hydrostatic conditions prevail during forming operations. When the ram shown in Figure 102 has been retracted, the rubber returns to its original diameter so that it may be withdrawn from the tube. This technique is commonly used because it does not present the sealing difficulties associated with the use of a liquid filler. The use of low-melting-point solids such as Wood's Metal as a filler material has shown promise for producing large deformations. In this process, the ram can apply axial force to the tube as well as pressure to the filler. If additional tubing material is fed into the die as the forming progresses, greater amounts of deformation are possible with this technique.

The use of expanding mandrels for bulging tubes is generally restricted to high-production applications because of the cost of the mandrels. Friction between the metal mandrel and the tubing limits the force that can be applied and the maximum deformation that can be obtained with this technique.

Some of the high-velocity techniques that have been applied to tube bulging with the greatest success employ low explosives and electric discharges as energy sources. The electric-discharge techniques are based on the liberation of energy stored in capacitors as sparks, exploding-bridge wires, or magnetic coils. All of these processes except magnetic forming require some medium, generally water, to transmit the pressure to the tubing. The closed-die systems used to insure maximum efficiently complicate sealing. Sealed systems between the tube and the die should be evacuated to prevent high temperatures and burning due to entrapped air. Shock-wave reflectors have been used with low-explosive and electrical-discharge systems to obtain unusual free-formed shapes. Most of the information on the subject, however, is considered proprietary and has not been released for general publication.

Magnetic forming is the only metalworking process that does not require direct contact between the forming medium and the workpiece. Consequently, the frictional limitations on forming encountered in most processes are absent.

If the pressure for deforming a tube is considered to be hydrostatic in nature, then the pressure required to initiate deformation can be determined from

$$P = 2TS/d \quad , \tag{22}$$

where

P = pressure, psi

T = tube wall thickness, inches

S = average flow stress of the tube material, psi

d = tube diameter, inches.

This equation is simple to use for estimating pressure requirements at the start of deformation, but some modifications are required to present the total picture. As the tube is stretched, the flow stress will increase due to work hardening of the material. At the same time, the diameter increases and the thickness decreases. For estimates of the final or maximum pressure, the conditions prevailing after forming should be considered in the equation.

Material Preparation. Due to very limited applications of titanium tubing in aircraft in the past, little information has been generated on the forming of titanium tubing. Furthermore, tubing has generally been made from roll-formed and welded sections. Some difficulty has been experienced in obtaining sufficient ductility in the heat-affected weld zone for bulge-forming operations. Some of the troubles may have been caused by improper manufacturing practices. It is normally desirable to planish weld beads before bulging and to stress relieve welded preforms.

Where considerable reduction in ductility is experienced in the weld heat-affected zone, a heavier section may be left in this area to equalize the strength of the tube. This technique, shown in Figure 103 will result in a part with uniform strength, but may cause considerable difficulty in forming due to the reduced ductility in the heat-affected zone.

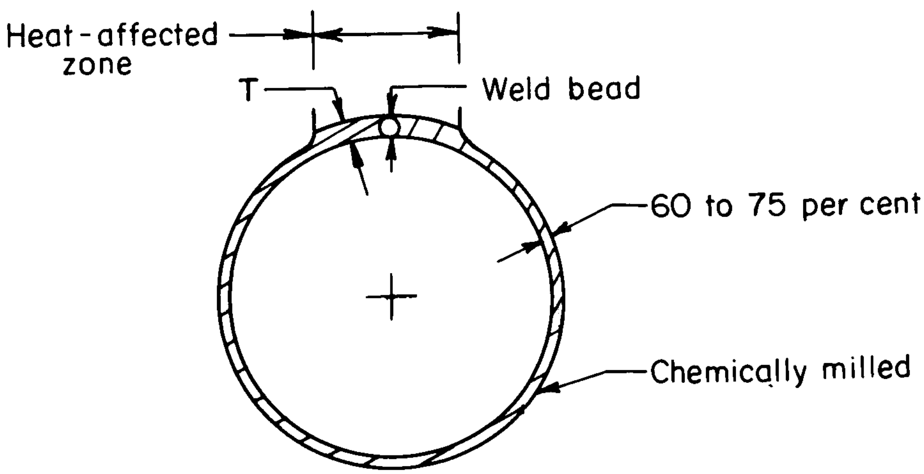


FIGURE 103. METHOD OF EQUALIZING STRENGTH BETWEEN WELD AND WALL AREAS FOR DIE-FORMED TUBES (REF. 52)

Bulge-Forming Limits. Two limitations must be considered in bulge forming operations: ductility of the workpiece material and design of the tooling. The ductility determines the maximum percentage strength as determined from the following equation:

$$\text{Per Cent Stretch} = \frac{d_f - d_o}{d_o} \times 100 \quad , \tag{23}$$

where

d_o = the original diameter

d_f = the final diameter.

The elongation values normally obtained in tensile tests cannot be used to determine this limitation since only uniform elongation is of practical importance. If necking occurs, as in the tensile test, the bulged component would be scrapped due to excessive metal thinning.

Tooling influences the amount of stretch because of the constraints it places on metal movement. If extra material is drawn in from the ends of the tubing or if the length of the tubing is shortened during forming, additional stretching is possible. The per cent stretch can sometimes be increased by applying an axial load to the tube to assure feeding additional material to the bulged section.

Another limitation besides per cent stretch is the bending strain that occurs if the tube is made to bulge over too tight a bend radius. This condition results in splitting as shown in Figure 104. The minimum bend radii in tube forming should not be less than that used in other forming operations such as brake forming.

If the bulged portion of a tube is considered as a bead, the strain for any given die design can be determined. The important strains on the basis of where failure will occur during bulge forming are represented in Figure 105. The severity of deformation is determined by the amount of stretching and the amount of bending. Consequently, the radius at the entrance to the bulged areas as well as the diameter of the bulged section are both important considerations in establishing design limits in bulge forming. A section through a bulged portion of a tube is shown in Figure 106 so that the necessary dimensions that control the strain can be analyzed. In that sketch, the radius of entrance to the bulge sections is R_1, the depth of the bulge is H, and the distance between tangent points on the bulge is W.

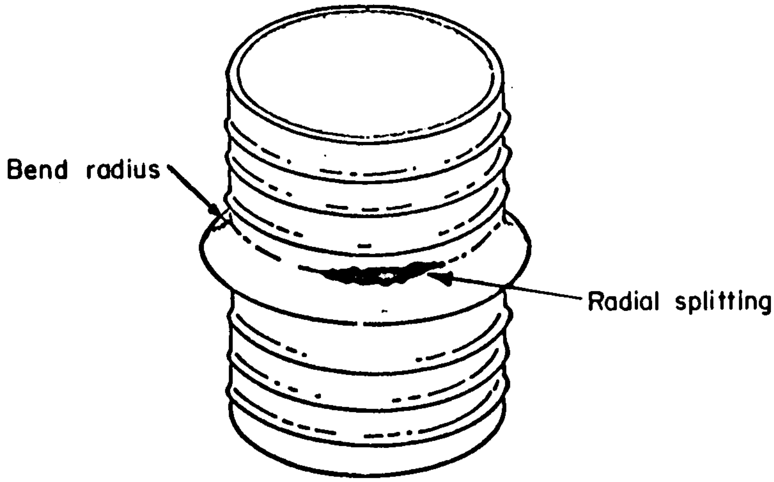


FIGURE 104. EXAMPLE OF FAILURE IN TUBE BULGING (REF. 52)

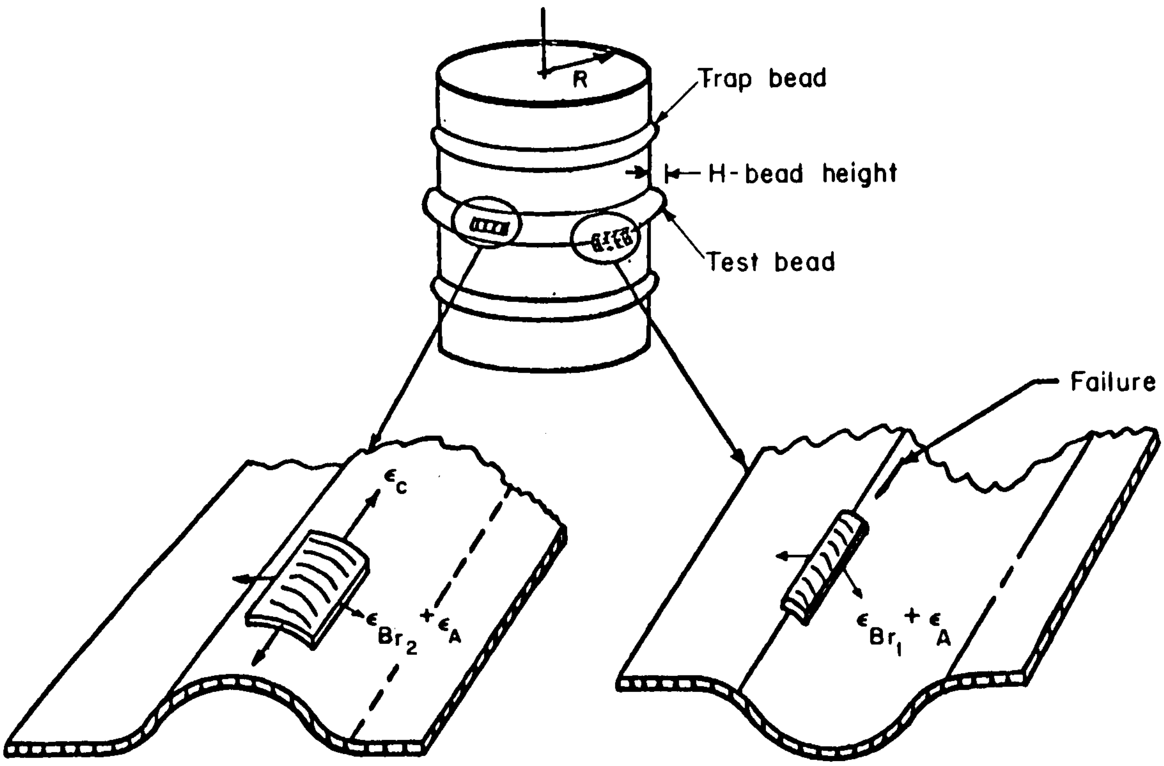


FIGURE 105. STRAIN CONDITIONS IN BULGE FORMING (REF. 52)

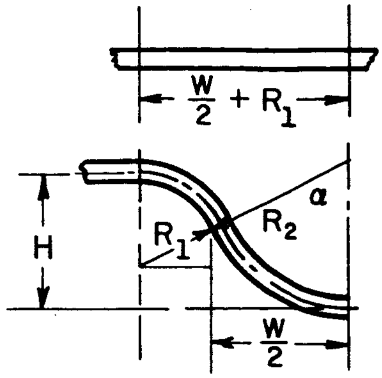


FIGURE 106. BULGE CONFIGURATION AND GEOMETRICAL PARAMETERS (REF. 52)

The strain, A, can be determined from the following equation (Ref. 52):

$$A\left\{\left[\frac{1+4\left(\frac{R_1}{W}\right)+4\left(\frac{R_1}{W}\right)^2+\left(\frac{H}{W}\right)^2}{4\left(\frac{H}{W}\right)+8\left(\frac{H}{W}\right)\left(\frac{R_1}{W}\right)}\right]\mathrm{sm}^{-1}\left[\frac{4\left(\frac{H}{W}\right)+8\left(\frac{H}{W}\right)\left(\frac{R_1}{W}\right)}{1+4\left(\frac{R_1}{W}\right)+4\left(\frac{R_1}{W}\right)^2+4\left(\frac{H}{W}\right)^2}\right]-1\right\}. \tag{24}$$

The relationships between ϵ_A, H/W, and R_1/W are shown in Figure 107 so that laborious calculations need not be carried out for each new design.

For example, consider the case of a bulge width, W, of 2 inches and an entrance radius on the die of 0.40 inch, which gives an R_1/W = 0.2. If a bulge height of 0.50 inch is required, then the H/W = 0.25. From Figure 107 the axial strain ϵ_A is found equal to 0.075 in./in. The combined strain $\epsilon_A + \epsilon_{BR_1}$ determines failure limits so that the limiting bending conditions must be considered for the particular alloy of interest. This limit based on R_1/T or bend radius over material thickness is the same as for brake forming.

Figure 108 shows the limiting permissible amounts of stretching and bending strain for two titanium alloys in the annealed condition. The curves are based on experience in experiments with two thicknesses of material. Fracture would be expected to occur if attempts were made to bulge from materials to larger strains than those indicated by the trend lines. For example, the curves indicate that a

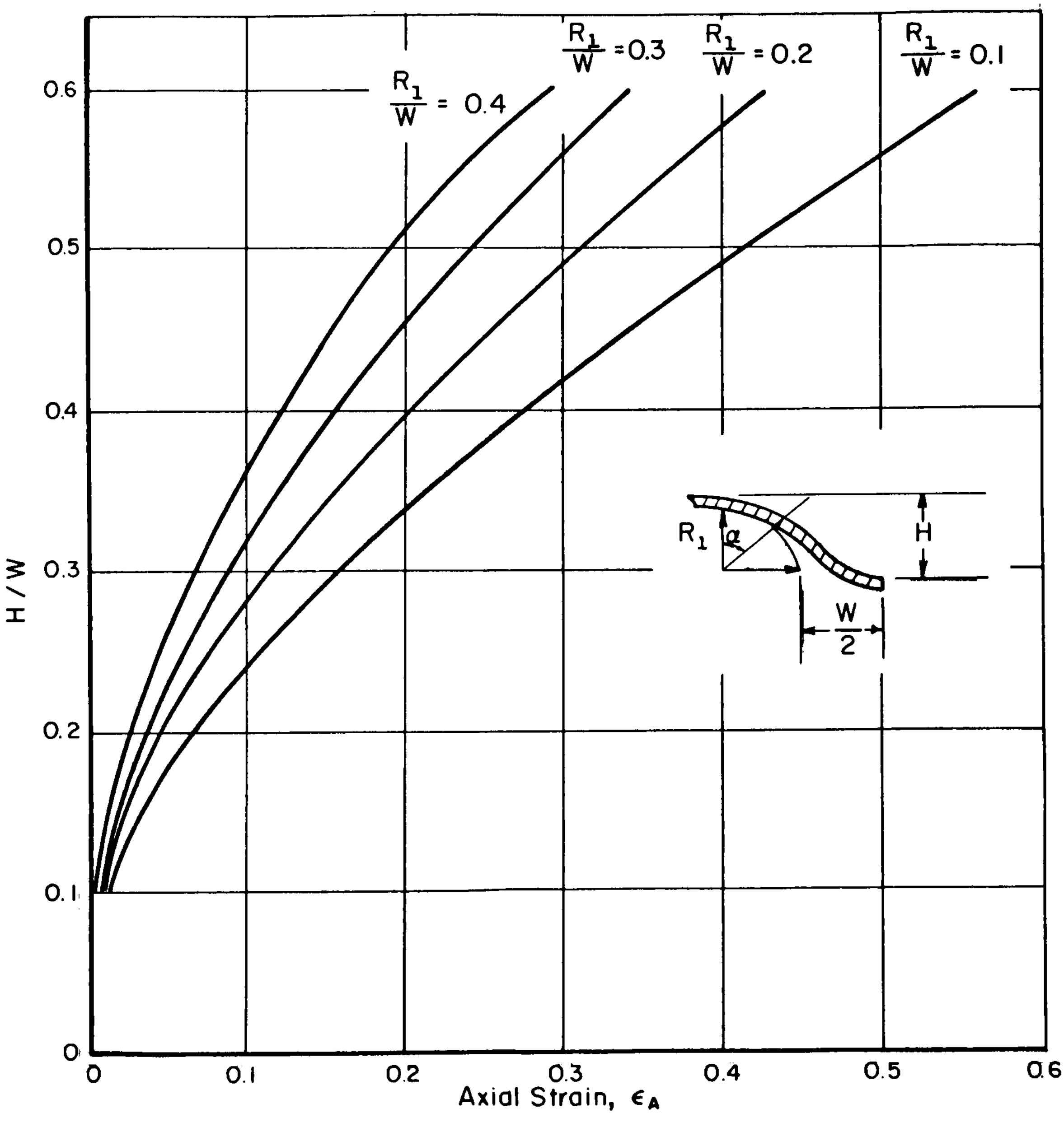


FIGURE 107. H/W VS AXIAL STRAIN ϵ_A FOR VARIOUS VALUES OF R_1/W (REF. 52)

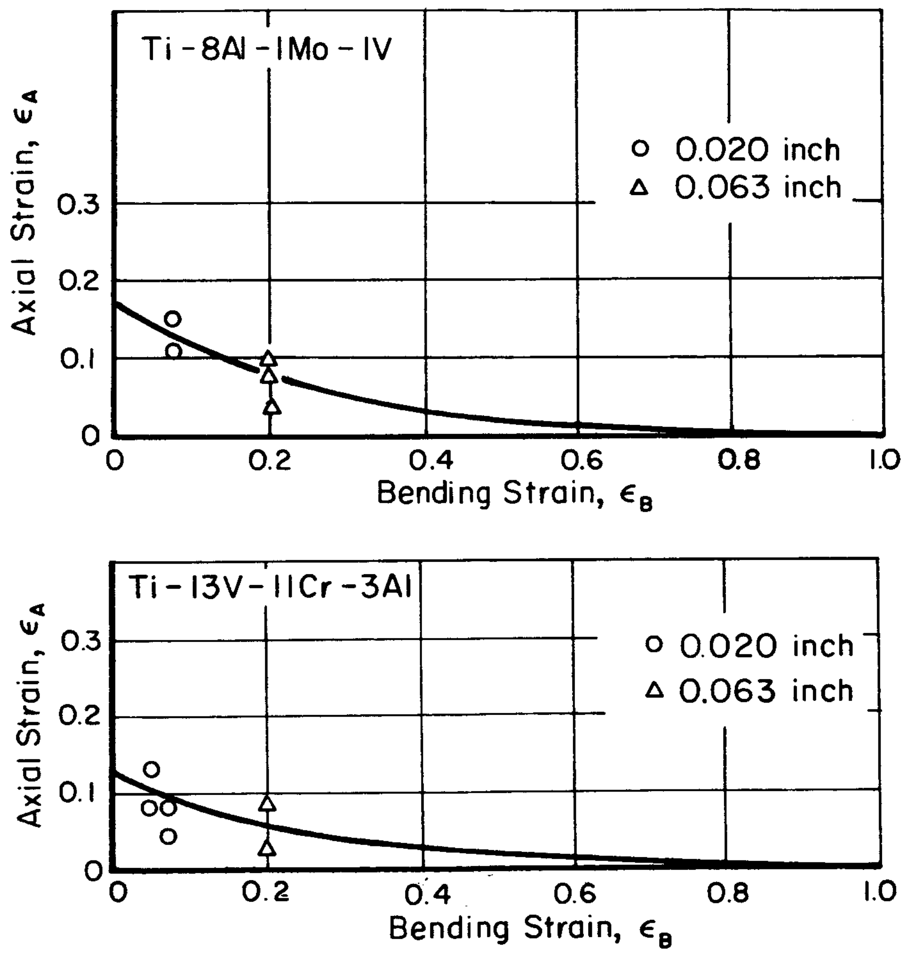


FIGURE 108. BULGE-FORMING LIMITS (AXIAL STRAIN ϵ_A VERSUS BENDING STRAIN ϵ_B FOR Ti-8Al-1Mo-1V AND Ti-13V-11Cr-3Al ALLOYS (REF. 52)

part with a stretching strain of 0.1 in./in. should not be bent to a strain of more than 0.1 in./in.

Care must be used in applying this technique to determine design limits for a particular material. The analysis is based on no axial movement of material from the ends of the tube into the die. When such movement occurs, the axial strain will be less than that indicated. The analysis does not hold for eccentric-forming operations, which have a different strain pattern than that considered here.

Additional information on tube forming is required and should be obtained through development programs with the specific alloys to be used as tubing. In the absence of additional specific information, the only approach is to predict bulge-forming limits for tubing from data for uniform elongation and permissible bend radii obtained on sheet.

ROLL FORMING AND ROLL BENDING

Introduction. This section of the report covers two types of secondary rolling operations used to change the shape of metals. They are:

(1) Forming by rolls whose contours determine the shape of the product. This process usually employs a sequence of power-driven rolls to produce long lengths of shaped products from sheet or strip.

(2) Bending between two or three cylindrical rolls that can be adjusted to curve sheet, bar, or shaped sections. With this technique, the length of sheet is controlled by the width of the rolls.

The term roll forming usually refers to a continuous bending process performed progressively by a series of contoured rolls in a special machine. With equipment of this kind (Figure 109), which can operate at high speeds, tolerances as small as ±0.005 inch can be obtained in cold forming. Roll forming is often used to bend strip into cylinders that are butt welded to produce thin-walled tubing with a relatively small diameter.

Similar products can be made by drawbench forming. That technique involves pulling the strip through a series of heads or stands containing undriven, or idling, rolls. Both methods, roll forming and drawbench forming, are used to form titanium and its alloys into

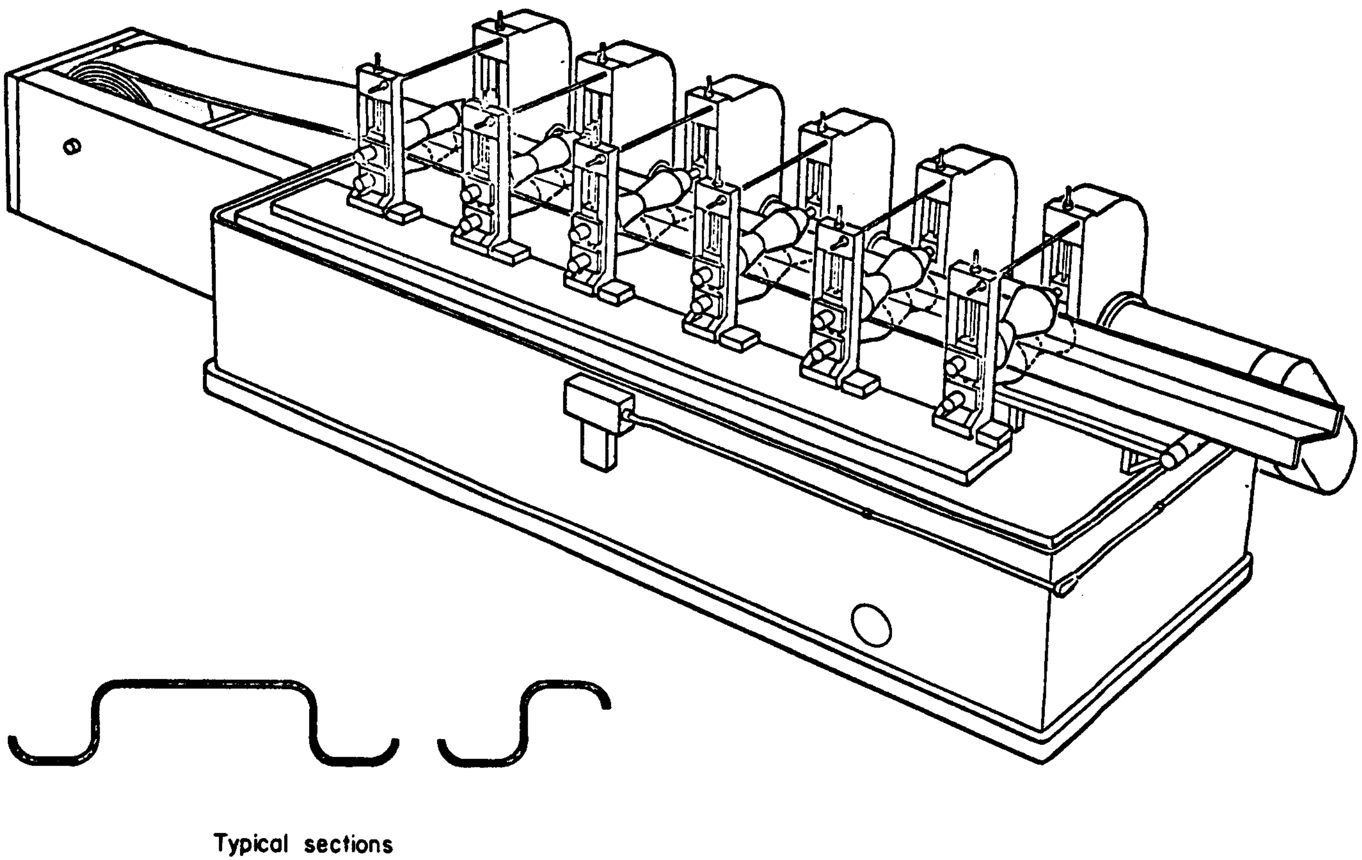


FIGURE 109. SCHEMATIC DRAWING OF ROLL-FORMING MACHINE (REF. 109)

structural hat sections, angles, tee sections, and channels. Normally these operations are performed at room temperature, but some of the stronger alloys must be roll formed at elevated temperatures to prevent cracking or to obtain tighter radii. Some facilities have been built to perform such hot-roll-forming operations.

The second process, roll bending, is often used to bend sheet into cylindrical, single-contour shapes that can later be welded to form tube or pipe of rather large diameters. Aircraft producers and fabricators have roll-bending facilities that are capable of contouring flat sheets into cylinders up to about 36 feet long. Facilities capable of bending structural shapes by means of rolls are available and frequently used to produce large-radius bends in channels and other sections. Such sections may be used to support skins in aircraft manufacturing.

Roll Forming. A schematic drawing of a six-stand Yoder roll-forming machine is shown in Figure 109. The strip, entering from the left, passes through a series of six rolls and emerges from the machine as a rolled shape. The method offers a number of advantages. A bend radius of one T less than the minimum bend radius in brake forming can usually be attained in roll forming titanium alloys. Parts can be produced with lower internal stresses than are present in parts formed by impact or brake forming. Roll forming is a high speed, fast production process. For instance, the man-hour savings by roll forming may amount to 85 per cent compared with brake forming the same shape in 8-foot lengths.

Roll-forming machines are operated at speeds up to 125 feet per minute. With the recent availability of many of the titanium alloys in strip form (Ref. 110), the full potential of roll forming can now be utilized. The availability of strip is particularly important in the case of the stronger alloys that are roll formed at elevated temperatures.

Equipment. Equipment for roll forming is available from a number of manufacturers in a range of sizes and capacities. Table XXXV gives comparative data on roll-forming machines produced by one manufacturer. The physical meaning of the dimensions used in this table is illustrated in Figure 110. The machines described are considered typical of the roll-forming equipment available in the industry. The size and weight of the equipment increases as the maximum sheet thickness increases. The number of roll stands required for a particular application depends on the complexity of the bending required. A machine may consist of from 2 to 20 roll

TABLE XXXV. COMPARATIVE CHART OF CAPACITIES OF VARIOUS ROLL-FORMING MACHINES PRODUCED BY ONE MANUFACTURER[a]

Reference to Figure 110		Model Designation					
		RLW	MLW	HMW	MW	HW	XHW
A	Spindle Diameter, in.	1	1-1/2	1-1/2 or 1-3/4	2 or 2-1/4	2-1/4 or 2-1/2	3, 3-1/2, or 4
B	Horizontal Center Distance, in.	5	8	9	12	14	18
C	Standard Roll Space, in.	3-1/2	6	6 or 8	10 or 12	10 or 12	18
D	Upper Spindle Adjustable From, in.	2-15/16 to 3-9/16	3-15/16 to 5-1/16	4-7/16 to 5-9/16	5-7/16 to 7-1/16	6-3/8 to 8-1/2	7-7/8 to 11-1/8
E	Roll-Pitch Diameter From, in.	3 to 3-1/2	4 to 5	4-1/2 to 5-1/2	5-1/2 to 7	6-1/2 to 8-3/8	8 to 11
F	Stockline From Floor, in.	36	36	36	36	36	36
G	Maximum Section Height From Pitch Line, in	9/16	3/4	1	1-3/8	1-5/8	2-3/4
H	Standard Spacer, OD, in.	1.720	2.720	2.720	3.470	4.220	4.720
J	Top of Base to Lower Spindle, in.	3	4	4-1/2	5	6	8
K	Approximate Maximum Height of Section That Can Be Rolled, in.	1-1/8	1-1/2	2	2-3/4	3-1/4	5-1/2
	Maximum Recommended Stock Thickness, approx in.	0.025	0.045	0.078	0.109	0.148	0.187
	Range of Roll Stands (Pairs of Spindles)	6-20	6-20	6-20	6-20	6-20	6-20
	Range of Overall Lengths, in.	53-123	72-184	80-206	95-263	110-314	136-396
	Range of Recommended Motor Horsepower	2-7-1/2	3-15	5-15	7-1/2-20	10-40	15-50
	Range of Weights, lb	1,900-5,275	2,600-8,050	4,100-11,800	5,000-18,050	7,500-23,500	11,000-40,000

(a) Data taken from booklet, "Modern Metal-Forming Machinery by Tishkin", Tishkin Products Company, 13000 West Eight Mile Road, P. O. Box 3798, Oak Park Station, Detroit 37, Michigan.

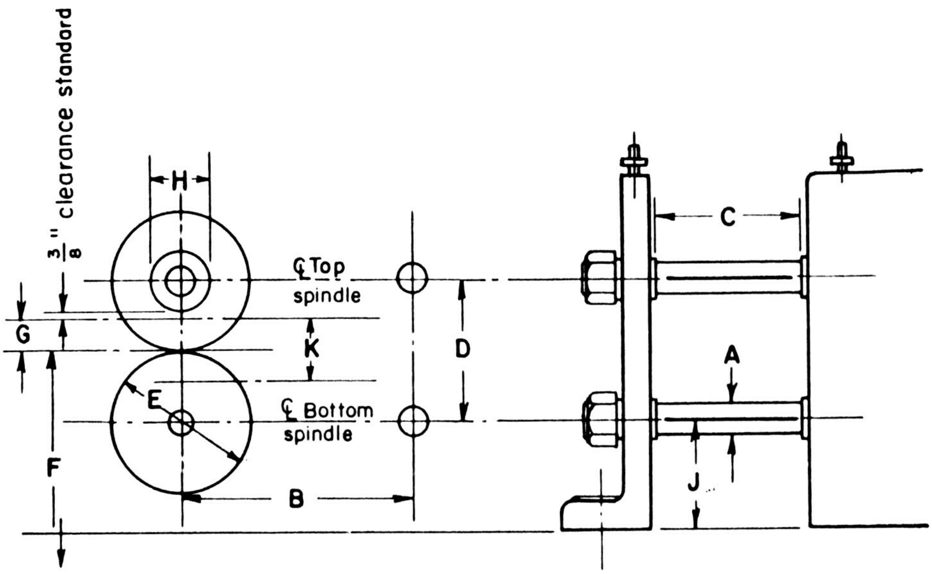


FIGURE 110. SKETCH SHOWING DIMENSIONS IN ROLL-FORMING STAND MENTIONED IN TABLE XXXV

Courtesy of Tishkin Products Company.

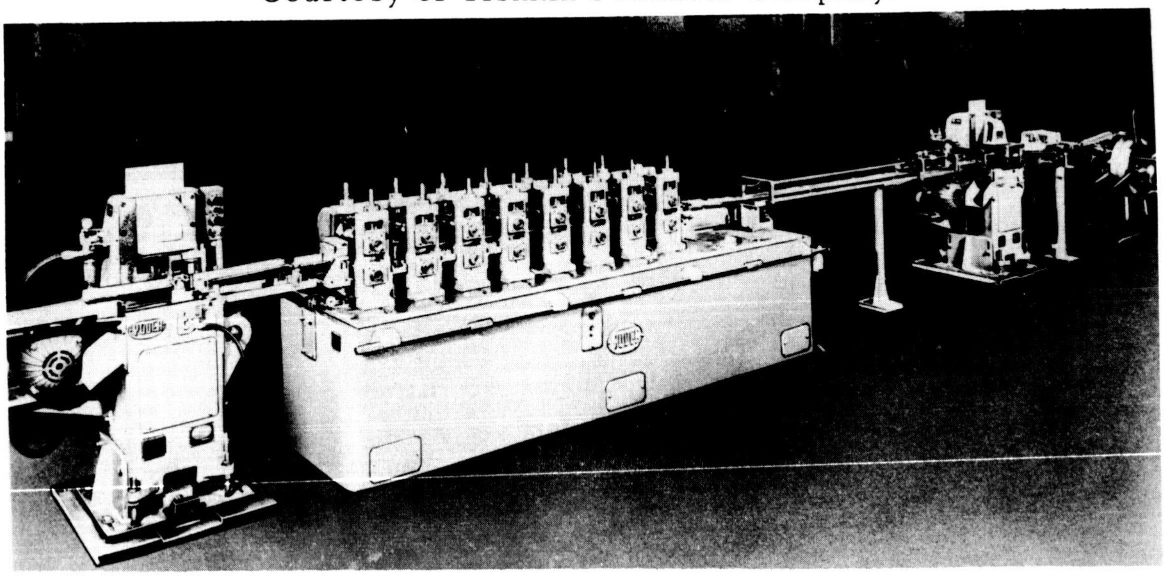


FIGURE 111. TYPICAL ASSEMBLY OF ROLL-FORMING PRODUCTION EQUIPMENT

Courtesy of The Yoder Company, Cleveland, Ohio.

stands. Relatively simple bending contours can be accomplished by using six or less rolls. Equipment manufacturers should be consulted on equipment requirements for specific applications.

The power available limits the size of the stock that can be processed. For instance, Convair (Ref. 55) found that a 10-hp mill was incapable of producing 1-1/2-inch hat titanium sections and angles from 0.040 or 0.063-inch stock at a speed of 100 feet/minute. However, the same dimensions could be made at 125 feet/minute from 0.090-inch stock of the Ti-4Al-4Mo-1V and the Ti-16V-2.5Sn alloys with a standard 50-hp roll-forming unit.

Figure 111 shows a typical assembly of equipment that may be used for titanium roll forming. The stock is fed from a coil through the roll-forming machine and the shaped product is cut into suitable lengths by the press shown at the left of the photograph.

High-temperature bearings are recommended for roll-forming equipment to be operated at elevated temperatures. In one study (Ref. 58), however, satisfactory results were obtained by replacing the shaft on each stand with hollow shafts through which cooling water was circulated. The tubular shafts were made from chromium-plated 4130 steel. The cooling system kept the bearing temperature below 300 F when the rolls were operating at 1100 F.

Before titanium-alloy strip was available in coils, it was necessary to cut sheets into strips of suitable width and butt weld them to obtain relatively long lengths. When only a few pieces are involved, the sheet can be cut on a power shear. However, where relatively large quantities of strip are required, alloy stock may be slit prior to roll forming. Equipment to slit titanium sheet into suitable strips is available in a variety of sizes from a number of manufacturers that supply the roll-forming equipment. Figure 112 illustrates a slitter capable of handling titanium sheet up to 60 inches wide.

Tooling. The rolls used in roll-forming equipment may be made from a variety of materials. Oil-hardened tool steel rolls are normally used. For high-production applications where long-wearing characteristics are desirable, rolls of steels containing about 1 to 5 per cent carbon and 12 to 13 per cent chromium are used. Chromium-plated rolls may be used where high-finish materials are to be formed. Sometimes duplex rolls are used where only the working surfaces are made of hardened tool steels. They are especially suitable for wide rolls with shallow contours.

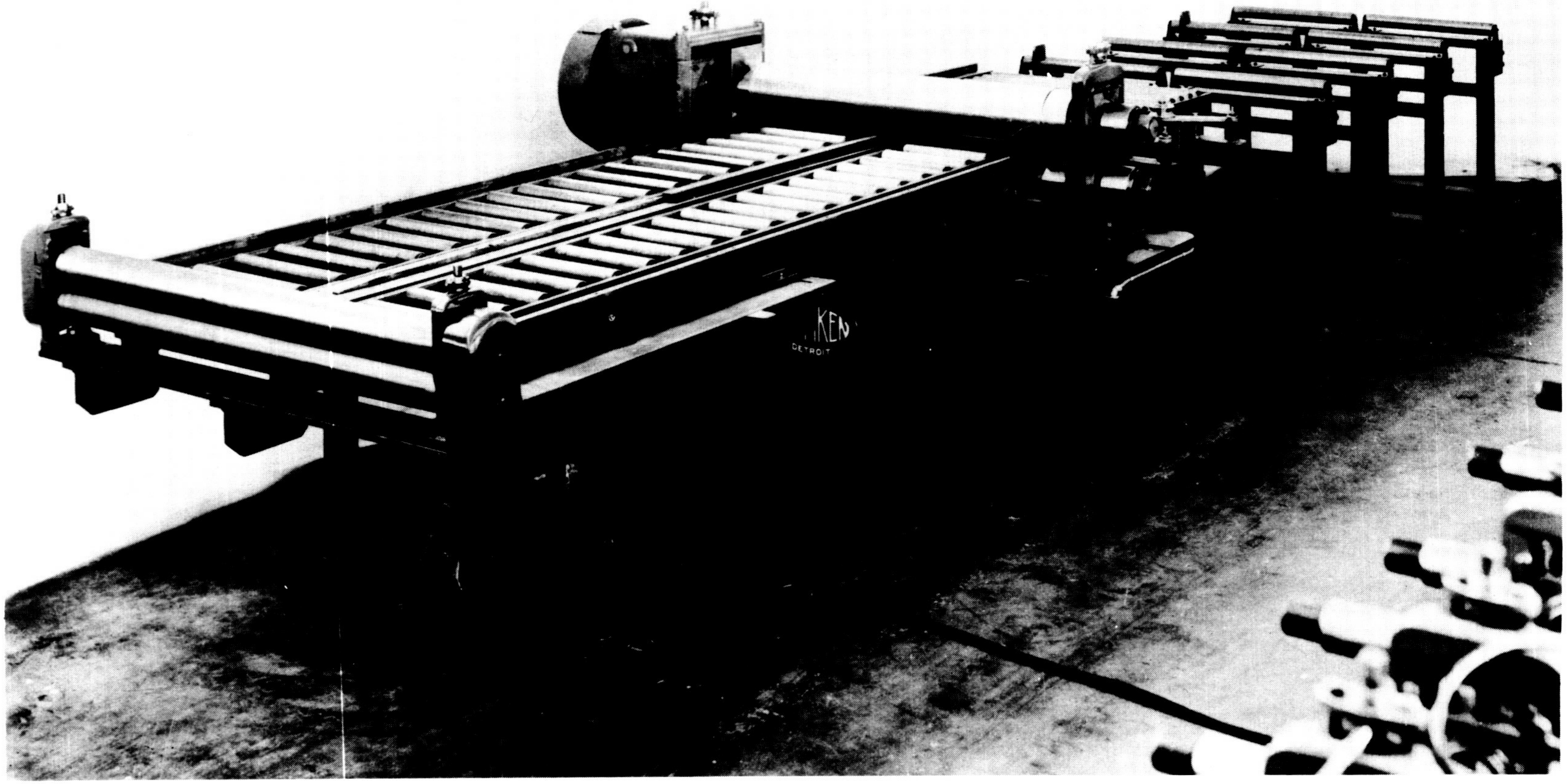


FIGURE 112. CUSTOM-BUILT SLITTER CAPABLE OF SLITTING SHEETS UP TO 60 INCHES WIDE

Courtesy of Tishkin Products Company, Detroit, Michigan.

Room-temperature roll forming of titanium alloys at Convair (Ref. 55) was performed with rolls made of AISI-E-52100, high-chromium tool steel.

Rolls used at the Los Angeles Division of North American Aviation (Ref. 61) to roll form the Ti-4Al-3Mo-1V alloy at room temperature were case-hardened chromium-molybdenum steel with case depth of 0.090 inch. In the Boeing program (Ref. 58), the rolls were fabricated from Class H-13 tool steel – a hot die steel chosen for its hardness, freedom from distortion, and resistance to scaling. These rolls were hardened to 52 to 54 on the Rockwell C hardness scale.

Tooling for drawbench forming of titanium alloys at room temperature has been made of Ampco bronze for some applications. Such tooling is used in stages, and four or more stages of idler rolls may be required to form a part.

Heating Methods. Work at Boeing (Ref. 58) indicated that both the rolls and the titanium strip should be heated in roll-forming operations. They experimented with induction heating, gas-fired muffles and electric muffle furnaces for heating each set of rolls. Best results were obtained with gas-heated muffles built around each rolling stand. Between the muffles insulated tunnels maintained a heated atmosphere around the strip to prevent excessive cooling. The gas flames impinged directly on the rolls made from H-13 steel on both sides of the forming area and provided heat for the system. Ten gas burners were used for the upper roll and 12 for the lower roll, the difference being necessary to counteract convection effects and balance the temperature between the two rolls. Valves regulating the gas-air mixture flowing to each roll were operated manually to control the temperature within ±25 F at 1100 F. Thermocouples connected to an electronic recorder both measured and recorded the temperature adjacent to the strip. A speed of 2 feet/minute was used in the experimental studies for forming the 0.025-inch-thick strip. This rolling speed probably could be increased for production applications by adding a strip-preheating stage.

Lubricants. Lubricants are almost always required for the roll forming of titanium and its alloys. For roll forming at room temperature, fluids such as SAE 60 oil or its equivalent function both as lubricants and coolants. Solid lubricants are often used for roll forming at elevated temperatures. Satisfactory results were obtained when one commercially available lubricant, Dag-41, was thinned with

10 parts of lacquer and sprayed on both sides of titanium-alloy strip prior to rolling at 1100 F (Ref. 58). Such lubricants also may be applied by dipping, brushing, or wiping. Upon heating to the rolling temperature, the carrier usually vaporizes leaving the filler as a solid residue to provide lubrication. Another lubricant that is used for elevated-temperature roll forming is Everlube T-50.

Strips of the titanium alloys, fabricated into shapes by drawbench forming are sometimes coated with a fluoride-phosphate conversion coating. The coating acts as a host for the lubricant.

Material Preparation. The general precautions given in the section on blank preparation should be observed. Especially detrimental in roll forming is the presence of grinding marks and scratches parallel to the length of the strip (Ref. 111). Such marks initiate cracking when the strip is formed into shapes. Their effects can generally be minimized by buffing or by a light chemical etch. Removing as little as 0.001 inch of metal by etching often significantly increases uniform elongation of titanium.

Variations in the thickness of the metal strip results in dimensional inaccuracy of roll-formed parts. Improvements in thickness and shape control by the metal-rolling mills has minimized this problem.

Roll-Forming Procedures. Relatively little information is available about roll forming of titanium, since the process has, until quite recently, seen very limited use in the aerospace industry. The process is a high-production technique not well suited to producing small quantities of a single shape. In addition, the stronger alloys that must be formed at elevated temperature present special problems because of the rather extensive setups that must be made to heat both the rolls and the strip. The information available originated mainly from experimental studies performed under Government contracts to evaluate the performance of specific alloys.

Experimental work at Convair (Ref. 55) was done on the room-temperature roll forming of the Ti-4Al-3Mo-1V and the Ti-2.5Al-16V alloys in the solution-treated condition. Studies on producing 90-degree-angle sections resulted in the information contained in Table XXXVI. Although the minimum radius was 20 T to bend 0.040 and 0.060-inch-thick sheet of the Ti-2.5Al-16V alloy and 3.0 T to bend the 0.090-inch-thick strip, the springback was approximately equal to that obtained with the Ti-4Al-3Mo-1V alloy, which required a 3 T bend radius for all three thicknesses of sheet. This work indicated that springback is influenced by the pressure applied by the work.

TABLE XXXVI. SUMMARY OF ROLL-FORMING TEST RESULTS ON SAMPLES OF SOLUTION-TREATED ALLOYS AT ROOM TEMPERATURE[a]

Alloy	Material Thickness, T, in.	Minimum T Radius	Average Springback, deg	Reference
Ti-4Al-3Mo-1V	0.020	3.0	11.2	61
	0.020	4.0	14.6	61
	0.040	3.0	10.4	61
	0.040	4.0	17.8	61
	0.040	3.0	3.5	55
	0.040[b]	1.0	0	112
	0.060	3.0	8.5	55
	0.060[b]	1.0	0	112
	0.063	3.0	10.8	61
	0.063	4.0	15.6	61
	0.090	3.0	14.0	55
Ti-2.5Al-16V	0.040	2.0	2.0	55
	0.060	2.0	7.0	55
	0.090	3.0	15.0	55

(a) The Ti-2.5Al-16V angles were made in a six-roll machine, the others in a seven-roll machine.
(b) Rolled at 1100 ± 25 F.

Using a seven-station roll-forming machine with a 1-1/2-inch spindle diameter, Spalding and associates (Ref. 61) roll formed the Ti-4Al-3Mo-1V alloy at room temperature. Their data also are given in Table XXXVI. The springback obtained in this study was somewhat higher than that reported by Langlois, et al. (Ref. 55). Rolling at 1100 F prevented springback.

Experimental work by Gunter (Ref. 58) indicates that the solution-treated Ti-6Al-4V alloy can be formed into a hat section at 1100 F. One of the principal difficulties encountered in this study was unevenness in the solution-treated strip that had been converted to strip by slitting of sheets that were not as flat as desired. Present production of strip of the titanium alloys in coil form should tend to minimize this problem.

It is known that some of the newer titanium alloys, such as the Ti-8Al-1Mo alloy, have been roll formed by heating the blanks to about 1000 F and rolling on rolls heated in the range of 200 to 500 F. Details on these recent experiments are not presently available.

It is also known that drawbench forming is being investigated as an alternative means of producing shapes. This method of forming is not continuous, but is limited by the length of the drawbench. In one application a forming speed of 18 feet per minute was used to draw strip of the Ti-8Al-1Mo-1V alloy in four stages into a "T" section, 3 inches high, at room temperature. The strip was overbent by 10 degrees to allow for springback. Additional details of this process are not available.

Post-Forming Treatments. After forming, sections are sheared to desired lengths and the forming lubricant is removed. This may be done by vapor blasting individual pieces or in a suitable cleaning-bath cycle. One such cleaning method is to treat for 20 to 30 minutes in an alkaline scale conditioner, Turco 4316*, at 280 F, followed by a 1-hour mild acid pickle in Turco 4104* at room temperature. Pickling baths must be controlled to prevent increases in hydrogen in the titanium above 250 ppm.

Inspection for cracks is done by the fluorescent die-penetrant method and/or visually under a low-power microscope.

Roll Bending. Roll bending is the most economical process for producing single-contoured skins from the titanium alloys. In addition to bending flat sheet into cylindrical contours, the linear-roll-bending technique also is commonly used to curve heel-in and heel-out channel sections with maximum flange heights below 1.5 inches. The channels may initially have been produced by roll forming on a press or even by extrusion. In addition to roll bending, the final contour of a channel or other section also might be produced by stretch-forming techniques. Angle sections are obtained by bending channel sections to the desired contour and then splitting the channels to form the angle sections.

Figure 113 is a sketch of a typical setup for the linear roll bending of channels (Ref. 53). The upper roll in the pyramid-type roll configuration can be adjusted vertically as shown in the figure, and the radius of the bend is controlled by the adjustment of this roll. The geometry for heel-in and heel-out channels also is shown in the sketch.

*Produced by Turco Products, Inc., Los Angeles, California.

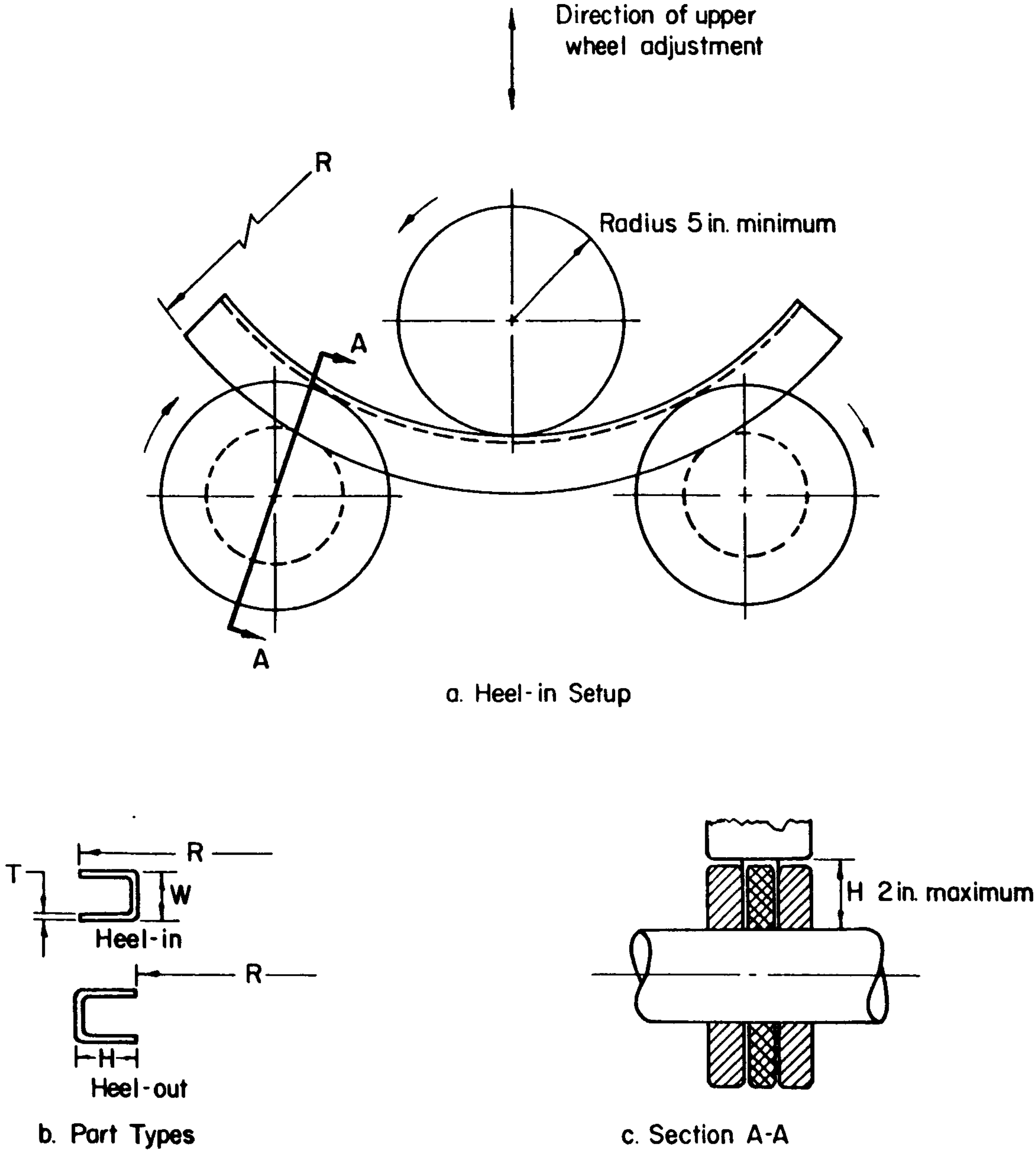


FIGURE 113. PART TYPES AND SETUP FOR ROLL BENDING (REF. 53)

Roll bending is a process that depends greatly on operator technique. Premature failures will occur if the contour radius, R, is decreased in increments that are too severe. On the other hand, too many passes through the rolls may cause excessive work hardening in the channel. An operator usually must form several trial parts of a new material in order to establish suitable conditions.

Equipment. Linear-roll-bending equipment generally is quite simple in design. One common type of equipment utilizes a pyramidal design both in vertical and horizontal machines. Three rolls are used, two lower rolls of the same diameter placed on fixed centers at the same elevation, and a third or upper roll placed above and between the lower rolls. The upper roll may be adjusted vertically to produce different curvatures and all three rolls are driven. Figure 114 shows a vertical roll bender of the type used by Wood, et al. (Ref. 53). in their study of linear roll bending of channels. Such equipment also can be used for making helical coils from angles and channels, flat sections edgewise, and pipes by changing the rolls to the appropriate design.

Another type of equipment for bending shapes is the pinch-type roll bender, so called because its two main rolls actually pinch the stock between them with sufficient pressure to pull the material through against the resistance of the bending stress. This equipment contains four rolls, as shown in Figure 115. The upper and lower main rolls are driven by a train of gears and the lower roll, directly beneath the upper one, is adjustable vertically. The large rolls support the flanges of the shape during bending and tend to minimize buckling by supporting the sides of the flanges. The small idler rolls can be adjusted up and down, as shown in Figure 115, for changing the bend radius.

Table XXXVII gives information on a number of roll-bending machines produced by one manufacturer. The pinch-type machines have smaller capacities than the pyramid-type rolls and are largely used for relatively light aircraft parts.

In addition to rolls for contouring channels and other shapes, equipment also is available for bending sheet sections into shapes. Such equipment is extensively used to bend aircraft skins, wing sections, and the like. Figure 116 is a view of the roll-bending equipment at the Columbus Division of North American Aviation. Three bending rolls of varying size are shown, the largest of which is about 15 feet long, and the smallest about 4 feet long. The equipment is

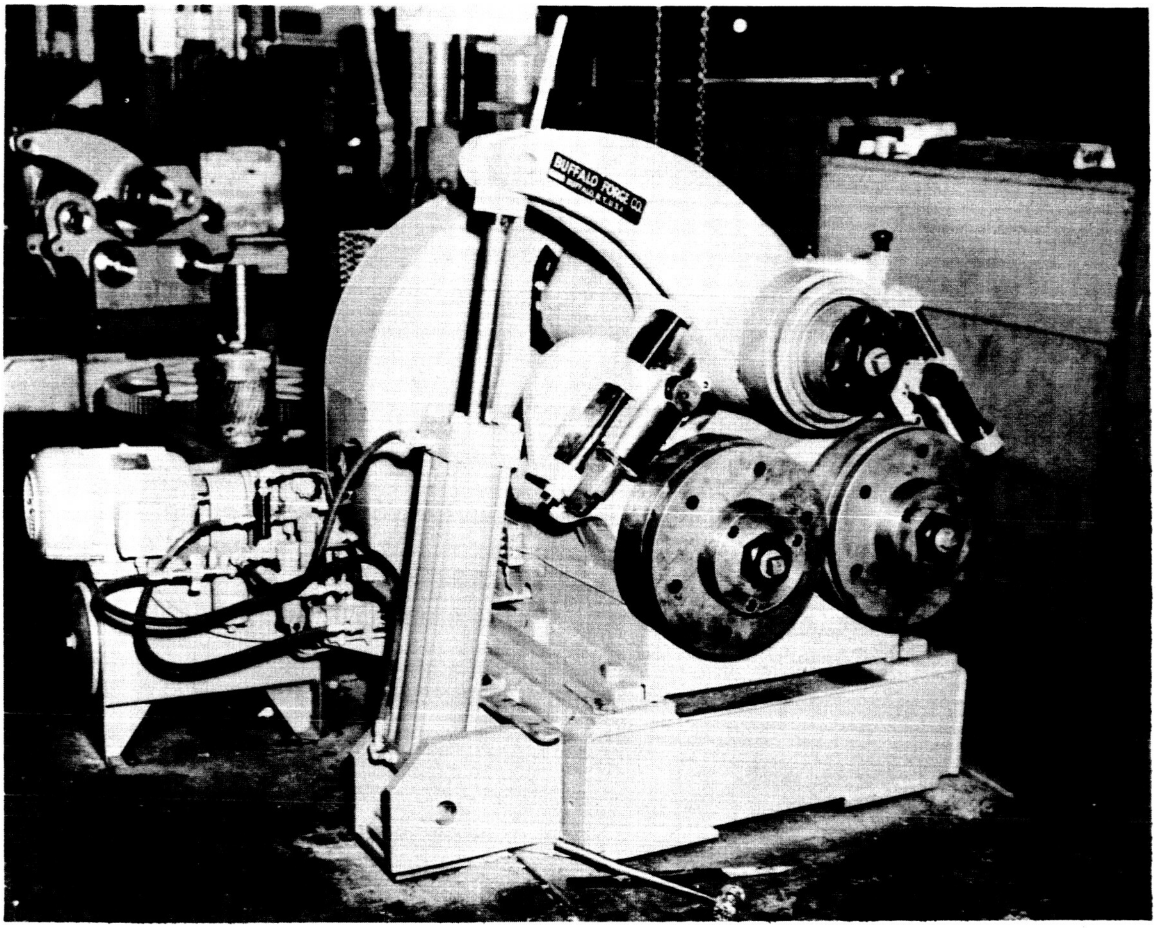


FIGURE 114. THREE-ROLL PYRAMID-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

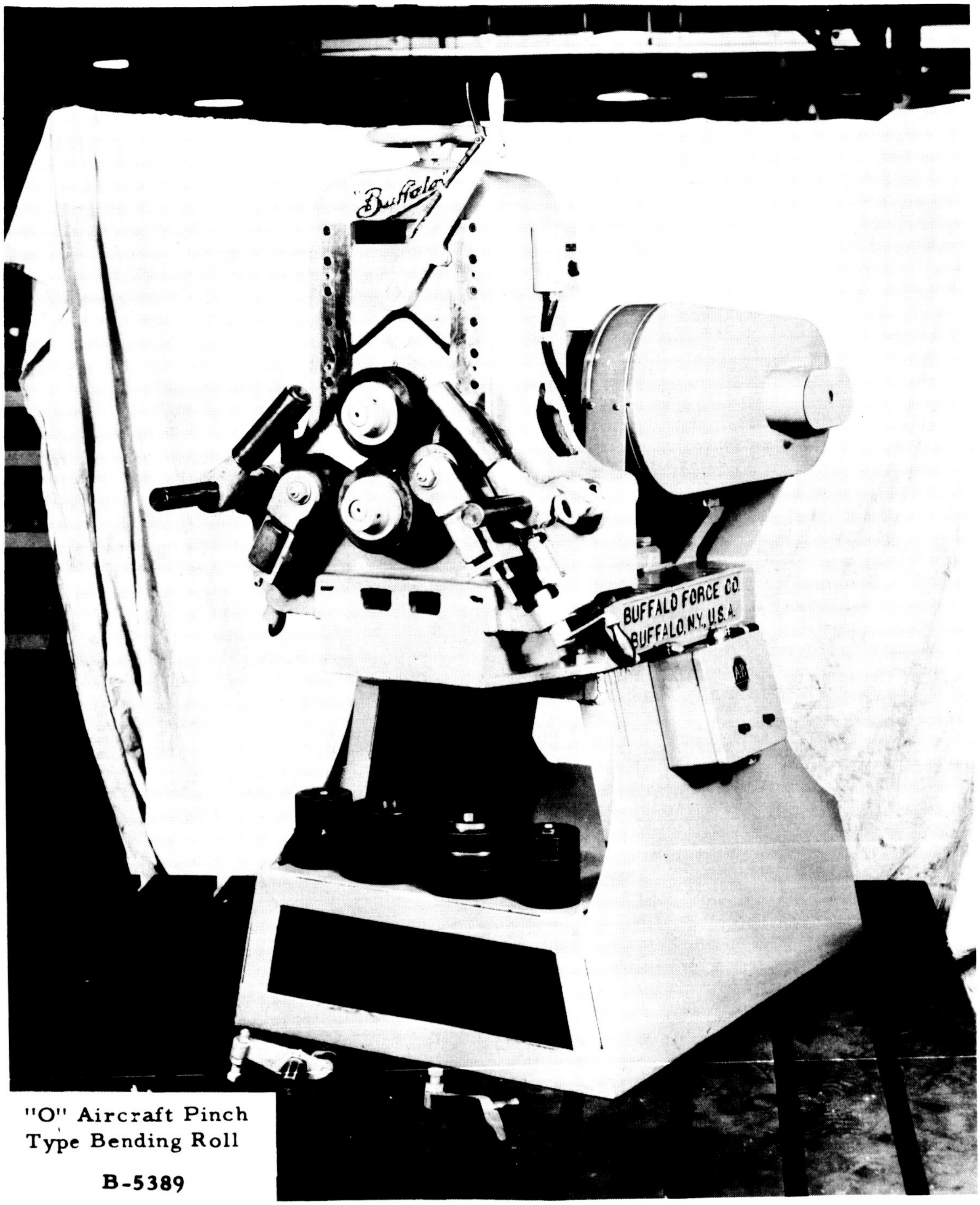


FIGURE 115. CONFIGURATION OF ROLLS IN AIRCRAFT PINCH-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

TABLE XXXVII. PERTINENT DATA ON ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[(a)]

Model No.	Vertical Bending			Vertical Pinch	
	1/2	1	2	00	0
Centers Lower Rolls	8	12	18	--	--
Diameter-Angle Rolls, in.	7	11-3/8	16-1/2	3-1/4	5-1/4
Rolls - Rpm	18	11.2	7	72.5	40
Feet per Minute	33	34	31	65	60
Size Motor, hp	5	10	20	1-1/2	2
Motor Speed, rpm	1800	1800	1800	1800	1800
Diameter, Upper Shaft, in.	3	4-3/4	6	1-5/8[(b)]	2-1/2[(b)]
Diameter, Lower Shaft, in.	2-1/2	4	5	1-5/8	2-1/2
Gear Ratio	97	156	250	24	45
Length, in.	47	61	82	34	42
Width, in.	60	62	78	30	36
Height, in.	41	58	65	34	50
Weight With Motor, lb	2300	6300	13,200	875	1175
Capacities (Typical)					
Angles, Leg-Out, in.	2 x 2 x 1/4	3 x 3 x 3/8	4 x 4 x 5/8	7/8 x 7/8 x 1/8	1-1/2 x 1-1/2 x 3/16
Minimum Diameter, in.	20	24	40	20	24
Angles, Leg-In, in.	1-1/2 x 1-1/2 x 1/4	2-1/2 x 2-1/2 x 3/8	3-1/2 x 3-1/2 x 5/8	3/4 x 3/4 x 1/8	1-1/4 x 1-1/4 x 3/16
Minimum Diameter, in.	18	30	48	30	48
Smallest Angle, Leg-Out, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	1-1/2 x 1-1/2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	8	13	18	4	6
Smallest Angle, Leg-In, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	2 x 2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	9	14	24	6	7
Channels, Heel-In, in.	3 - 4 #	5 - 11-1/2 #	9 - 20 #	-	-
Channels, Heel-Out, in.	-	5 - 9 #	7 - 14-3/4 #	-	-
Minimum Diameter, in.	16	18	48	-	-

(a) Data taken from Bulletins 326/F and 352/G of the Buffalo Forge Company, Buffalo, New York.
(b) At roll.

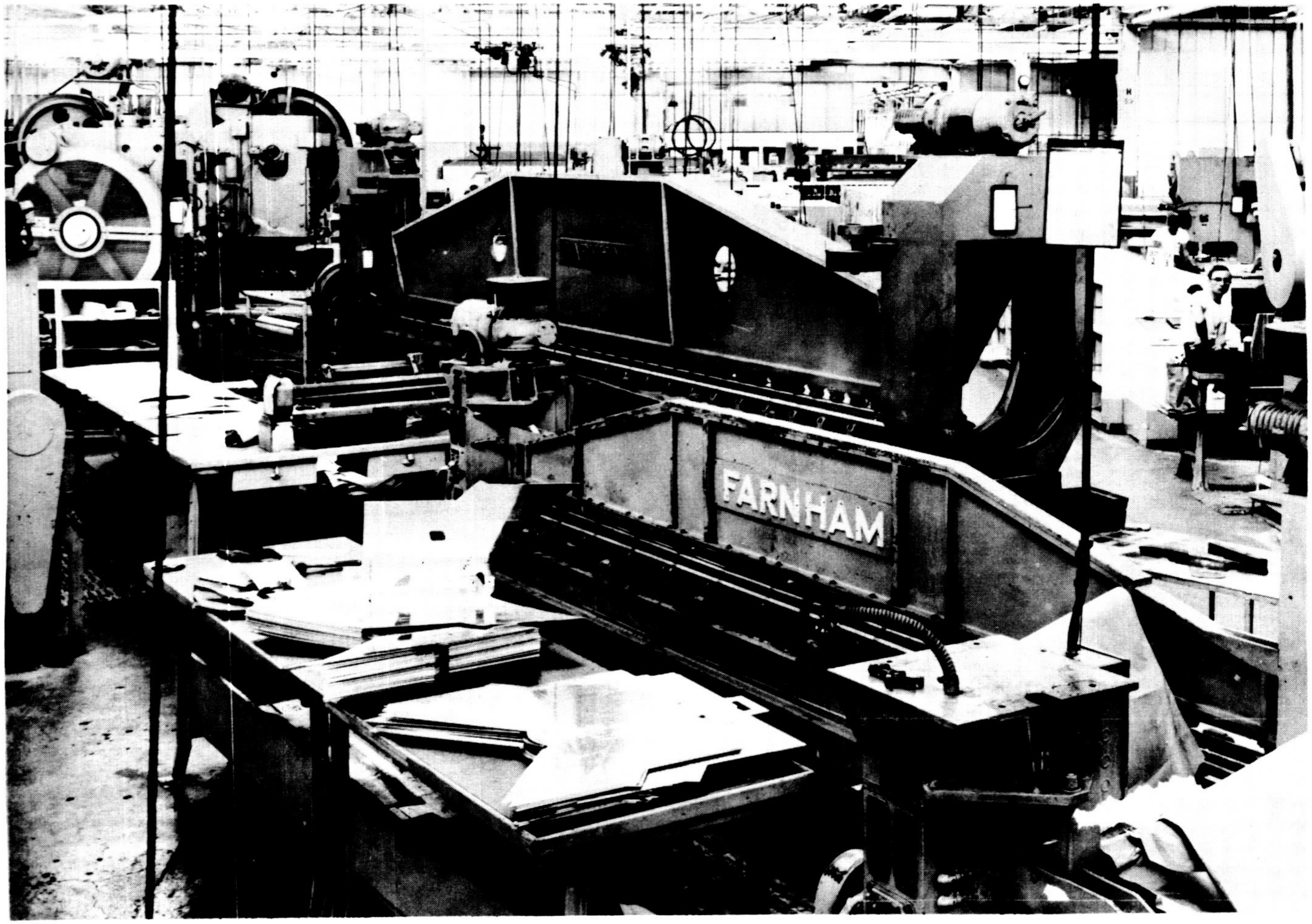


FIGURE 116. PHOTOGRAPH SHOWING THREE SIZES OF SHEET-ROLL-BENDING EQUIPMENT RANGING IN CAPACITY FROM 4 TO 15 FEET

Courtesy of Columbus Division, North American Aviation, Inc.

used to bend such aircraft parts as wing-leading edges, doors, etc. Table XXXVIII gives data on the sizes and other characteristics of sheet-forming rolls produced by one manufacturer. One characteristic of this type of equipment is that the diameter of the rolls is rather small, frequently being of the order of 1-1/2 or 2 inches. The rolls are backed up, as can be seen in Figure 116, by a series of smaller rollers to prevent bending deflections during rolling.

Another type of roll-bending equipment is made specifically for producing cylindrical and other closed sections from sheet. Such equipment is called a slip roll former or bender, and these machines feature pinch-type rolls. They are very versatile and adaptable to many operations. The equipment uses larger diameter rolls than the sheet-forming rolls just described, and is characterized by the ability of the upper roll to swing open at one end (outboard bearing) to permit easy removal of the completed cylinder or other closed shape without distortion. Table XXXIX gives data on the sizes and other pertinent characteristics of these slip-roll-bending machines.

Tooling. Rolls for linear-contour bending of shapes have been made from a variety of materials. Sometimes the rolls are made from hard rubber for use at room temperature. Adams and Cattrell (Ref. 57) used 6-inch-diameter beryllium copper rolls for bending channels of titanium alloys at room temperature, 400 F, and 800 F. Since those rolls scored badly, beryllium copper rolls probably are not suitable for use in the production roll bending of titanium and its alloys, especially at elevated temperatures.

The most common materials for the rolls on roll-bending machines are the tool steels. These may range from Grades O-2 for room-temperature application to Grades H-11 and H-13 for elevated-temperature use.

Rolls for the sheet-roll-bending machines, such as shown in Figure 116, most often consist of low-alloy steels such as Grade 4130 with flame-hardened surfaces. The surfaces usually have a Rockwell C hardness of about 50.

Heating Methods. Roll bending of titanium and many of its alloys is done at room temperature whenever possible. However, some of the stronger and stiffer alloys cannot be bent to as small a radius at room temperature as they can be at elevated temperatures. Shapes such as channels should be contoured at elevated temperatures. In one experimental setup (Ref. 57), beryllium copper rolls were heated by resistance-heating elements. The rolls were brought

TABLE XXXVIII. COMPILATION OF DATA ON SHEET-FORMING ROLLS PRODUCED BY ONE MANUFACTURER[(a)]

Model No.	Useable Length of Rolls, ft	Minimum Bend Radius, in.	Maximum Material Thickness (Tensile Strength, <60,000 psi), in.	Approximate Weight, lb	Dimensions, ft Overall Length	Height
			Model E			
658-E	6	5/8	0.063	4,300	11-5/12	7-1/3
610-E	8	1	0.063	4,400	11-5/12	
858-E	8	5/8	0.063	5,035	13-5/12	7-1/2
1058-E	10	5/8	0.063	5,765	15-1/3	7-1/3
1258-E	12	5/8	0.063	6,500	17-1/3	7-1/3
1558-E	15	5/8	0.063	7,300	20-1/3	7-1/3
1510-E	15	1	0.063	7,550	20-1/3	7-1/3
1810-E	18	1	0.063	8,500	23-1/3	7-1/3
			Model EX			
1010-EX	10	1	0.094	6,900	16-1/2	8-1/3
1210-EX	12	1	0.094	7,740	18-1/12	8-1/3
1510-EX	15	1	0.094	9,000	21-5/6	8-5/6
2015-EX	20	1-1/2	0.094	21,000	26-1/2	9-2/3
2010-EX	24	1	0.094	32,700	33-1/2	9-3/4
			Model EXX			
610-EXX	6	1	0.125	5,150	12-1/12	8-1/3
810-EXX	8	1	0.125	6,800	14-1/12	8-1/3
1010-EXX	10	1	0.125	8,450	16-5/6	8-1/3
1210-EXX	12	1	0.125	10,100	18-5/6	8-1/3
1515-EXX	15	1-1/2	0.125	23,400	22-1/4	9-1/2
2015-EXX	20	1-1/2	0.125	26,000	27-1/4	9-3/4
			Model EXXX			
1015-EXXX	10	1-1/2	0.190	15,775	18-3/4	9
1215-EXXX	12	1-1/2	0.190	19,635	20-3/4	9-1/3
1515-EXXX	15	1-1/2	0.190	25,400	23-5/6	9-3/4
1615-EXXX	16	1-1/2	0.190	26,450	25-1/6	9-3/4
2015-EXXX	20	1-1/2	0.190	30,600	28-5/6	9-3/4
			Model H4X			
606-H4X	6	6	0.250	22,000	16	9
806-H4X	8	6	0.250	25,000	18	9
1006-H4X	10	6	0.250	28,000	21	10
1206-H4X	12	6	0.250	31,000	23	10
1506-H4X	15	6	0.250	35,400	26-1/12	10-3/4
1606-H4X	16	6	0.250	37,300	27-1/12	10-3/4
1806-H4X	18	6	0.250	40,000	29-1/2	10-3/4
2006-H4X	20	6	0.250	42,500	31-1/2	10-3/4
2406-H4X	24	6	0.250	47,500	35-1/2	10-3/4

(a) Data taken from Booklet 1-58 from Farnham Division, The Wiesner-Rapp Co., Inc., 1600 Seneca St., Buffalo 10, New York.

TABLE XXXIX. SUMMARY OF SLIP-ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[a]

Model No.	Number of Roll Lengths Per Model	Range of Rated Capacity, Mild Steel, Sheet Thickness, in. or gage	Range of Working Length of Rolls, in.		Diameter of Rolls, in.	Speed of Rolls, fpm	Approximate Range of Shipping Weight, pounds	
			Longest	Shortest			Longest	Shortest
1-1/2-1	2	24 to 30 gage	20	16	1 or 1-1/2	(b)	85	45
2	6	16 to 24 gage	42	12	2	18[c]	405	270
3	3	14 to 18 gage	48	36	3	22[c]	920	850
4	4	10 to 18 gage	72	36	4	15[c]	2,235	1,965
5	5	3/16" to 16 gage	96	36	5	25	4,320	2,750
6	4	5/16" to 12 gage	120	48	6	25	8,665	4,950
9	6	5/8" to 10 gage	168	48	9	16	19,725	10,725
10	6	3/4" to 3/16"	168	48	10	18	20,450	10,950

(a) Based on data in Booklet 203C and Bulletin 77H from Niagara Machine and Tool Works, 683 Northland Avenue, Buffalo, New York.
(b) Hand operated.
(c) Available also as hand-operated machines.

to the desired temperature before each pass, the power supply line and the controlling thermocouple were removed from the rolls, and the unheated parts were inserted between the rolls for preheating. The part was run through the rolls in approximately 2-inch increments with an intermediate dwell time of about 10 seconds between increments to permit additional heating of the part. After completing each pass, the rolls were reheated to the desired temperature, the idler rolls were advanced to the next position, the workpiece turned end for end to minimize spiraling, and the forming cycle repeated. It appears that in production operations the part to be roll bent also should be heated prior to bending. Figure 117 shows the setup used for the forming of channel sections at elevated temperature.

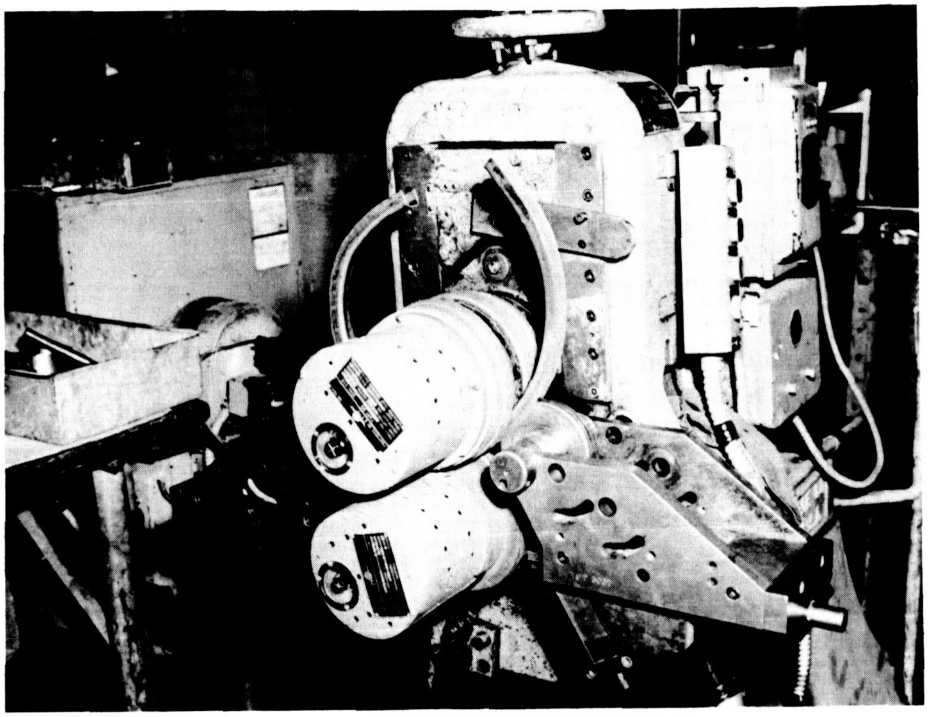
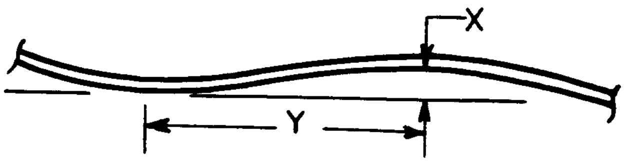


FIGURE 117. EQUIPMENT USED FOR ELEVATED-TEMPERATURE ROLL BENDING OF TITANIUM-ALLOY CHANNELS (REF. 57)

Lubricants. The lubricating practices and materials used for roll bending are similar to those previously described for roll forming.

Preparation for Roll Bending. The precautions given in the section on blank preparation must be observed. For the roll bending of flat sheet of titanium and its alloys, the flatness of the sheet is extremely important. The sheet must be flat within 0.6 per cent as shown in the sketch. In addition, the corners of the sheet part to be contoured should be chamfered prior to rolling to prevent marking of the rolls.



$$\frac{X}{Y} \times 100 = \text{flatness per cent}$$

$$X = \text{maximum variation}$$

Linear-Roll-Bending Limits for Channels. Transverse buckling and wrinkling, respectively, are the common modes of failure in bending heel-out and heel-in channels. Basic equations for predicting the bending behavior of channels of various alloys in linear roll bending were developed by Wood and his associates (Ref. 53). The principal parameters, shown in Figure 113, are the bend radius, R, the channel height, H, the web width, W, and the material thickness, T. The following three equations were developed for heel-in channel to construct a formability curve of the type shown in Figure 118.

The equation for the inflection line is

$$\frac{H}{R} = 0.0146 \left(\frac{H}{T}\right)^{1/2} . \qquad (26)$$

The equation for the elastic buckling line below the inflection line is

$$\frac{H}{R} = \frac{E_t}{S_{ty}} \left[\frac{0.025}{\frac{H}{T}^{2}} \right] . \qquad (27)$$

The equation for the buckling line above the inflection line is

$$\frac{H}{T} = \left[1.713 \frac{E_t}{S_{ty}} \right]^{2/5} . \qquad (28)$$

Similar equations were developed for the linear roll bending of heel-out channels.

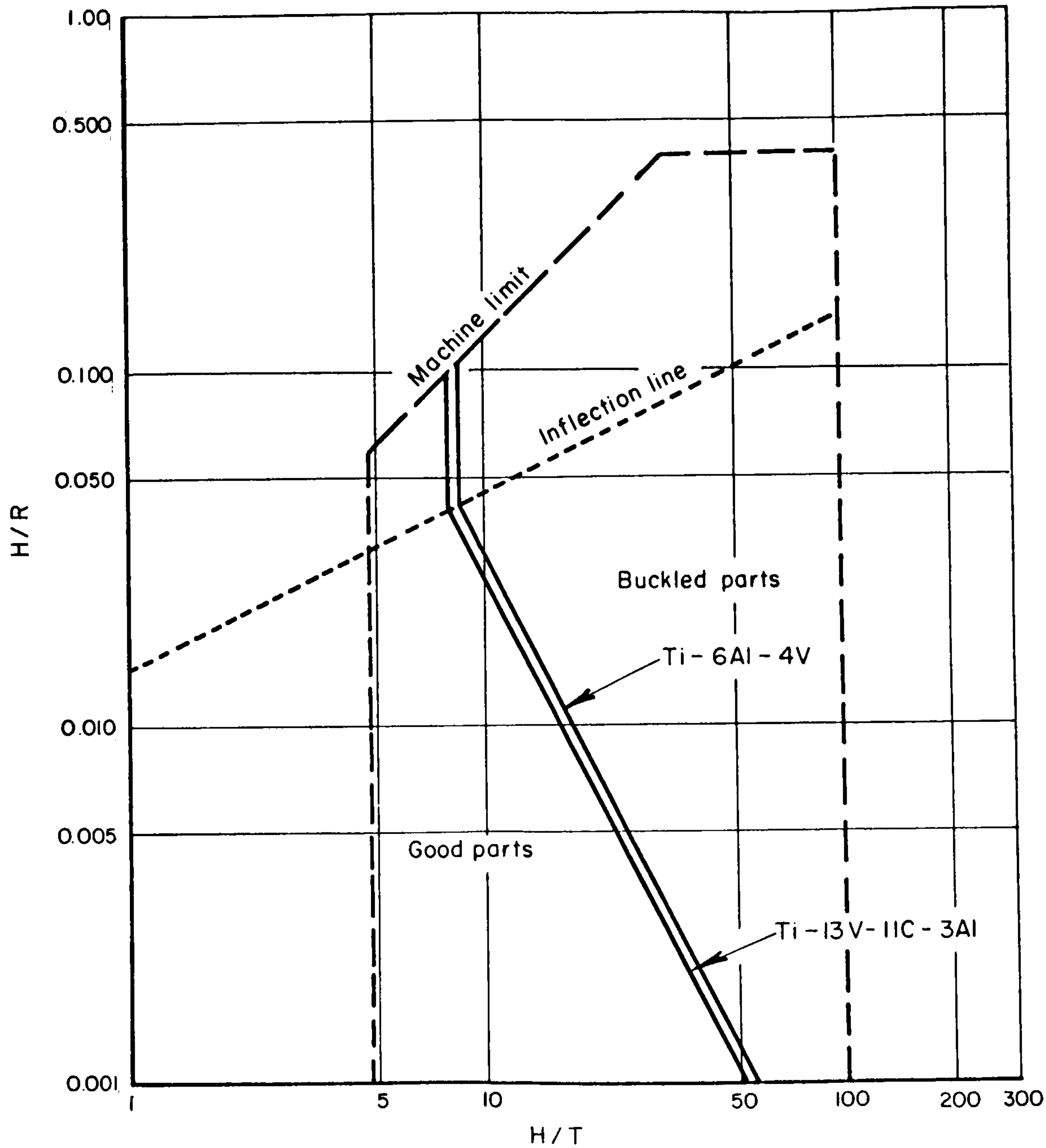


FIGURE 118. LINEAR ROLL BENDING OF HEEL-IN CHANNELS FOR TWO TITANIUM ALLOYS (REF. 53)

The equation for the inflection line is

$$\frac{H}{R} = 0.0209\left(\frac{H}{T}\right)^{1/2} \quad . \tag{29}$$

The equation for elastic buckling below the inflection line is:

$$\frac{H}{R} = \frac{E_c}{S_{cy}}\left[\frac{0.02116}{\left(\frac{H}{T}\right)^2}\right] \quad . \tag{30}$$

The equation for buckling above the inflection line is:

$$\frac{H}{T} = \left[1.01\,\frac{E_c}{S_{cy}}\right]^{2/5} \quad . \tag{31}$$

The formability curve for heel-out channels is shown in Figure 119.

In addition to the values defined above, the following values also are required to solve these equations:

E_t and E_c = moduli of elasticity in tension and compression, respectively. These values are very nearly equal for practical purposes.

S_{ty} = tensile yield strength.

S_{cy} = compressive yield strength.

The tensile yield strength is a characteristic of sheet that is commonly measured to define the strength of the sheet. Values of tensile yield strength and elastic modulus found in the literature are listed in Table XL. These values cover both room temperature and 600 F. Values of E/S_{ty} used by Wood, et al. (Ref. 53), for the mill-annealed Ti-6Al-4V and the solution-treated Ti-13V-11Cr-3Al alloys are similar to those given by others as can be seen.

The compressive yield strength is a property that commonly is not determined for sheet materials. However, ASTM standards have been agreed upon for performing this test both at room and elevated temperature. Although the elastic modulus in compression is generally slightly higher than that in tension, it usually is considered to be equal for all practical purposes. For some titanium alloys, the elastic moduli vary considerably depending on processing history.

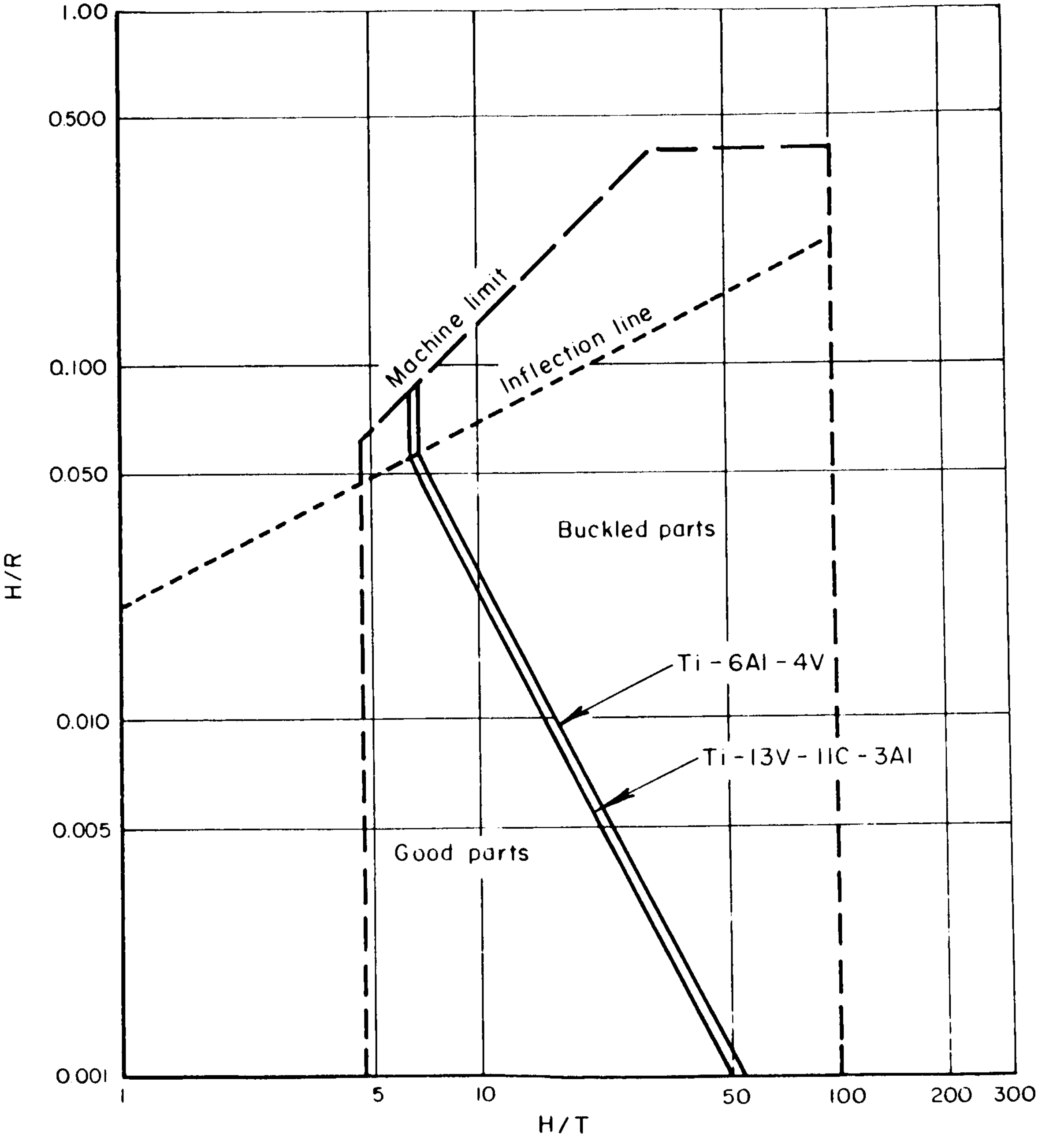


FIGURE 119. LINEAR ROLL BENDING OF HEEL-OUT CHANNELS FOR TWO TITANIUM ALLOYS (REF. 53)

TABLE XL. TYPICAL VALUES OF YOUNG'S MODULUS OF ELASTICITY AND TENSILE YIELD STRENGTHS FOR TITANIUM AND A NUMBER OF TITANIUM ALLOYS (REFS. 53, 19)

Alloy	Condition	Room Temperature: $E \times 10^6$ psi	Room Temperature: Tensile Yield Strength, S_{ty}, ksi	Room Temperature: E/S_{ty}	600 F: $E \times 10^6$ psi	600 F: Tensile Yield Strength, S_{ty}, ksi	600 F: E/S_{ty}
99.5% Ti	Annealed	14.9	27	552	12.1	10	1210
99% Ti	"	15.1	75	201	12.5	27	464
Ti-5Al-2.5Sn	"	16.0	117	137	13.4	65	206
Ti-5Al-2.5Sn (low 0)	"	16.0	95	119	13.4	60	224
Ti-5Al-5Sn-5Zr	"	16.0	120	133	14.2	74	192
Ti-8Al-1Mo-1V	"	18.5	150	123	--	--	--
	Duplex annealed	18.0	138	130	--	--	--
Ti-8Mn	Annealed	16.4	125	131	14.4	75	192
Ti-4Al-3Mo-1V	"	16.5	120	137	--	--	--
Ti-5Al-1.25Fe-2.75Cr	"	16.8	145	116	15.5	102	152
Ti-6Al-4V	Mill annealed	--	--	115	--	--	--
	Annealed	16.5	128	129	13.5	95	142
Ti-6Al-4V (low 0)	"	16.5	127	130	13.5	95	142
Ti-13V-11Cr-3Al	Solution treated	--	--	112	--	--	--
	Annealed	14.2	130	109	13.2	--	--
	Aged	14.8	175	85	13.8	145	96

For many materials, the compressive yield strength also is slightly higher than the tensile yield strength. Wood, et al. (Ref. 53), report the following ratios of E/S_{cy} for the Ti-13V-11Cr-3Al and the Ti-6Al-4V alloys at room temperature:

	E_t/S_{ty}	E_c/S_{cy}
Ti-13V-11Cr-3Al	112	117
Ti-6Al-4V	115	125

The higher ratios for the compressive properties bear out the above generalities.

In addition to the limitation on the production of suitable roll-bent parts by both buckling and splitting of the channel, another limiting parameter is the mechanical limit of the bending machine. This limit depends on the thickness of the material, the maximum section height that the tooling will accommodate, and the minimum part radius that the machine and tooling will produce. If any of these variables are changed, the position of the machine-limit line also will be changed. Needless to say, the use of other roll-bending equipment will change the position of the machine-limit line and also of the buckling-limit line of the alloy. Therefore, it should be emphasized that roll-bending limits derived by Wood, et al., are probably valid only when used with a pyramid-type, three-roll-bending machine. The added support provided by pinch-type rolls probably would move the buckling-limit line to the right.

Figures 118 and 119 give the limits for the linear roll bending of heel-in and heel-out channels, respectively, for two titanium alloys. The two alloys behave similarly, the all-beta alloy (Ti-13V-11Cr-3Al) being slightly more difficult to bend than the Ti-6Al-4V alloy. The data in Figures 118 and 119 can also be presented in tabular form in which the section height limits, H, are given for various material thicknesses, T, as a function of the contour radius. Graphs similar to Figures 118 and 119 can be constructed for other titanium alloys provided that experimental values of E_t/S_{ty} and E_c/S_{cy} are available for the alloys of interest.

Roll Bending of Titanium Sheet. Sheet of titanium and its alloys has been contoured by rolling, but to date no systematic study such as that conducted by Wood, et al. (Ref. 53), for the roll bending of channels has been reported. Most of this work is done at room temperature. Most of the difficulties previously encountered were the result of dimensional variations in the sheet and overloading of the rolls. Where a flatness of 1 per cent is adequate for other forming processes, sheet for roll forming must be flat to within 0.6 per cent.

Most of the roll-bending equipment for contouring sheet is rated on the bending of mild steel or an aluminum alloy. The yield strength of the mild steel is about 50,000 psi, of the aluminum alloy about 73,000 psi, and of some of the titanium alloys up to about 130,000 psi. The capacity of a given sheet-roll-bending machine for bending titanium can usually be estimated on the basis of the square of the thickness. For example, if a machine is capable of bending 1/4-inch-thick aluminum plate (73,000 psi yield), it probably would only have the capacity to bend about 0.187-inch-thick titanium alloy (130,000 psi yield). This rule-of-thumb is useful in preventing overloading of bending rolls. The above assumes that the cylinder lengths of the two materials are equal. Conversely, if the two materials were of the same thickness, then the length of titanium that could be bent would need to be reduced proportionately using the same relationship.

Post-Bending Treatments. Most post-bending operations consist of removing the lubricants, followed by pickling, rinsing, drying, and paper wrapping to minimize scratching and marring. Appropriate methods for cleaning titanium are described under "Blank Preparation".

DIMPLING

Introduction. Dimpling is a process for producing a small conical flange around a hole in sheet-metal parts that are to be assembled with flush or flat-headed rivets. The process is often used for preparing fastener holes in airframe components because the flush surface reduces air friction. Dimpling is most commonly applied to sheets that are too thin for countersinking. Since drilled holes have smoother edges than punched holes, they are more suitable for dimpling. Sheets are always dimpled in the condition in which they are to be used because subsequent heat treatment may cause distortion and misalignment of holes.

Principles. Figure 120 is a sketch of the dimpled area in a sheet. As would be expected in a press-die-forming operation of this kind, the permissible deformation depends on the ductility of the sheet. The amount of stretching required to form a dimple, e,

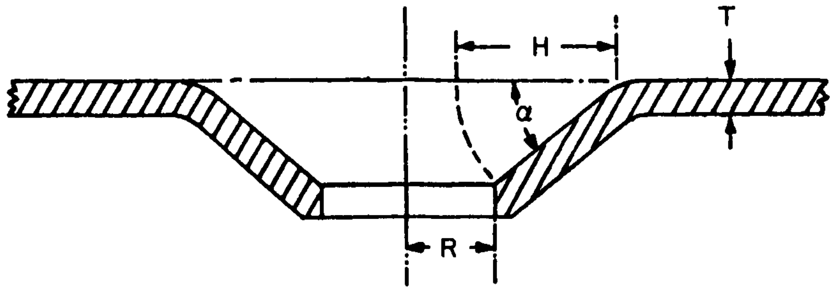


FIGURE 120. PARAMETERS FOR DIMPLING (REF. 53)

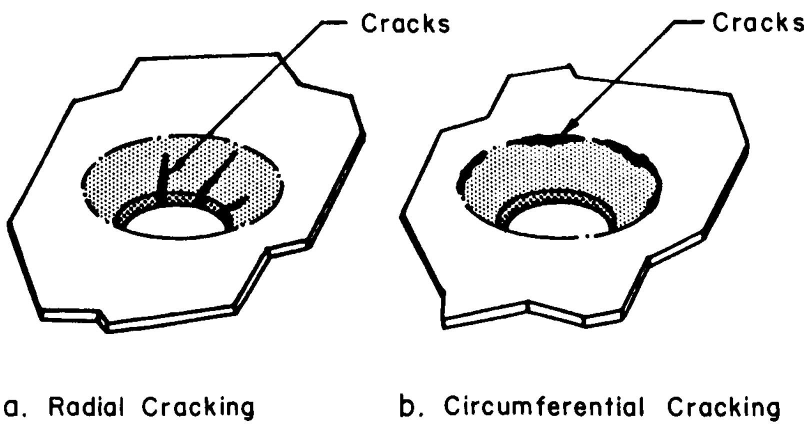


FIGURE 121. MAJOR FAILURES IN DIMPLING (REF. 59)

varies with the head diameter, D, of the fastener, the rivet diameter, 2R, and the bend angle, α, according to the relationship (Ref. 65):

$$e = \left(\frac{D}{2R} - 1\right)\left(1 - \cos\alpha\right) \quad . \tag{32}$$

If the ductility of the material is insufficient to withstand forming to the intended shape, cracks will occur radially in the edge of the stretch flange or circumferentially at the bend radius, as shown in Figure 121. The latter type of failure is more prevalent in thinner sheet. Radial cracks are more common in thick stock.

The general equation developed by Wood and associates (Ref. 53) for predicting dimpling limits from the parameters indicated in Figure 120 is

$$\frac{H}{R} = \frac{0.444\,(\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} \quad . \tag{33}$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material and temperature of interest.

The standard dimple angle, α, in Figure 120, is 40 degrees although other angles may be used for special purposes. Since dimpling requires a considerable amount of ductility, titanium alloys are ordinarily dimpled at elevated temperatures. The ram-coining-dimpling process is most common although dimples have been produced at room temperature by swaging. The essential features of the ram-coin-dimpling operations are indicated in Figure 122. In this process a

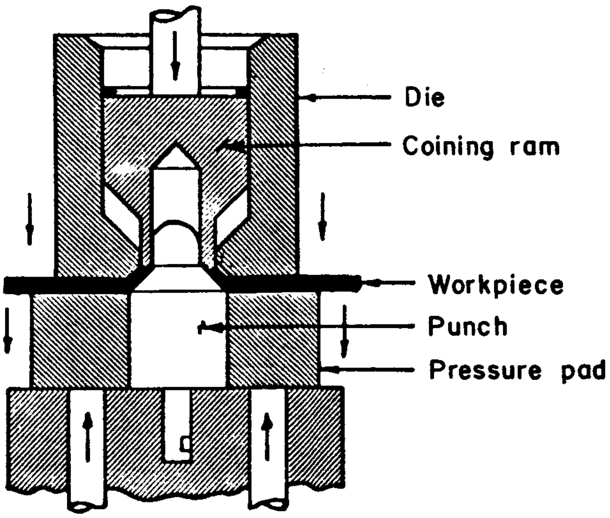


FIGURE 122. CROSS SECTION OF RAM-COIN DIMPLING (REF. 59)

pressure in excess of that required for forming is applied to coin the dimpled area and reduce the amount of springback.

Equipment. The choice of the size of ram-coining-dimpling equipment depends on the pressures needed to deform the sheet. A guide in choosing size ranges for dimpling machines needed to produce dimples for various rivet and screw sizes is tabulated below (Ref. 50):

Size	Dimpling-Pressure Capacity, lb
3/32- to 1/8-inch rivets	Up to 10,000
5/32-inch rivet	10,000 - 20,000
3/16-inch rivet and screw	15,000 - 25,000
1/4-inch rivet and screw	18,000 - 40,000
5/16-inch screw	25,000 and up

The actual pressures vary according to the sheet thickness being dimpled. The limits of a 20,000-pound-capacity dimpler for various thicknesses of sheet are shown in Table XLI (Ref. 50). Dimpling sheet thicknesses above the maximum given for each fastener size will require a change in punch and die geometry as well as an increase in the diameter of the pilot hole.

The capacities of four commercially available dimplers are given in Table XLII. A photograph of the Chicago Pneumatic CP450EA Dimpling Machine Frame equipped with a hot, triple-action, ram-coin die unit (Ref. 55) is shown in Figure 123. A competitive machine in which the dies are heated by induction coils is shown in Figure 124.

One fabricator used two versions of the Chicago Pneumatic Model CP450EA machines to dimple titanium-alloy sheet (Ref. 99). One version was a basic double-action machine and the other was modified for triple-action ram-coin dimpling. Both of these machines were equipped with electrically heated dimpling dies, which heated the sheet by contact under pressure. A minimum dwell time of 15 seconds was used to heat the sheet. These machines have controls available for varying the forming pressure and forming rates by rather simple adjustments.

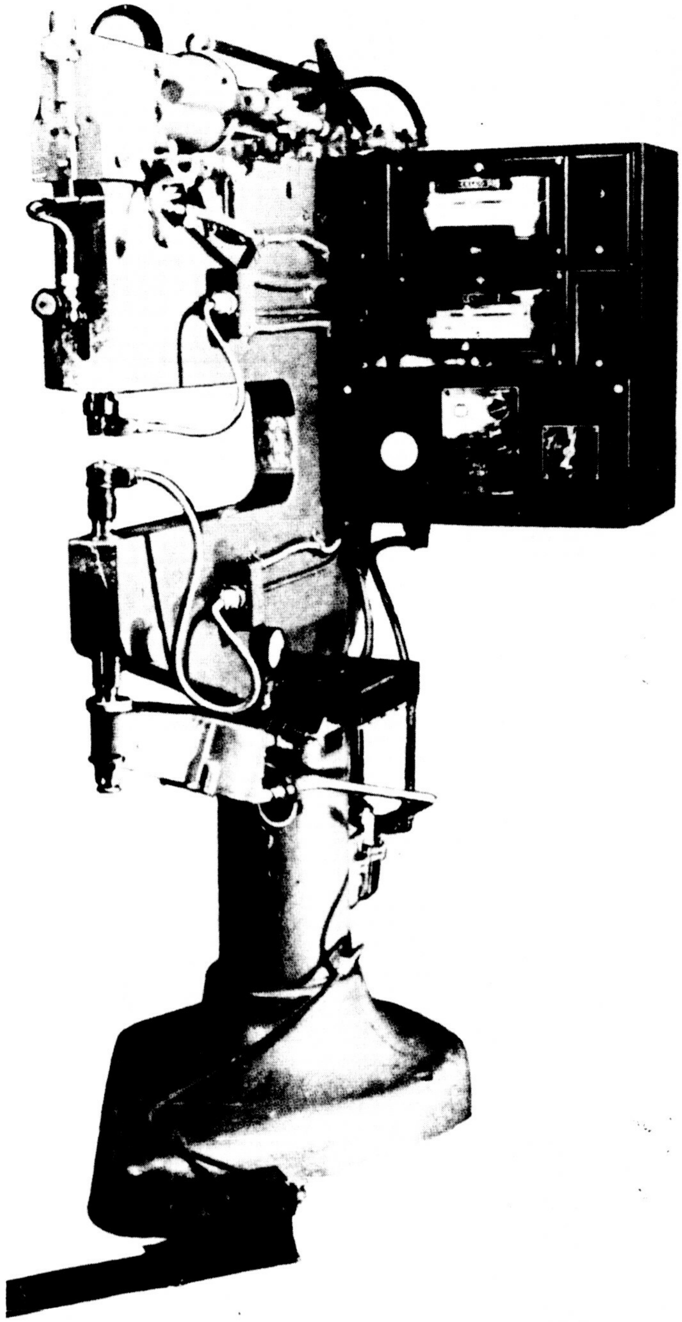
TABLE XLI. LIMITS OF DIMPLING TITANIUM SHEET FOR AN426-TYPE RIVETS ON A 20,000-POUND-CAPACITY MACHINE (REF. 50)[a]

Fastener Designation	Diameter, in.	Sheet Thickness, in.	
		Unalloyed Titanium	Ti-8Mn Alloy
AN426-3	3/32	0.016 - 0.063[b]	0.025 - 0.063
-4	1/8	0.016 - 0.063	0.025 - 0.071
-5	5/32	0.020 - 0.063	0.025 - 0.071
-6	3/16	0.020 - 0.063	0.025 - 0.071
-8	1/4	0.025 - 0.063	0.025 - 0.071

(a) Thicker sheet must be dimpled with equipment having a larger capacity.
(b) Dimpled using 20,000-pound-capacity machine, Model Model CP450EA, Chicago Pneumatic Tool Company.

TABLE XLII. CAPACITIES AVAILABLE IN COMMERCIALLY AVAILABLE DIMPLING MACHINES (REF. 50)

Model No.	Dimpling Pressure Capacity, lb	Manufacturer
CP450EA	20,000	Chicago Pneumatic Tool Co.
AT256S	30,000	Aircraft Tools Company
CP640EA	40,000	Chicago Pneumatic Tool Co.
AT260A	100,000	Aircraft Tools Company



Left side view showing triple-action controls

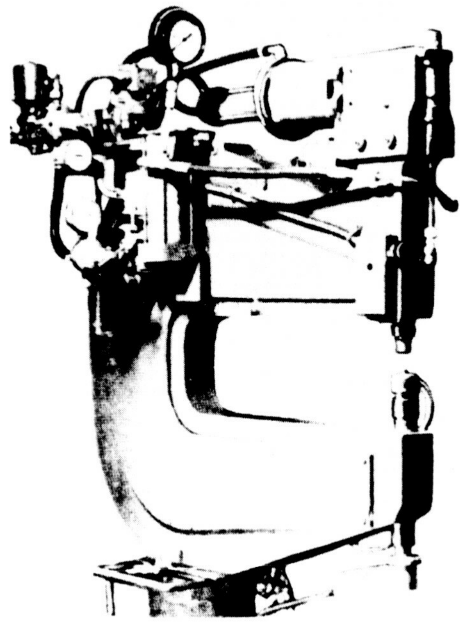


FIGURE 123. CP450EA HOT, TRIPLE-ACTION RAM-COIN DIMPLER WITH FULLY AUTOMATIC ELECTRIC AND PNEUMATIC CONTROLS (REF. 55)

Courtesy of Zephyr Manufacturing Company.

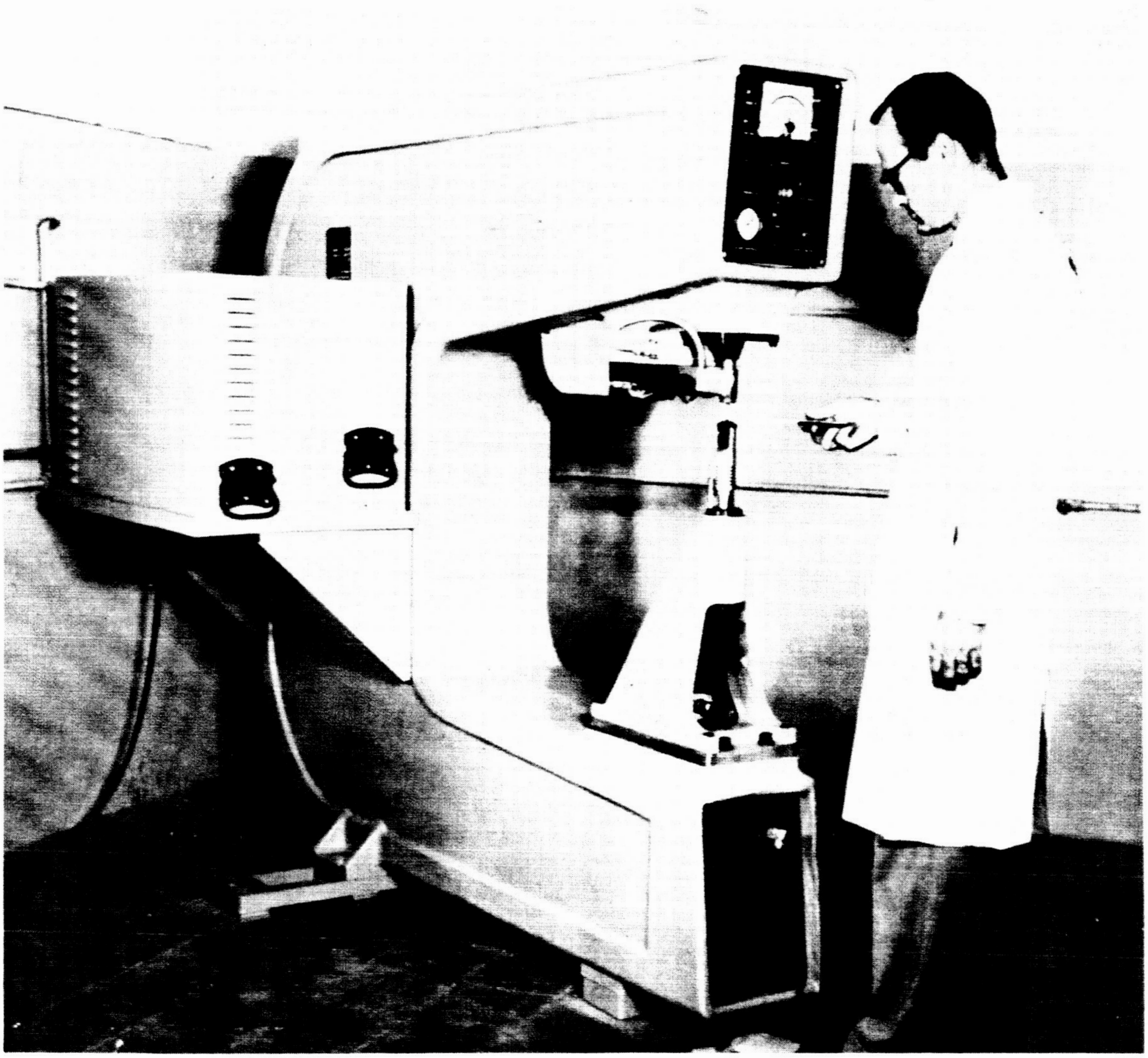


FIGURE 124. AIRCRAFT TOOLS, INC., INDUCTION-COIN-DIMPLING MACHINE (REF. 55)

Courtesy of Aircraft Tools, Inc.

Tooling. A typical sequence of operations for dimpling is shown in Figure 125. The five positions shown for a triple-action ram-coin dimpling machine are the approach, preform, coining, end of stroke, and retraction.

Titanium alloys must be dimpled at elevated temperatures. The practical optimum temperature limit is 1200 F, which is about the highest temperature at which tool steels may be used as die materials. If dimpling must be done at higher temperatures, the use of high-strength, high-temperature alloys or ceramic tooling materials is required to prevent deformation of the die materials during dimpling.

Elevated-temperature dimpling is usually done with heated dies, the sheet to be dimpled being heated by contact with the dies, as shown in Figure 125 (Ref. 55). Conduction-heated, ram-coin tooling may be used for temperatures up to 1000 F. Resistance-heated-dimpling equipment is used for higher temperatures. The tooling that is heated by resistance in one application is shown in Figure 126 (Ref. 55). The tooling consists of a solid die and a two-piece punch assembly. The die is made of high-temperature-resistant steel. The punch cone is a composite of Kentanium and steel base. The pad is a special high alumina composition. The strap heaters were used to heat the punch pad and die, to reduce heat-sink effects, and to eliminate thermal shock on the pad. The dies may also be heated by induction, and such systems have been produced by one or more suppliers of dimpling dies (see Figure 124) (Ref. 55).

One fabricator describes a triple-action machine that has a maximum die temperature of 1000 F and a constant forming rate, and a second machine, of the double-action design, in which the dies may be heated to 800 F (Ref. 99).

Material Preparation for Dimpling.

Sheet Quality. As for other bending operations with titanium and its alloys, low interstitial contents of hydrogen and oxygen in the sheet are essential to give maximum formability. One fabricator believes that a maximum of 150 ppm hydrogen should be set to provide acceptable quality sheet (Ref. 99). Other factors that permit maximum formability are consistent yield strengths from sheet to sheet, minimum thickness and flatness variations between sheets, and high-quality surface finishes (Ref. 113).

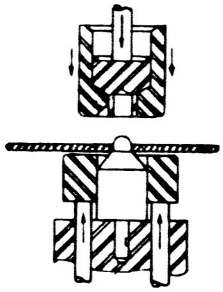
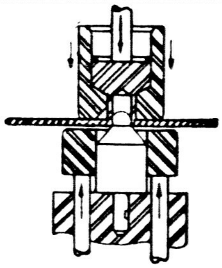
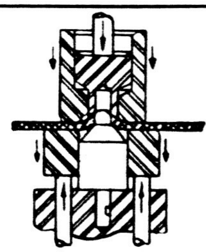
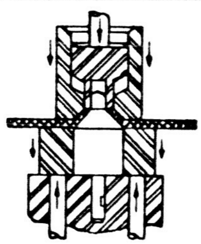
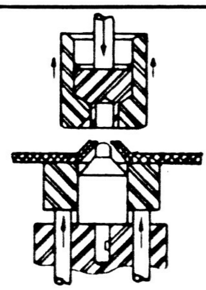
Position 1		**a. Approach** Sheet is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading force on coining ram is at preselected value
Position 2		**b. Preform** Die assembly has just contacted work, and timed heating state is beginning; controlled preforming pressure is increasing to partially form dimple and to further accelerate heat transfer
Position 3		**c. Coining** Timed "Preform" stage has ended, and final coining stage begun; downward movement of die assembly is creating firm gripping action between die and pad faces in area around dimple, preventing outward flow of material as dimple is coined; coining ram controls hole stretch and balances internal strains, eliminating radial and internal shear cracks
Position 4		**d. End of Stroke** Dimple is now fully formed; the confining action of pad face, die face, and coining ram has forced material into exact conformation with tool geometry
Position 5		**e. Retraction** As die assembly retracts to starting position, load on pressure pad raises pressure pad to starting position and strips dimple from punch cone **f. Result** Minimum sheet stretch, minimum hole stretch, maximum definition, improved nesting

FIGURE 125. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING (REF. 55)

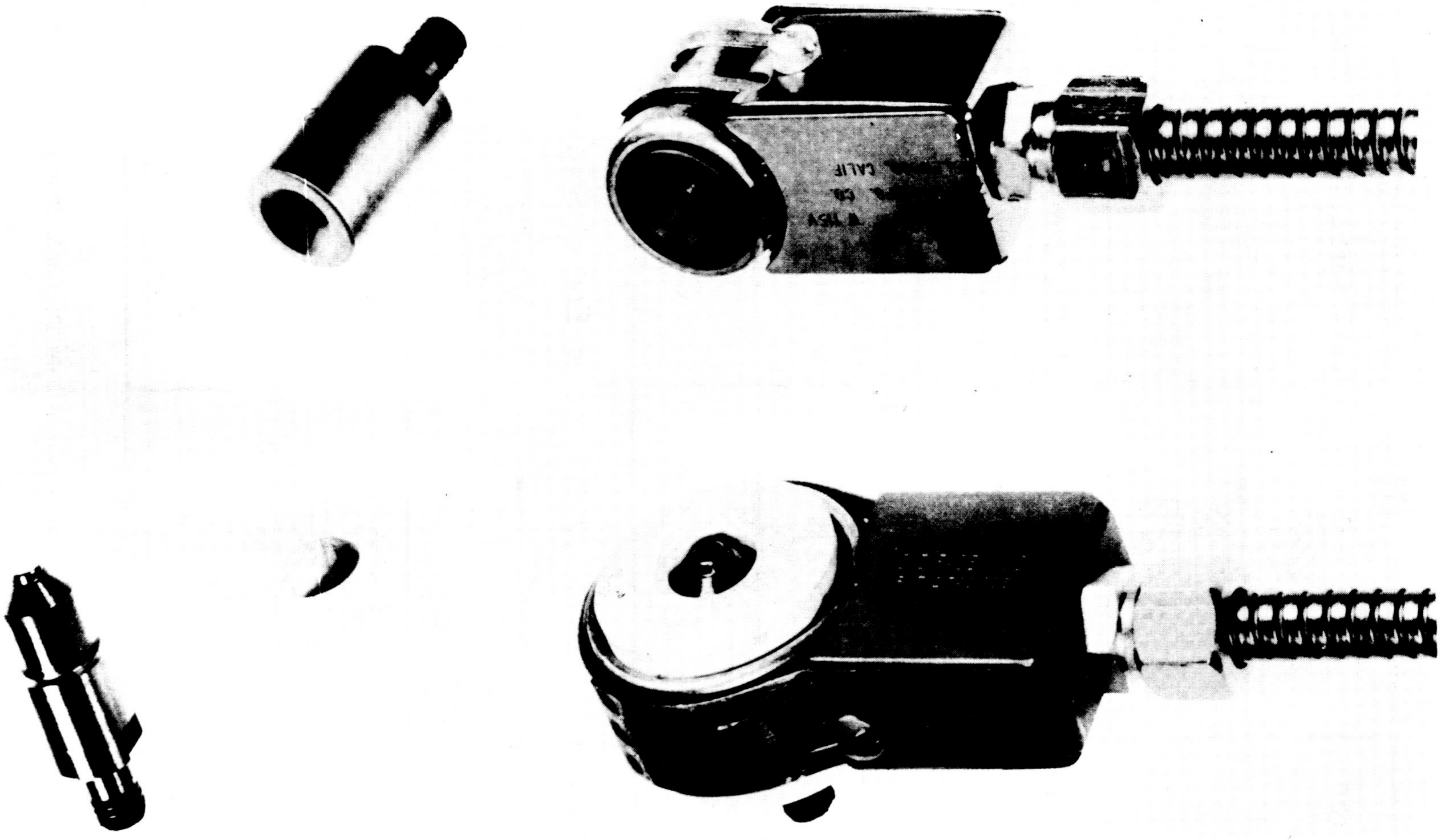


FIGURE 126. RESISTANCE-HEATED-DIMPLING TOOLING (REF. 55)
Courtesy of Zephyr Manufacturing Company.

Drilling Sheet. The quality of the drilled pilot hole has an important influence on the success of dimpling. The holes must be smooth, round and cylindrical, and free of burrs. Hand drilling is not recommended. Burrs or wire edges remaining around the holes may be detached during dimpling and lodge on the punch or die.

Pilot-hole sizes should conform to specifications applicable to aluminum alloys. The pilot holes should be drilled with stub drills designed for titanium that conform to the Aircraft Industries Association drill purchasing specification (Ref. 50). Such drills produce holes with straight sides that are satisfactory for dimpling.

Deburring Drilled Holes. Care must be taken in deburring holes for dimpling. Because of the notch sensitivity of titanium, only the material turned up by the drill at the edges of the hole should be touched and removed. Hand deburring with a countersink cutter has proven satisfactory (Ref. 50). Power-driven countersinks that chatter are not satisfactory since chatter marks are potential sources of radial cracks.

A power-driven deburring tool* has been used successfully in production with titanium (Ref. 50). The tool is mounted in the chuck of a 1000-rpm pneumatic-drill motor, and a microstop is adjusted to cut the burr flush with the sheet surface. Such a machine produces a satisfactory deburr and leaves a smooth hole edge.

Lubricants. Dimpling at both room and elevated temperatures with titanium and its alloys is done dry.

Dimpling Limits.

Theoretical. The general theoretical predicability equation for dimpling based on the parameters indicated in Figure 120 is (Ref. 53):

$$\frac{H}{R} = \frac{(0.444)\,(\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} \qquad (34)$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material at the temperature of interest. Figure 127 shows the relationship between elongation and temperature for the Ti-8Al-1Mo-1V and the Ti-13V-11Cr-3Al alloys (Ref. 52). Temperatures above

*Tool Number ZP339, The Zephyr Manufacturing Company, Inglewood, California.

1200 F must be used for dimpling both alloys. The Ti-13V-11Cr-3Al alloy has a 75 per cent elongation in a 2-inch gage length at 1500 F. It also inhibits exceptional ductility characteristics above 1200 F.

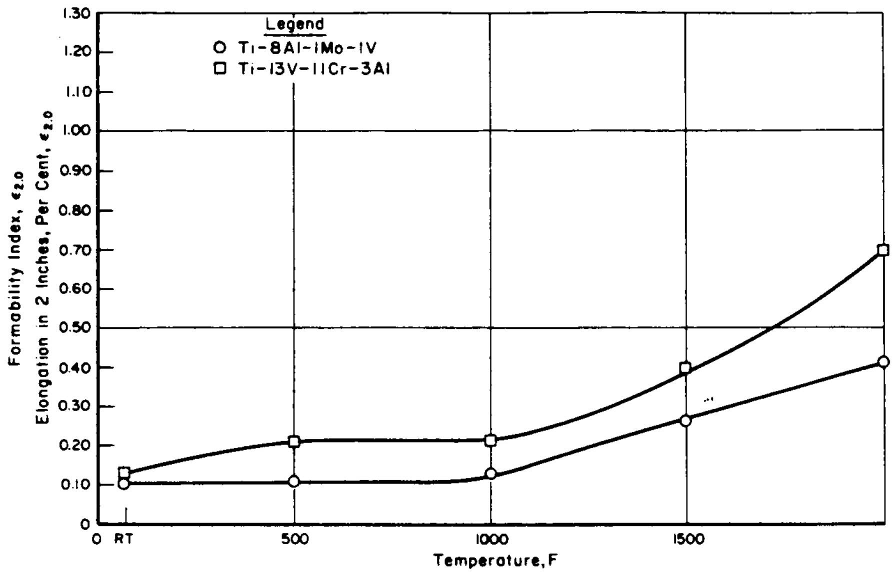


FIGURE 127. RELATIONSHIP BETWEEN ELONGATION AS DETERMINED IN TENSILE TEST AND TEST TEMPERATURE (REF. 52)

These are optimum forming temperature curves for the dimpling, linear-stretch-, sheet-stretch-, and rubber-stretch-flange processes.

Figure 128 shows the theoretical relationship between the H/R ratio and the bend angle, α, for the Ti-13V-11Cr-3Al and the Ti-8Al-1Mo-1V alloys at room temperature, 1200 F, and 2000 F (Ref. 52). The Ti-13V-11Cr-3Al alloy can be more readily formed at all three temperatures than the Ti-8Al-1Mo-1V alloy. Good parts can be formed for values under the curves, while split parts can be expected for values above the curves. The major failure in dimpling is caused by simple tension (Ref. 52).

Table XLIII gives dimpling limits for radial splitting at the edge of the hole for two titanium alloys dimpled at room temperature. Bend angles above and below the standard 40-degree angle are given. Other conditions of heat treatment and dimpling at elevated temperatures would necessitate the use of dimpling limits other than those given in Table XLI.

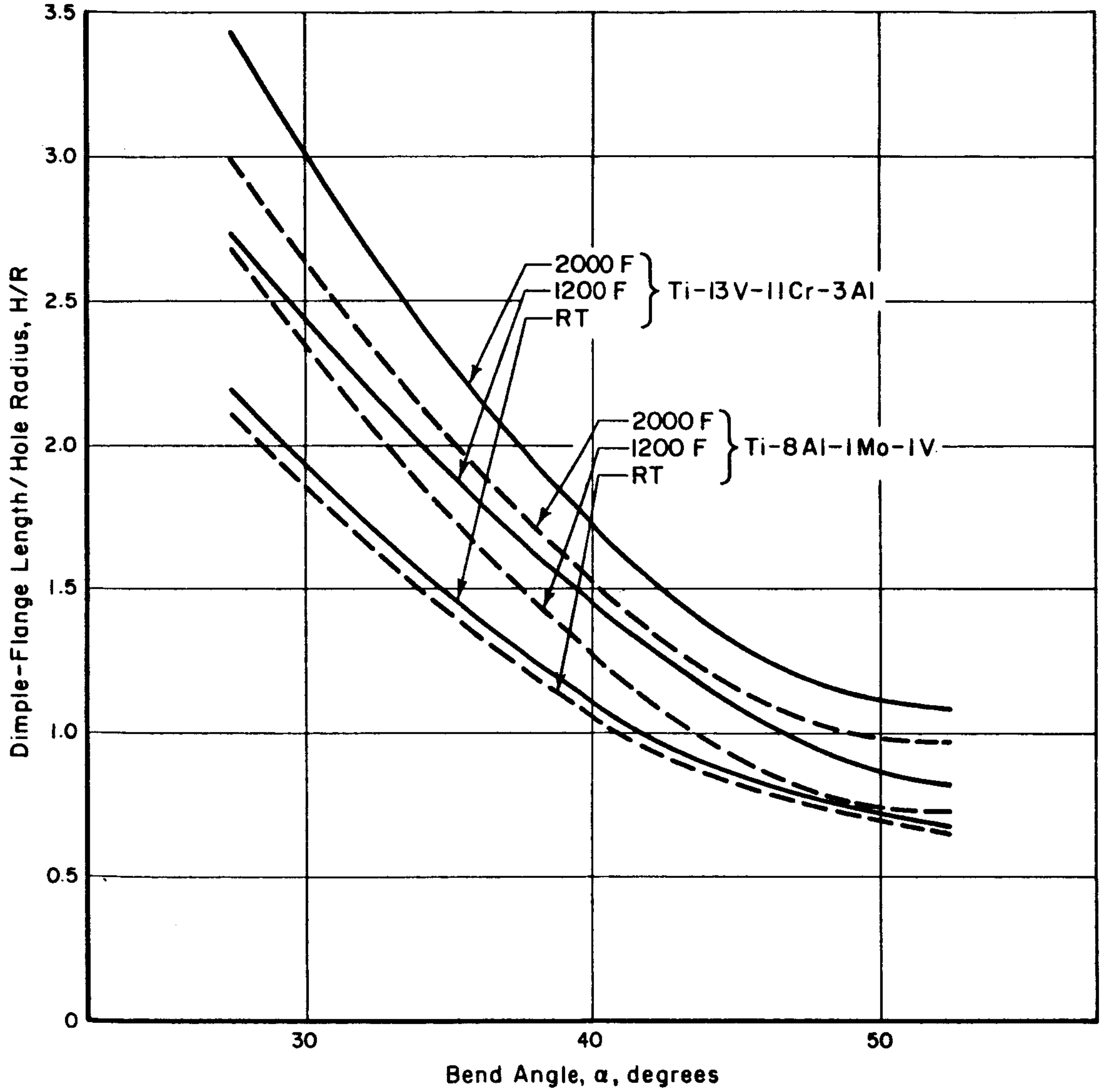


FIGURE 128. THEORETICAL RELATIONSHIP BETWEEN RATIO H/R AND BEND ANGLE FOR THE DIMPLING OF TWO TITANIUM ALLOYS (REF. 52)

TABLE XLIII. DIMPLING LIMITS (REFS. 52, 59)

Radial Splitting at Edge of Hole.

Material	Condition	Dimpling Temperature, F	Dimpling Limits, H/R For Various Bend Angles, α, Above and Below Standard Bend Angle				
			30°	35°	40° (Standard)	45°	50°
Ti-6Al-4V	Mill annealed	RT	2.00	1.5	1.17	0.92	0.74
Ti-13V-11Cr-3Al	Aged 900 F	RT	1.58	1.17	0.91	0.73	0.60
Ti-8Mn-1Mo-1V	Duplex annealed	RT	1.88	1.42	1.08	0.82	0.70
Ti-13V-11Cr-3Al	Solution annealed	1200	2.58	1.95	1.48	1.15	0.96
Ti-8Mn-1Mo-1V	Duplex annealed	1200	2.30	1.72	1.30	1.00	0.85

The following example may be used to illustrate the use of these data:

Problem: Determine the maximum length of dimple flange, H_{max}, for the Ti-6Al-4V alloy in the mill-annealed condition at room temperature using a hole radius of 1/4 inch and a bend angle of 40 degrees.

From the table $H_{max}/R = 1.17$

$$H_{max} = 1.17 \times 0.250 = 0.293 \text{ inch.}$$

Dimpling Temperatures. The temperatures in Table XLIV are suggested for dimpling commercially pure titanium sheet and also sheet of several titanium alloys. Dimpling, under certain conditions, can be done at somewhat lower temperatures, but the springback will be greater and more erratic, higher forming pressures will be needed, and the possibility of failure by cracking is greatly increased.

In dimpling applications, the temperature to which the sheet is heated (by resistance) prior to dimpling is a function of the dwell time, which is the time of contact between the heated dies and the sheet before dimpling (Ref. 50). The dwell time required to insure the correct dimpling temperature can be determined from test strips or coupons of the same sheet to be dimpled. The sheet is painted around the pilot hole with temperature-indicating lacquers or paints having the desired melting temperature. The test piece is clamped between the heated die and punch and held until the temperature-indicating material melts, noting the time that elapsed between the

TABLE XLIV. SUGGESTED TEMPERATURES FOR HOT DIMPLING TITANIUM AND ITS ALLOYS

Alloy	Condition	Temperature, F	Reference	Remarks
Commercially pure		500-600	50	
Ti-8Mn		725-775	50	0.025 to 0.091-inch-thick sheet
Ti-8Al-1Mo-1V		750	114	0.022 to 0.063-inch-thick sheet
Ti-6Al-4V	Mill annealed	900	53	
		1300-1350	96	
Ti-5Al-2.5Sn		1600-1800	96	
Ti-4Al-3Mo-1V	Annealed (ST)	>1000	99	
	Aged (STA)	>1000	99	Special tooling required; maximum thickness, 0.045 inch
Ti-4Al-3Mo-1V	Aged	1300-1350	115	Zephyr process
Ti-2Al-6Mo-2V		1200-1250	96	
Ti-2.5Al-16V		600-800	55	
Ti-13V-11Cr-3Al	Aged, 900 F	900	53	
Ti-5Al-2.75Cr-1.25Fe	Solution heat treated	600	55	
	Aged	1200	116	
Ti-13V-11Cr-3Al	Solution heat treated	600	55	

clamping in the die and the melting of the Tempilaq*. This time is the required dwell time.

To avoid stress-corrosion cracking, it is important that temperature-indicating paints not be used on production parts. All traces of the temperature-indicating material must be removed from the punch and die before proceeding to dimple on a production basis.

The proper dwell time is variable and depends on the ambient temperature, the size of fastener, and the type and thickness of material to be dimpled. Reference 50 gives dwell-time settings for a particular machine for various size fastener holes in several thicknesses of sheet for both commercially pure titanium and the Ti-8Mn alloy. Such data can only be used as a guide, and dwell times for a production setup must nearly always be determined experimentally or based on the operations experience with other sheet having similar hole diameter and thickness.

Post-Dimpling Treatments. Normally titanium sheet is dimpled in the condition in which it is to be utilized. Therefore, no post-dimpling heat treatment is required. Also, if properly performed, the sheet will not warp or deform during dimpling, and straightening or flattening of the sheet is not generally required.

Flash occurring at the edges of the dimple is common for all types of dimpling. It generally is removed after dimpling by drilling or reaming.

Properties of Dimpled Titanium. Since titanium-alloy sheet generally must be dimpled in the condition of heat treatment in which the sheet is to be used, it does not appear unlikely that the properties in the vicinity of the sheet contacted by the heated-dimpling dies might be somewhat altered. Results of microhardness surveys performed at Chance Vought Aircraft, Inc. (Ref. 99), on the cross sections of two dimples made in sheet ranging from 0.020 to 0.063 inch thick of the Ti-4Al-3Mo-1V alloy both in the annealed condition are shown in Table XLV. These data represent dimples made by two organizations. The dimpling performed at Zephyr Manufacturing Company obviously was done at a higher temperature than that performed at Aircraft Tool Manufacturing Company, as was evident from the lower hardnesses determined in the dimple radius and base and also from the relative coloration of the sheet adjacent to the dimples. The

*Tempil Corporation, New York, New York.

TABLE XLV. RESULTS OF MICROHARDNESS SURVEYS ON DIMPLES FORMED BY TWO COMPANIES ON ANNEALED Ti-4Mn-3Mo-1V TITANIUM ALLOY (REF. 99)

	Formed by Aircraft Tool Manufacturing Company (Temp, >1000 F)														
	0.020-Inch Thickness					0.040-Inch Thickness					0.063-Inch Thickness				
DPN values for parent metal	344	330	339	317	Avg 332	370	370	370	364	Avg 368	354	385	359	344	Avg 360
	348	321	313	339	Avg 330	354	354	380	349	Avg 359	364	374	359	354	Avg 363
	344	325	317	317	Avg 326	364	344	364	344	Avg 354	354	385	359	344	Avg 360
DPN values for dimple radius	344	317	309	325	Avg 324	359	344	354	344	Avg 350	354	354	364	339	Avg 353
	344	317	325	313	Avg 325	359	339	344	330	Avg 343	344	344	364	334	Avg 347
	339	309	309	289	Avg 311	344	339	344	330	Avg 339	354	349	354	334	Avg 348
DPN values for dimple base	330	317	317	305	Avg 317	344	344	354	344	Avg 346	359	364	364	349	Avg 359
	293	313	313	297	Avg 304	349	339	349	344	Avg 345	369	354	359	344	Avg 356
	313	321	309	289	Avg 308	354	354	349	349	Avg 341	321	349	369	349	Avg 347
	Formed by Zephyr Manufacturing Company (Temp, about 1000 F)														
	0.020-Inch Thickness					0.032-Inch Thickness					0.040-Inch Thickness				
DPN values for parent metal	344	354	364	359	Avg 355	380	385	364	354	Avg 371	364	385	391	385	Avg 381
	349	349	354	344	Avg 349	391	380	374	354	Avg 375	364	374	385	380	Avg 376
	344	354	354	349	Avg 350	380	385	364	354	Avg 371	364	385	374	398	Avg 380
DPN values for dimple radius	349	344	334	359	Avg 346	364	369	354	321	Avg 352	369	334	354	364	Avg 355
	286	286	289	282	Avg 286	304	313	286	309	Avg 303	321	325	321	317	Avg 321
	330	330	325	301	Avg 322	330	335	334	309	Avg 327	325	334	334	339	Avg 333
DPN values for dimple base	325	344	321	321	Avg 328	334	344	321	317	Avg 329	325	334	325	354	Avg 334
	317	335	349	335	Avg 334	344	330	325	317	Avg 329	334	330	334	344	Avg 336
	325	344	325	317	Avg 328	339	309	334	330	Avg 328	334	325	334	334	Avg 332

decreased hardness amounts to a reduction in tensile strength estimated to be about 16,000 psi for the Aircraft Tool dimpled sheet and 32,000 psi for alloy dimpled at Zephyr. However, the sheet dimpled at the lower temperature at Aircraft Tool Manufacturing Company warped badly causing the dimpled holes to be misaligned, while that dimpled at the higher temperature at Zephyr Manufacturing Company showed negligible warping. This would appear to be justification for using the higher dimpling temperature (about 1000).

It appears likely that sheet heat treated to higher strength levels would show a greater reduction in strength in the vicinity of the dimple as a result of hot dimpling than that in the softer, annealed condition. No actual strength data comparisons have been found in the literature.

Workers at McDonnel Aircraft (Ref. 114) report that no loss in strength resulted when the failure loads of tensile-strip specimens, successfully dimpled at 750 F, were compared with loads required to fail specimens of the Ti-8Al-1Mo-1V alloy with only pilot holes drilled in their centers. These results are shown in Table XLVI.

TABLE XLVI. FAILING LOADS OF DIMPLED TENSILE-TEST STRIPS (REFS. 59, 114)

Type Specimen	Specimen	Ultimate Load, lb
Drilled only for 3/32 AD rivets in 0.022-in. Ti-8Al-1Mo-1V	1	2750
	2	2770
	3	2815
		Avg 2780
Dimpled for 3/32 AD rivets; temp range 900 to 950 F; dwell time 15 sec in 0.022-in. Ti-8Al-1Mo-1V	4	2800
	5	2780
	6	2775
		Avg 2785
Drilled only for 5/32 Hi-Shear rivets in 0.063-in. Ti-8Al-1Mo-1V	7	8400
	8	8470
	9	8500
		Avg 8460
Dimpled for 5/32 hi-shear rivets; temp range 900 to 950 F; dwell time 15 sec in 0.063-in. Ti-8Al-1Mo-1V	10	8540
	11	8520
	12	8440
		Avg 8500

Future Use of Dimpling for Titanium. It appears likely that as increased amounts of titanium and its alloys are used in subsonic aircraft much more use will be made of dimpling as a recess for fasteners. However, the aircraft in which titanium is being considered for use includes the proposed supersonic transport. This plane will be designed to fly at speeds faster than that of sound. Parts of this and other future planes probably will include skins of titanium alloys welded to bulkheads. The welding of skins is less costly and avoids some of the problems met in using mechanical fasteners. Therefore, the use of skins welded to bulkheads instead of fastened mechanically appears to be a distinct possibility for these supersonic applications.

JOGGLING

Introduction. A joggle is an offset in a flat plane produced by two parallel bends, in opposite directions, at the same angle. Joggling permits flush connections to be made between sheets, plates, or structural sections. The bend angle for joggles is usually less than 45 degrees, as indicated in Figure 129. Because the bends are close together, the same flange will contain shrunk and stretched regions in close proximity to each other. The two types of deformation tend to compensate for each other.

Equipment. Joggles may be formed either in straight or curved sheet-metal titanium sections by a variety of techniques. Drop hammers or power brakes with special joggle dies and presses are often employed. Hydraulic presses are preferred for joggling at elevated temperatures because they simplify control of pressure and dwell time. The joggles usually are formed either by a wiping action or a section movement, as shown in Figure 130.

Tooling. Joggling of titanium often is done at elevated temperatures. Tool steels are limited to service temperatures below approximately 1200 F. For higher temperatures, tooling constructed from high-strength, heat-resistant alloys or ceramic materials must be used.

Figure 131 is a photograph of a hot joggle die used in a preliminary study at Convair to establish joggle parameters (Ref. 55). The joggle pad holder is made from hot-rolled steel. The Meehanite joggle pads (four in number) have four electric cartridge heaters. The pads have varying radii to accommodate different thicknesses of metal. The die set can be used for temperatures up to 1400 F and is

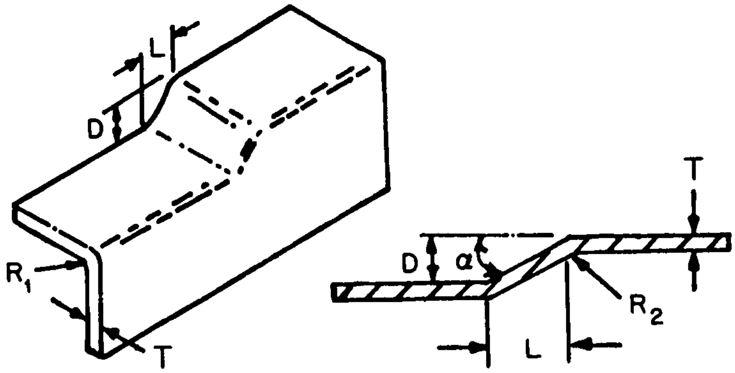
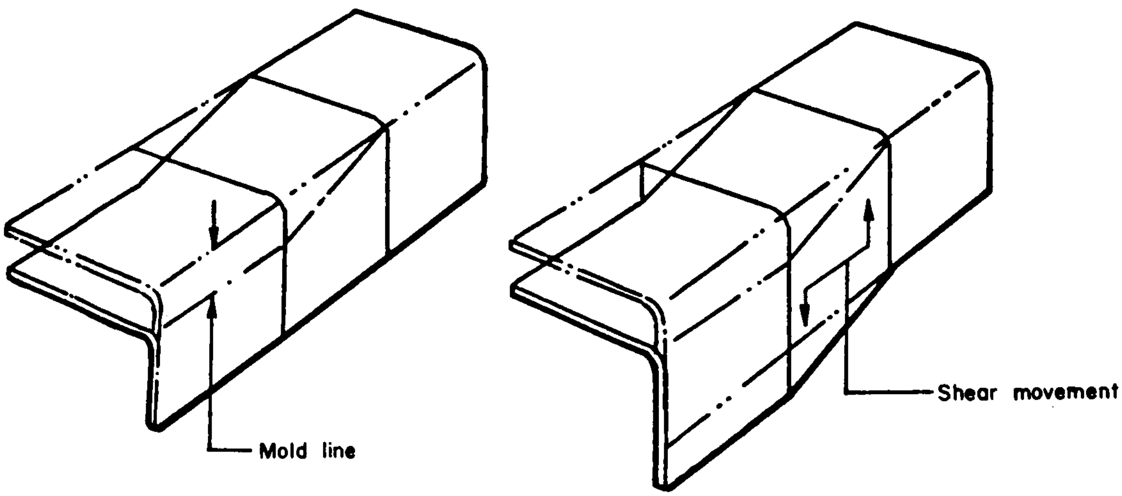


FIGURE 129. JOGGLE IN AN ANGLE (REF. 53)

α = joggle-bend angle
D = joggle depth
L = joggle length or runout
T = thickness of workpiece
R_1 = radius on joggling block
R_2 = radius of bend on leading edge of joggle block.



a. Wipe Joggling

b. Section Joggling

FIGURE 130. BASIC METHODS OF FORMING JOGGLES (REF. 53)

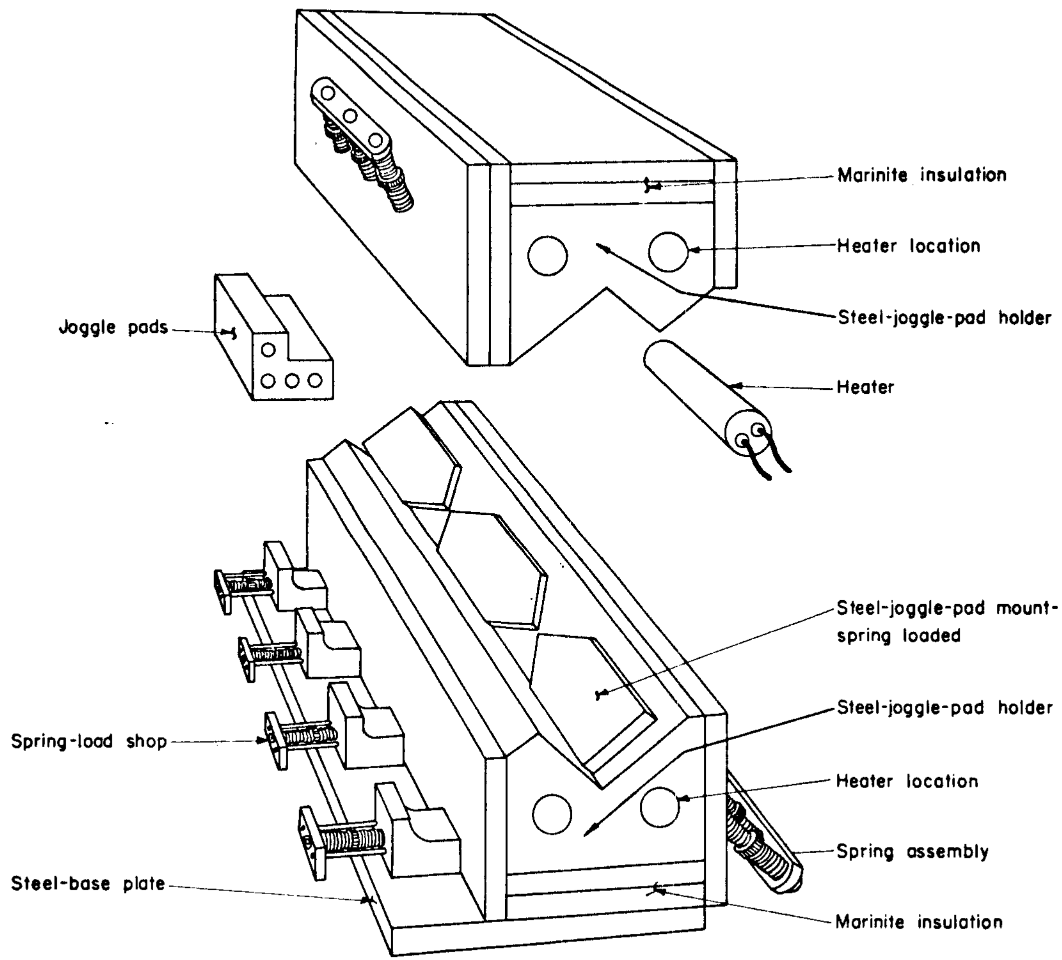


FIGURE 131. JOGGLE-DIE SET DESIGNED TO OPERATE UP TO 1400 F (REF. 55)

thermocouple controlled to ±25 F. Tests using this die were conducted at 1100 F. This study indicated that joggles with two titanium alloys could also be made satisfactorily at room temperature. Hardened tooling is recommended for room-temperature joggling.

A schematic drawing of the "universal" joggle dies used by Wood, et al. (Ref. 53), in their studies is shown in Figure 132. This type of tooling requires an additional hydraulic cylinder to apply horizontal forces to clamp the side of the angle specimen to the die. A sketch showing details and operating principles of a universal joggle die is shown in Figure 133 (Ref. 61). Suitable shims are added to the die to produce the shape desired in the part. Figure 134 shows a mated "V" joggle die.

Mating dies were used successfully by Handova (Ref. 56) to produce a joggle in an 0.063-inch-thick sheet of the Ti-3.25Mn-2.5Al alloy. The die contained a 62.5 per cent springback allowance, the joggle in the die being 0.130 inch deep to produce an 0.080-inch-deep joggle in the titanium alloy "U" section. The construction of the die provided full support to the web- and cap-bend radii of the channels at all times during the forming operation. The die was heated to 1000 F, the sheet samples inserted, and the mating die or ram was then closed and held for 3 to 5 minutes. The temperature of the die was determined to be about 850 F at the start of the dwell cycle and about 450 to 500 F when the pressure was released.

Heating Methods. Four methods are used for heating dies and/or sheet stock for joggling (Ref. 59). They are integrally heated dies, radiant heating, resistance heating, and gas-torch heating. Gas-torch heating is a good, inexpensive way to heat dies to the forming temperature. Rather than preheating them, thin workpieces are often heated by contact with hot tools.

The use of cartridge-type heaters for the heating of joggle dies is illustrated in Figure 131 (Ref. 55). The self-contained cartridge-type heaters are inserted into the joggle-die set. Close temperature control is possible with this heating method. Sometimes both the sheet and the dies are heated by radiation; quartz lamps have been used for this purpose.

Material Preparation. Precautions covered in the section on blank preparation apply to the preparation of sheet for joggling. Surface imperfections such as scratches and file marks must be avoided.

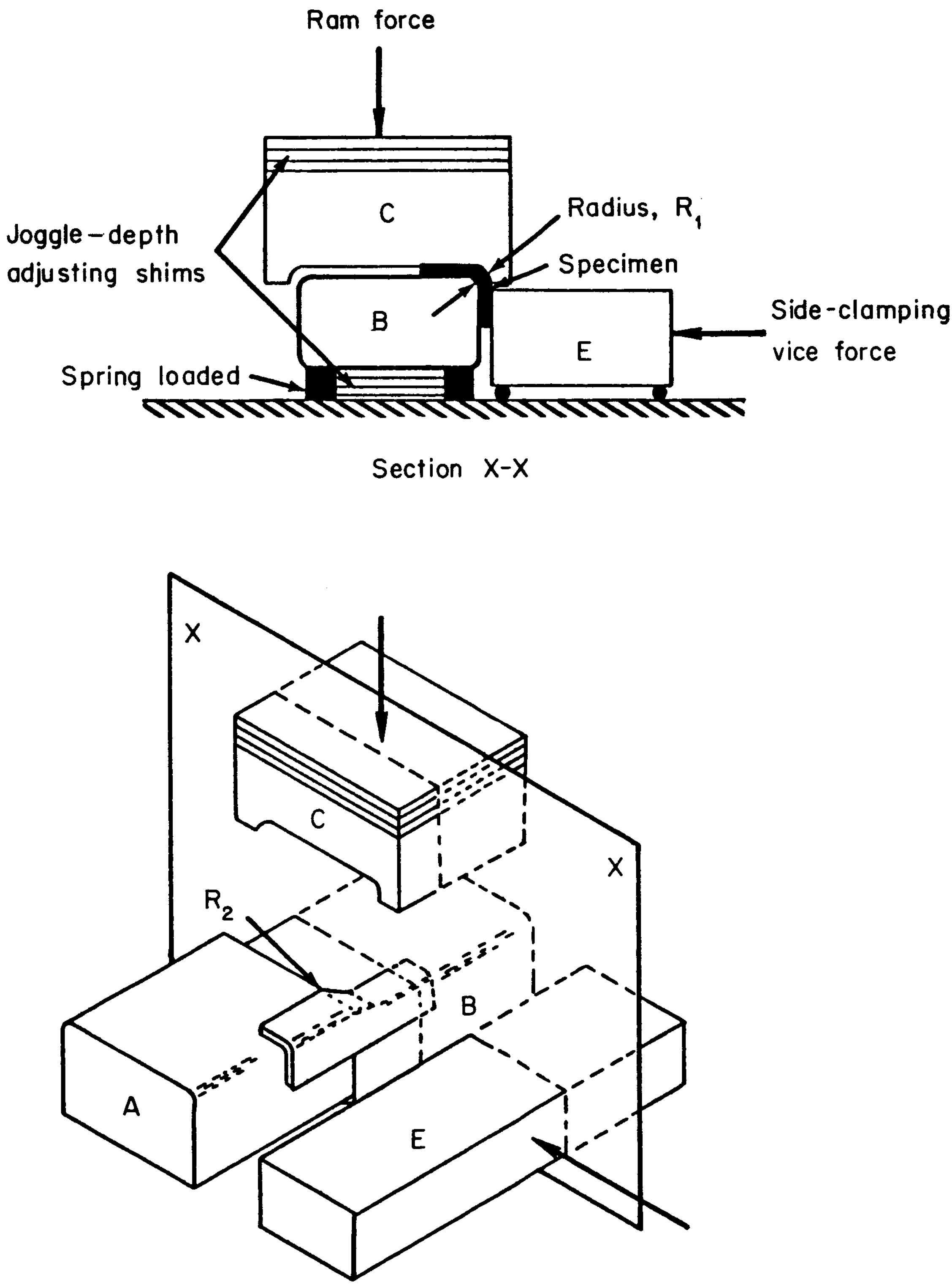


FIGURE 132. SCHEMATIC OF JOGGLE DIES (REF. 53)

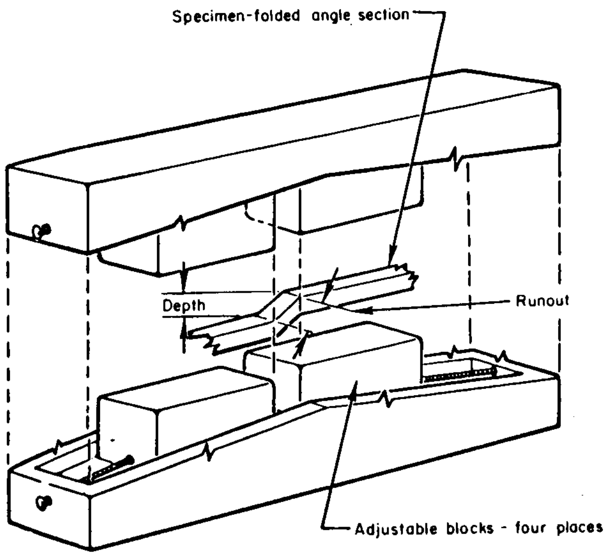


FIGURE 133. UNIVERSAL JOGGLE DIE (REF. 61)

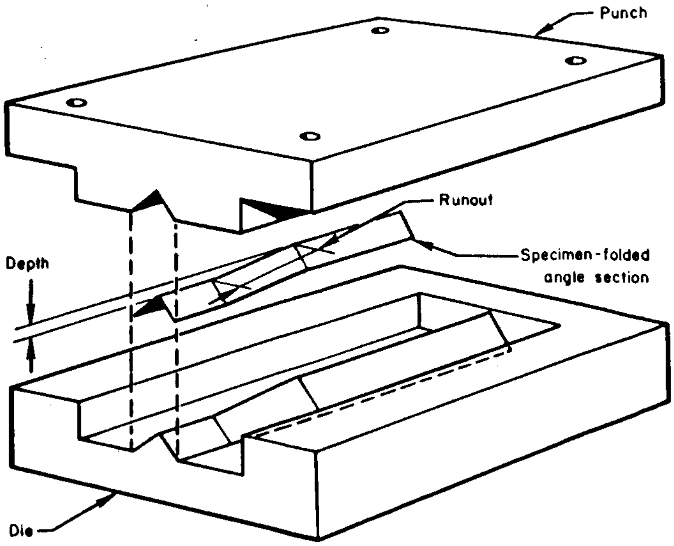


FIGURE 134. MATED "V" JOGGLE DIE (REF. 61)

Blanks for joggling should be protected by interleaving with paper or cardboard to minimize scratching of the sheet surfaces during handling.

Lubricants. Lubricants are generally used in the production joggling of titanium sheet metal. Test performed at North American Aviation (Ref. 56), however, were made at temperatures ranging from that of the room to 1125 F without the use of lubrication. A variety of experimental alloys were tested as part of this program. Lubricants containing flake or powdered graphite have been used for joggling at 850 F. One such commercial product is Dag-41, which was used successfully for joggling the Ti-8Mn alloy (Ref. 117) at 850 F. Lubricants containing molybdenum disulfide also are used for joggling and other metal-forming operations, especially those performed at elevated temperatures. Mineral oil and other oil bases containing various additives are used at room temperature.

Joggling Limits. Wood and his associates (Ref. 53) conducted an extensive study on joggling that included experiments on two titanium alloys. Their data permitted relationships to be established between the properties of the workpiece and the formability limits in joggling. Figure 135 shows schematically the effects of geometry on failure or success in joggling. The common types of buckling and splitting failures are illustrated in Figure 136. Formability charts of the type shown in Figure 135 can be constructed from a knowledge of the properties of the material and joggling geometry by the five following equations (Ref. 53).

The equation for the splitting limit of any material based on its mechanical properties is

$$\frac{D}{L} = \left[\epsilon_{0.02} (1.44\,\epsilon_{0.02} + 2.4)\right]^{1/2} . \tag{35}$$

The equation for the elastic buckling limit line is

$$\frac{D}{L} = \frac{E}{S_{cy}} \left[\frac{0.0050625}{\left(\frac{D}{T}\right)^2}\right] . \tag{36}$$

The equation for the elastoplastic-buckling-limit line is

$$\frac{D}{T} = \left[0.0118 \frac{E}{S_{cy}}\right]^{2/5} . \tag{37}$$

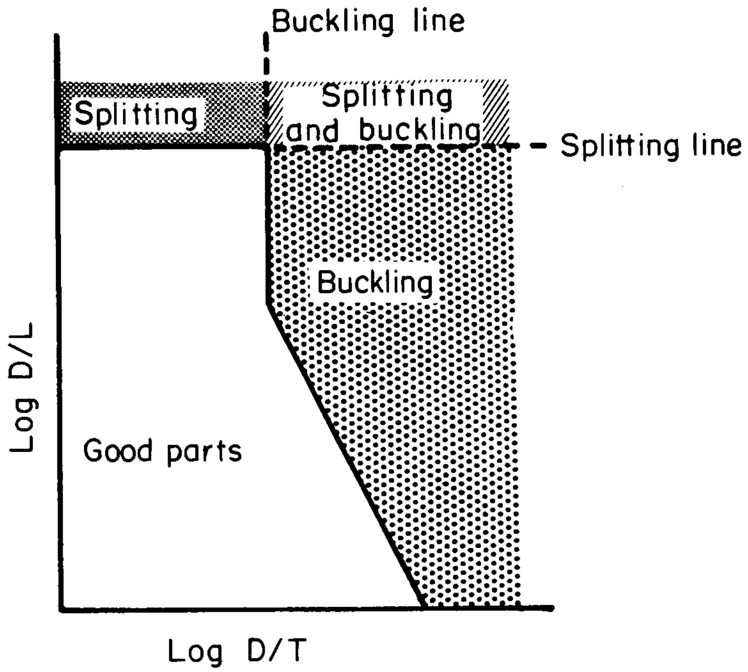


FIGURE 135. EFFECT OF GEOMETRY ON SUCCESS OR FAILURE IN JOGGLING (REF. 53)

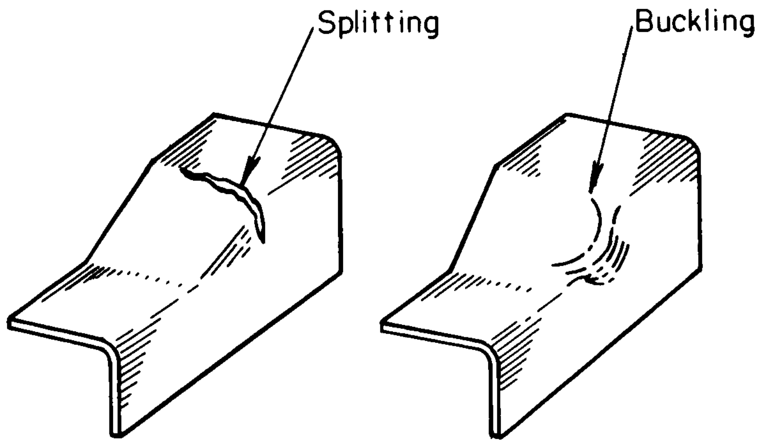


FIGURE 136. MAJOR JOGGLING FAILURES (REF. 59)

The equation for the inflection line is as follows. This line is at a slope of (+1/2) and crosses the D/L axis at 0.43.

$$\frac{D}{L} = 0.43\sqrt{\frac{D}{T}} \quad . \tag{38}$$

The equation for finding the intersection of the elastoplastic- and elastic-buckling-limit line at a point on the inflection line is

$$\frac{D}{T} = \left[0.0118 \frac{E}{S_{cy}}\right]^{2/5} \quad . \tag{39}$$

The buckling-formability index line runs vertically upward from the D/T intercept 2.25.

The terms D, L, and T defining the geometry of the joggle are illustrated in Figure 129. The mechanical properties of the work-piece needed for solving the equations are:

E = Young's modulus of elasticity

S_{cy} = yield strength in compression based on the original cross-sectional area

$\epsilon_{0.02}$ = conventional strain to rupture measured on a 0.02-inch gage length.

Although values of $\epsilon_{0.02}$ are not commonly reported, they can be determined by special tests. If the mechanical properties are known, Equations 35 through 39 can be used to construct joggling limits by following the procedures indicated in Figure 137. Limits determined in that way for the Ti-13V-11Cr-3Al alloy are given in Table XLVII. The data are for joggling under conditions where $R_1 = 6T$, and $R_2 =$ 0.032 inch. (Figure 129 shows radii of interest.)

Another empirical approach that may be used to choose joggle dimensions is described in a North American Aviation Specification (Ref. 118). The length or runout, L, of the joggle, shown in Figure 129, can be determined from the following formulas and the factors A, B, and C given in Table XLVIII.

(1) If the joggle depth is greater than A, the length of the joggle runout equals B times the joggle depth or $L = BD$ (when $D > A$).

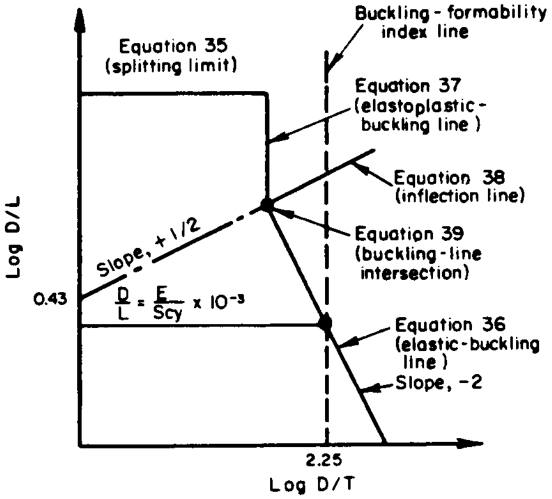


FIGURE 137. TYPICAL JOGGLING-FORMABILITY CURVE (REF. 53)

TABLE XLVII. JOGGLING LIMITS FOR SOLUTION-TREATED Ti-13V-11Cr-3Al ALLOY (REF. 53)

	D/L	Buckling Limit for D/L Indicated[(a)], D/T	Corresponding Ratio, L/T
	0.05	3.55	71
	0.10	2.50	25
	0.20	1.76	9
	0.30	1.45	5
	0.50	1.15	2.3
Splitting limit	0.80		
Critical ratio			1.44

(a) These limits appear to be based on the performance expected for a material with a E/S_{cy} ratio of 208 and an $\epsilon_{0.02}$ value of 0.23.

TABLE XLVIII. FACTORS FOR ROOM-TEMPERATURE JOGGLING OF TITANIUM ALLOYS (REF. 118)

Alloy Thickness[a], inch	Factors for Minimum Bend Radii, R/T[b]	Factors for Minimum Joggle Runout — Joggle Factors[c]		
		A/T	B	C/T
Commercially pure titanium				
Through 0.070	3	0.54	5	14
Over 0.070	3-1/2	0.62	5	16
4Al-3Mo-1V condition ST				
Through 0.080	5-1/2	2.4	3	24
Over 0.080	6	3.6	3	26
5Al-2.5Sn				
Through 0.080	5-1/2	0.92	5	24
Over 0.080	6	1.00	5	26
6Al-4V condition ST	7	0.81	6	30
8Mn				
Through 0.080	4	0.69	5	18
Over 0.080	5	0.85	5	22
13V-11Cr-3Al				
Condition ST	3	1.4	3	14

(a) Condition ST is the solution-treated condition.
(b) To obtain the bend radii, multiply R/T value in the table by material thickness, T.
(c) To obtain A and C, multiply A/T and C/T values by material thickness, T.

(2) If the joggle depth is less than A, the length of the joggle runout is equal to the square root of the joggle depth times the quantity C minus the joggle depth or

$$L = \sqrt{D(C - D)} \quad \text{(when } D < A\text{)}.$$

(3) For joggles in flat sheets, the projected distance between tangents may be determined from the equation for reverse curve as follows:

$$L = \sqrt{D(4R_2 + 2T - D)} \quad \text{(see Figure 129)}.$$

Values recommended for minimum runout and minimum bend radii are given in Table XLVIII for commercially pure titanium and a number of titanium alloys.

Work at Convair (San Diego) (Ref. 55) has also been concerned with establishing practical joggling parameters for a number of titanium alloys. These data for four alloys are summarized in Table XLIX. Springback of the Ti-2.5Al-16V alloy at the minimum joggle length was 10 to 15 per cent greater than that of the Ti-4Al-3Mo-1V alloy. The minimum joggle length of the all-beta alloy (Ti-13V-11Cr-3Al) is roughly half that determined for the Ti-4Al-3Mo-1V and the Ti-2.5Al-16V alloys for sheet up to about 0.063 inch in thickness. For 0.090-inch-thick sheet, the minimum radii are very nearly equal.

Figure 138 is a composite of joggle data on three of the titanium alloys in which the joggle depth is plotted against joggle length for three titanium alloys (Ref. 55). A direct comparison among the three alloys can be made for the 0.063-inch-thick sheet joggled at room temperature. For a joggle depth of 0.080 inch, the following joggle lengths are shown in Figure 138:

Alloy	L	D	L/D
Ti-4Al-3Mo-1V	0.296	0.08	3.70
Ti-5Al-2.75Cr-1.25Fe	0.188	0.08	2.35
Ti-13V-11Cr-3Al	0.138	0.08	1.72

These data indicate that the Ti-13V-11Cr-3Al alloy is most easily formed and the Ti-4Al-3Mo-1V alloy most difficult of the three alloys to form. This conclusion agrees with other data on the formability of titanium alloys.

TABLE XLIX. SUMMARY OF DATA ON JOGGLING FOUR SOLUTION-TREATED TITANIUM ALLOYS (REFS. 55, 116)

Alloy	Sheet Thickness, T, in.	Temperature, F	Minimum Joggle Length[a], L, in.	Springback at Minimum Joggle Ratio, per cent
Ti-4Al-3Mo-1V	0.040	--	--	35
	0.063	RT	3.5 D	35
	0.090	"	4.25 D	~50
	0.063	600	3.0 D	--
	0.090	600	3.5 D	--
Ti-2.5Al-16V	0.040	RT	--	~45-50
	0.063	"	3.5 D	~45-50
	0.090	"	4.25 D	~60-65
Ti-13V-11Cr-3Al	0.025	RT	1.5 D	13
	0.040	"	1.7 D	32
	0.063	"	1.7 D	40
	0.090	"	3.4 D	50
Ti-5Al-2.75Cr-1.25Fe	0.025	RT	--	32.5
	0.040	"	--	46.8
	0.063	"	--	46.5

(a) D = depth of joggle.

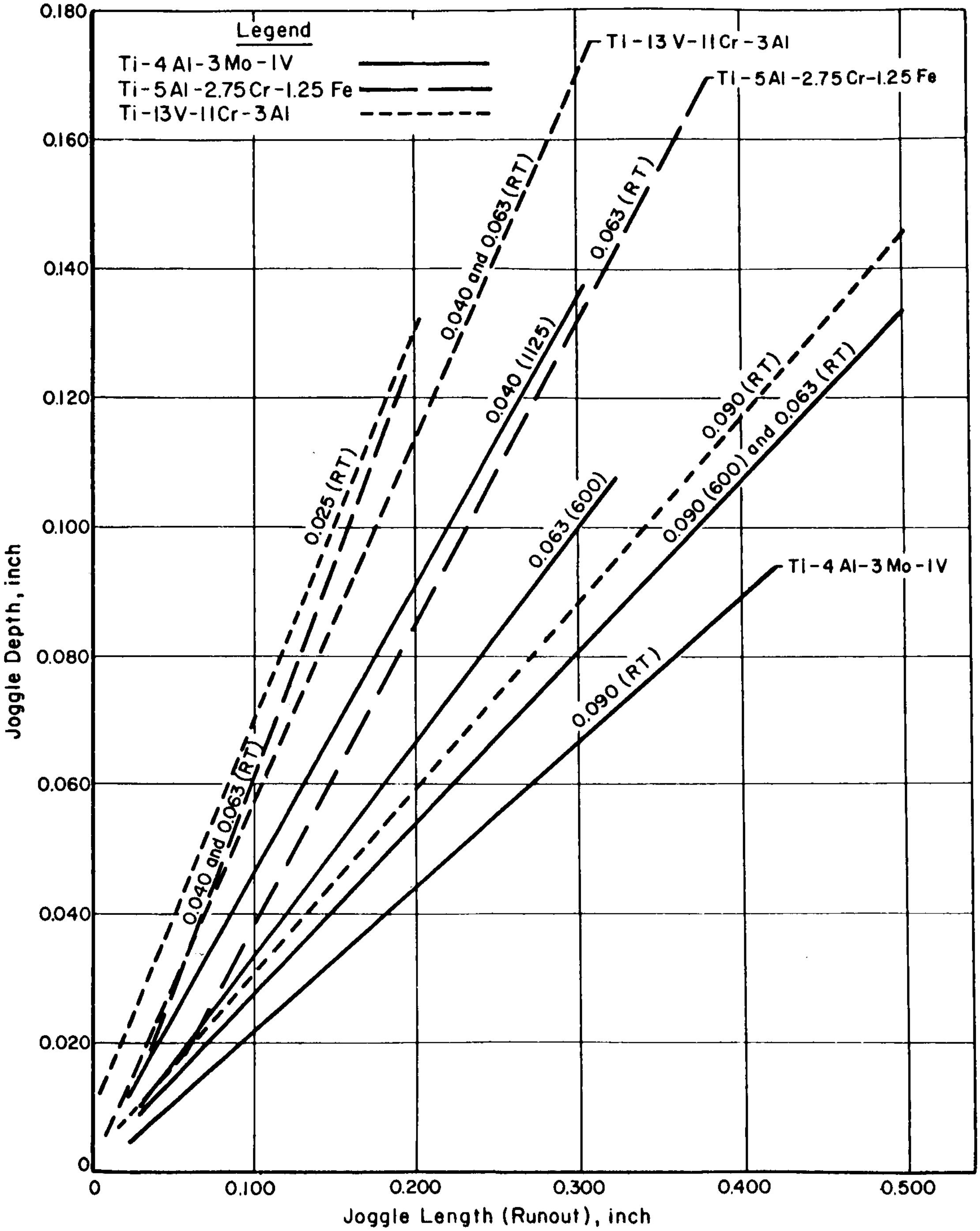


FIGURE 138. JOGGLE RELATIONSHIPS FOR THREE SOLUTION-TREATED TITANIUM ALLOYS (REF. 55)

Other data on the work at Convair indicate that the Ti-2.5Al-16V alloy was much more difficult to joggle than the three alloys listed above. Length-to-depth ratios of 8 and 9 to 1 were required to joggle 0.063-inch-thick sheet using a bend radius of 5.5 T (0.347 inch) and a joggle depth of 2 T (0.126 inch) (Ref. 115). Chem milling of the surfaces prior to joggling permitted joggling over a 5.5 to 7.3 radius at a joggling depth of 3.5 T with a 3 to 1 length-to-depth ratio.

Post-Joggling Treatments. Springback in joggles formed at room temperature or slightly elevated temperatures may exceed 50 per cent. Unless the parts are overbent to compensate for the springback, they usually need to be hot sized to meet dimensional specifications. Specific details on hot sizing are contained in the section on hot sizing.

Joggles produced at elevated temperatures above about 1100 F generally require no further fabrication treatments.

Joggled and formed parts generally cannot be solution heat treated and aged after joggling because they distort excessively during the heat treatment.

It goes without saying that any residual lubricant residue must be thoroughly and completely removed after joggling. If the forming was done at elevated temperature, the surface discoloration can be removed by the usual pickling or etching treatment.

HOT SIZING

Introduction. Hot sizing utilizes the creep-forming principle to produce parts accurately formed to specified dimensions by the controlled application of pressure, temperature, and time. Two methods of hot sizing commonly employed in production are hot-press sizing and hot sizing in fixtures placed in conventional furnaces. In the first method, horizontal and vertical pressures, usually applied by presses, force irregularly shaped parts to assume the desired shape against a heated die. The pressure generally is applied in a vertical direction, the horizontal force resulting from reaction with rigid tooling. The minimum pressure required to form the part from the thickness and alloy should be used. Forces that approach the yield strength of the material at the forming temperature are used.

In the second process, parts are wedged in fixtures to obtain the necessary pressures, and then the assembly is heated in a conventional furnace. This method is simpler and cheaper because expensive hot-sizing presses are not required.

A temperature of 950 F or higher is usually required to hot size titanium alloys. The desired deformation takes place because the sizing temperature lowers the creep strength of the material below the level of the applied stress.

The time required for forming varies with the alloy, thickness of material, and temperature of tooling. Most production operations are regulated to take place between 10 and 30 minutes. After forming or sizing, parts are removed from the die and air cooled. The parts retain the room-temperature shape of the die against which they were formed.

Hot sizing is nearly always necessary for parts cold formed to rough dimensions by brake press, drop hammer, rubber, Hydropress, forming, or deep-drawing processes.

Equipment. A hot-sizing machine consists of two heated platens, one mounted directly over the other. The upper platen is hinged so that it can be opened to expose the lower platen. The upper platen is operated by hydraulically actuated jack rams. The platens are heated either by gas firing or electrical-resistance heating. Figure 139 shows a gas-fired, hot-sizing machine in the open position with the dies in place (Ref. 56). This machine has a maximum operating temperature of 1150 F. The recording temperature controls are shown in the background.

Figure 140 shows an electrically heated hot-sizing press that has a bed 24 feet long by 4 feet wide (Ref. 109). This press is another example of the clam-shell design and consists of six units on a single frame. It can be operated either as a single press to make parts 24 feet long or as six smaller, individual presses. Each unit of the press has its own clam-shell top closure and four hydraulic clamps. Horizontal pressure is applied through hydraulic cylinders located in the rear of the press and not shown in Figure 140. The figure shows three of the individual units in the open position and three closed. The dies are heated by electrically heated platens as is shown schematically in the lower right side of Figure 140. Vertical pressures up to 120 tons are available with each unit, and horizontal cylinders apply side loads up to 75 tons. The presses for each unit are controlled individually. For smaller applications, single-, double-, or triple-unit presses may be installed as the expected operation dictates. Figure 141 shows a smaller electrically heated

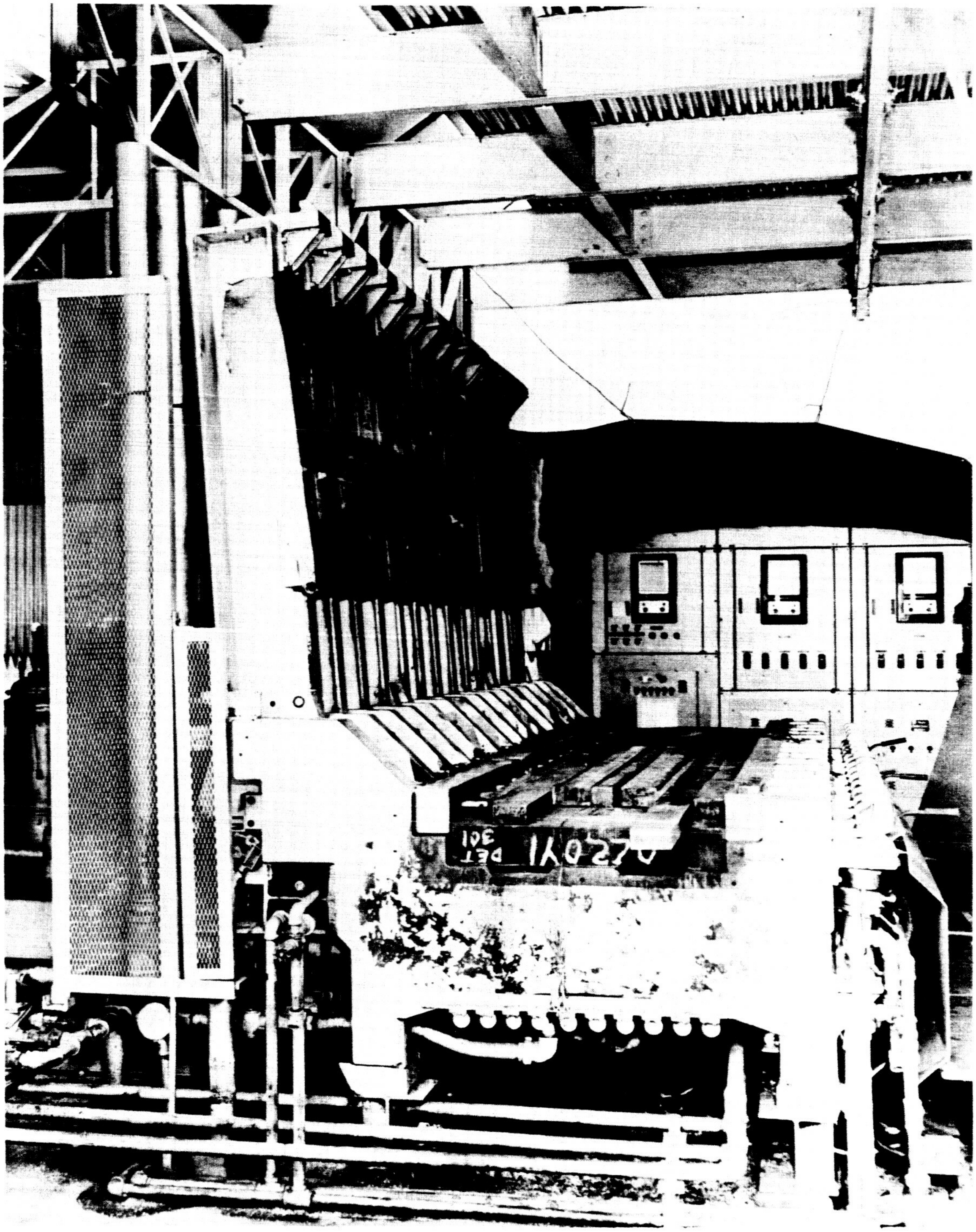
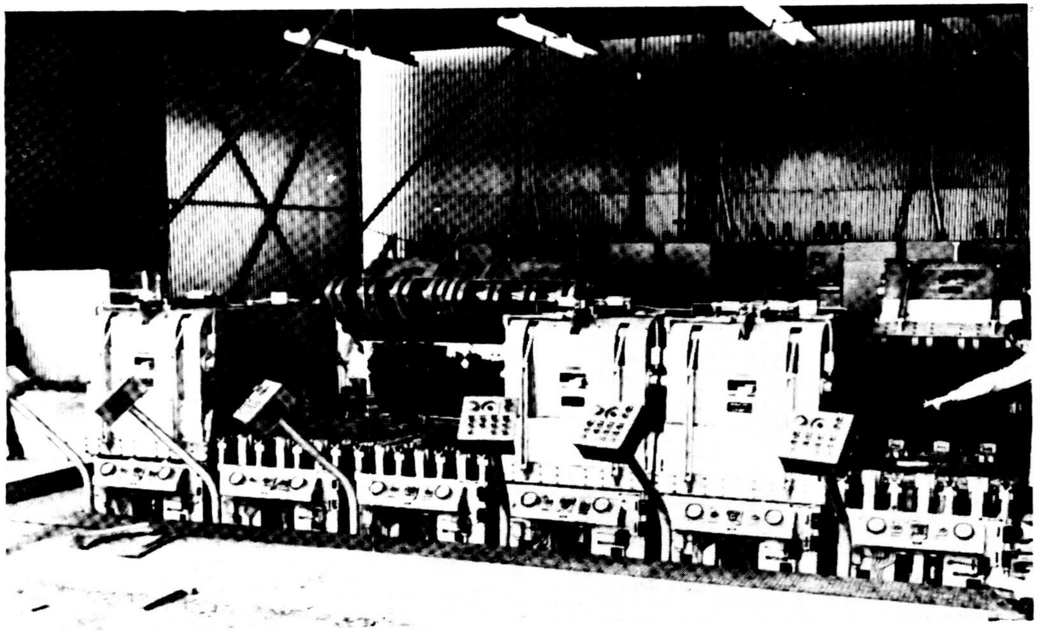
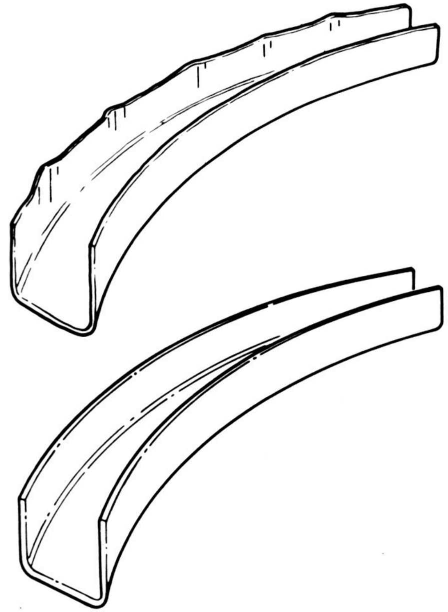


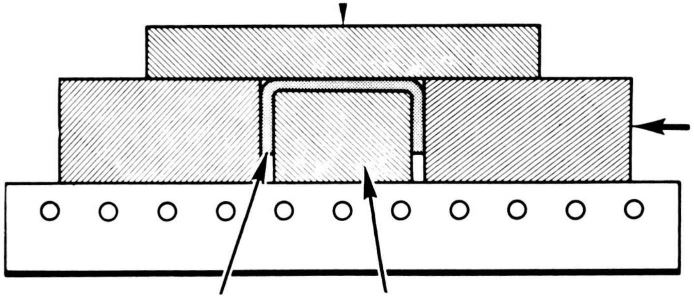
FIGURE 139. HOT-SIZING MACHINE WITH DIES IN PLACE (REF. 56)



Hot-size press



Principle - heat and pressure



Hydraulic cylinder pressure

Electrically heated platen

FIGURE 140. HOT-SIZING PRESS (REF. 109)

FIGURE 141. SHERIDAN HOT-SIZING MACHINE (REF. 101)

hot-sizing machine. This unit is capable of sizing a variety of small shapes in a single press.

No special equipment is necessary for hot sizing with wedge-type fixtures. Tooling can be made that will lock a part into position by driving wedges between retaining rings and dies and then placing the entire assembly in a furnace. Figure 142 shows the principle of design of a number of hot-sizing fixtures (Ref. 109). One of these fixtures contains electrically heated platens and can be used in a conventional arbor press as shown in Figure 142 (lower right corner).

Except for the wedge-type hot-sizing tool for use on an arbor press (see Figure 142), the pressure attainable in wedge sizing is limited and generally can be applied in only one direction.

Tooling. In the selection of tooling materials for hot sizing, the effect of cycling the tools from room temperature up to 1500 F must be considered. Most tool steels will lose their strength at this level, and the application may justify the consideration of superalloys. Tooling materials that soften or distort in service are of little value in sizing operations.

Hot-rolled steel can be used for small production lots, up to about 20 pieces, provided the sizing temperature does not exceed 1000 F. Scaling is a severe problem with these tools (Ref. 55).

Quality-controlled, high-silicon cast-iron (Meehanite) dies can be used for medium-run parts up to 100 pieces at temperatures to 1100 F. Scaling of this material restricts its use at higher temperatures. Wire brushing at intervals of 35 to 50 parts and light sand blasting of the die surface after 100 parts have been formed prevents contamination of the titanium parts during hot sizing.

Greater quantities of parts can be obtained from tooling made of quality-controlled nodular cast iron (high-silicon, nickel, molybdenum nodular cast iron). This material has been used at temperatures up to 1700 F.

Some other die materials that have shown promise for hot sizing are summarized in Table L with their probable limitations.

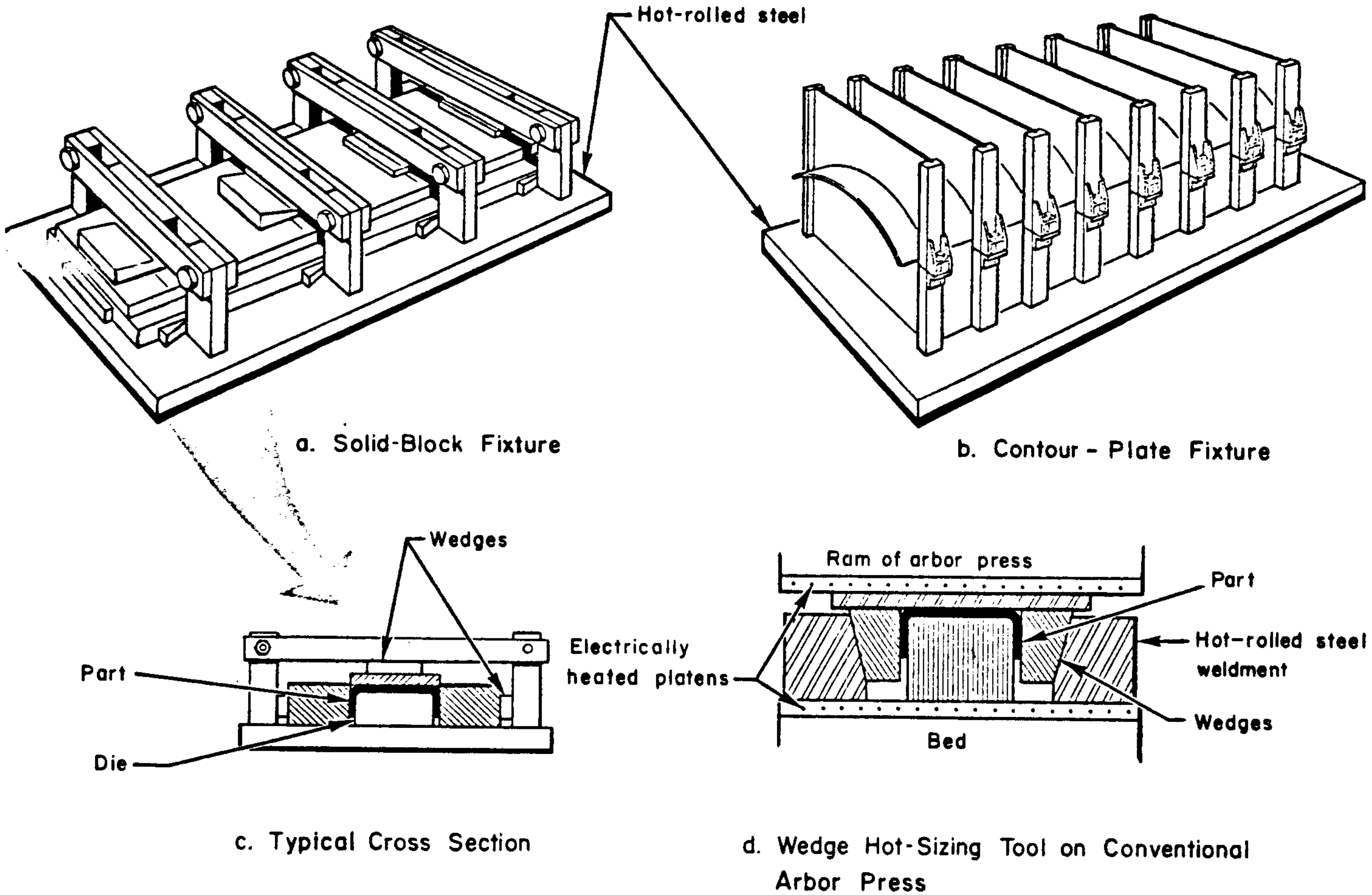


FIGURE 142. HOT-SIZING FIXTURES (REF. 109)

TABLE L. SUMMARY OF TOOLING MATERIALS FOR HOT SIZING (REFS. 55, 99, 119)

Material	Number of Parts	Temperature Limit, F	Remarks
Hot-rolled steel	<20	1000	Not recommended for production tooling because of scale problems
Meehanite[(a)]	<100	1200	Wire brush at intervals of 35 to 50 parts; light sand blast after 100 parts; good resistance to oxidation
Nodular cast iron[(b)]	>100	1700	
Stabilized H13	200	1000	
Type 310 stainless steel	200	1500	
Type RA330 stainless steel	>200	1450	
Inconel	>200	1450	
Hastelloy	>200	1450	
Ceramic[(c)]		>1500	Ceramic dies are covered with stainless steel sheets, 0.050 inch thick
Modified H13[(d)]	>100	1300	Prehardened to R_C 32 to 36.

(a) Meehanite is quality-controlled, high-silicon cast iron.
(b) High-silicon, nickel, molybdenum nodular iron.
(c) Produced by Glasrock Products, Torrance, California.
(d) A chromium, molybdenum, vanadium tool steel produced by Columbia Tool Steel Company, Chicago Heights, Illinois.

The use of ceramic materials for dies is a rather new development. One of these materials is a castable ceramic, and the holes for heater wires are cast into the die (Ref. 109). The ceramic faces of the die are covered with stainless steel sheets about 0.050 inch thick. Face temperatures higher than 1500 F are possible with these tools. The flat titanium sheet is formed between the stainless steel sheets in mating dies. Figure 143 shows such a combination skin form and sizing tool (Ref. 55). The titanium sheet to be bent is laid over the integrally heated die and covered with an overlay sheet that is clamped in place. This unit is a deviation from the standard wedge-type fixtures in that the lighter overlay clamp pieces are used instead of a mating upper die. Skin sections of titanium alloys have been formed by this technique.

Another development that is being considered is the use of ceramic dies for contouring large panels with integral stiffeners in vacuum and argon at very high temperatures (Ref. 109). The heating

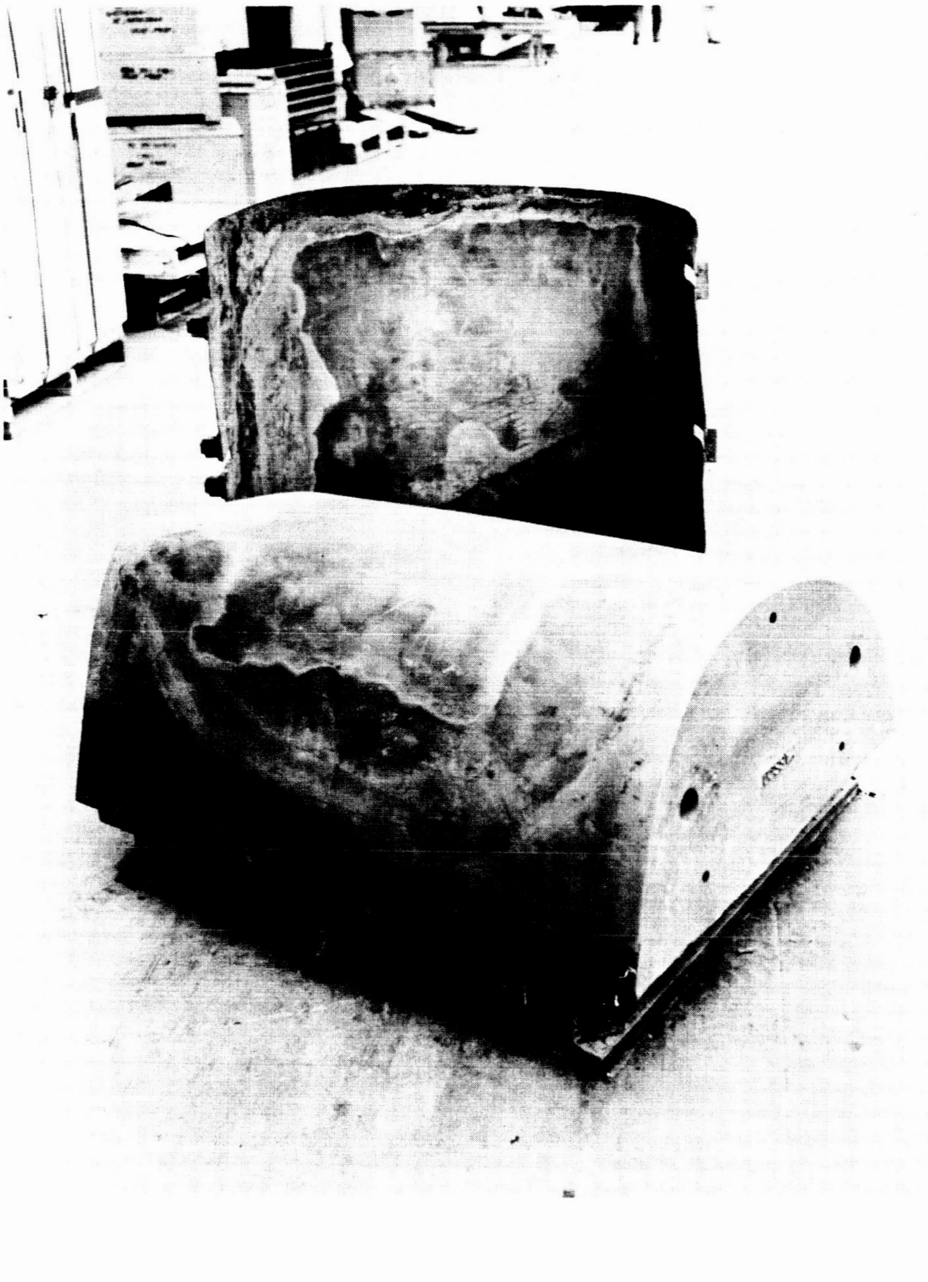


FIGURE 143. COMBINATION SKIN FORM AND SIZING TOOL SHOWING OVERLAY SHEET AND CLAMPS (REF. 55)

wires are buried in the die. This is a proprietary development, and not all of the important details of the process have been disclosed.

Techniques for Hot Sizing.

Material Preparation. It is sometimes necessary to apply a protective coating or lubricant to the surface of the part to aid in forming and reduce oxidation, especially if the hot-sizing temperature is higher than 1000 F. One material that has been used for this purpose is a lubricant, Everlube T-51. Another commercial product used as a lubricant and parting agent at elevated temperatures is Dag-41. Other materials are applied especially to minimize scaling and are used in addition to lubricants.

The usual precautions mentioned in the section on blank preparation concerning edge cracks, nicks, and scratches must be observed also for hot sizing. Surfaces of sections to be sized must be suitably protected to avoid scratches and other defects.

Sizing Conditions. The hot-sizing process is used mainly to correct for springback and warpage in parts that have been formed, usually at room temperature, by other processes. Because of this, no definite forming limits can be given. The removal of springback and warpage in titanium parts resulting from previous forming operations depends on time, temperature, and pressure. In general, the higher the temperature, the shorter the necessary dwell time. The sizing temperature and the time at that temperature are more important than the pressure in hot-sizing parts. Generally, little more than the weight of the dies is necessary to form the part to the final dimensions. The pressure should always be kept as low as possible to prevent deformation to the dies at the sizing temperature.

The relationship between temperature and dwell time is shown graphically in Figure 144 for the creep forming of the Ti-4Al-3Mo-1V alloy in the solution-heat-treated and aged condition (Ref. 99). If a maximum of 20 minutes is chosen as a practical time limit for a production hot-sizing operation, then a forming temperature of 1075 F or higher will be required for this alloy on the basis of these data. Similar curves can be produced for the other titanium alloys.

Table LI gives data on the hot sizing of a number of titanium alloys from several different sources. The lowest reported temperature for sizing is 600 F for 15 minutes for the Ti-16V-2.5Al alloy.

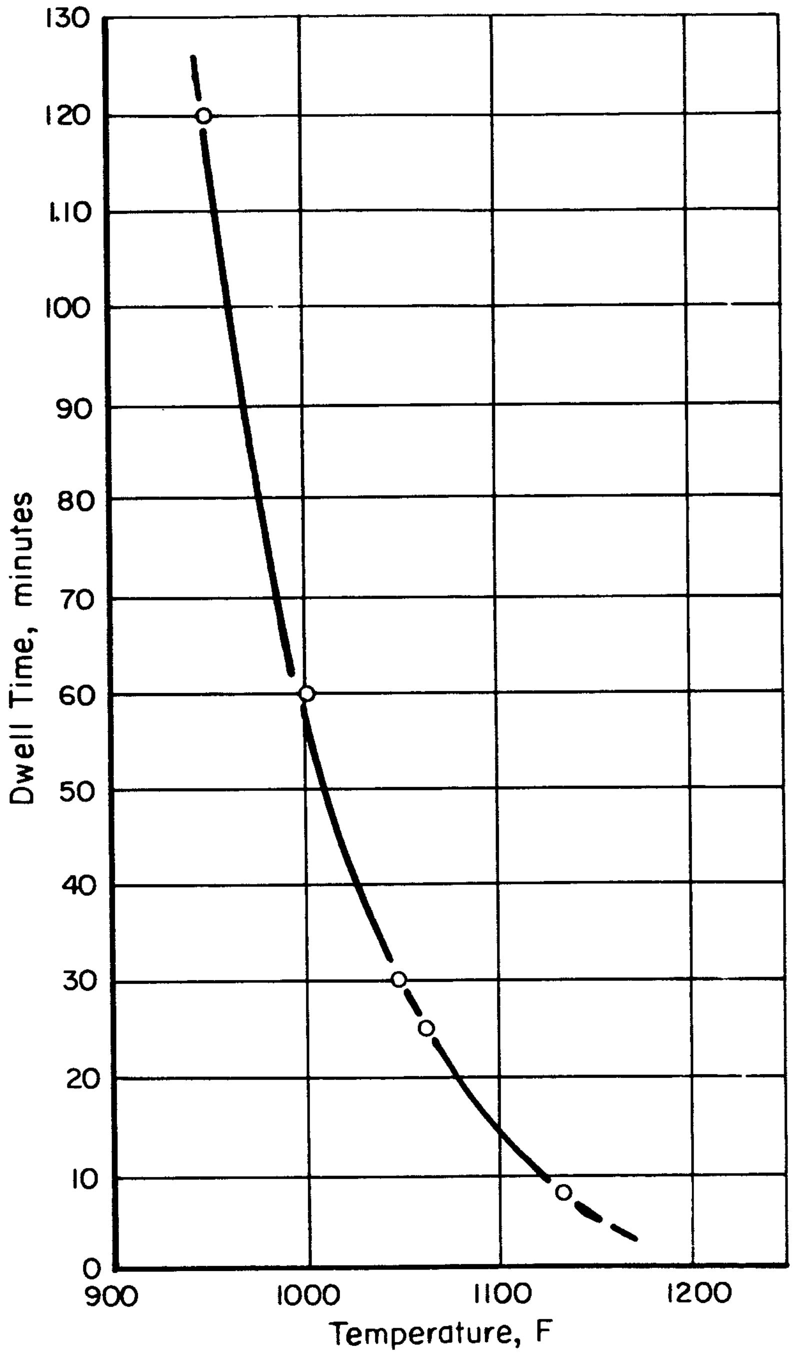


FIGURE 144. TIME AT TEMPERATURE FOR CREEP FORMING SOLUTION-TREATED AND AGED Ti-4Al-3Mo-1V ALLOY (REF. 99)

Each point represents two successfully formed test samples.

The Ti-8Al-1Mo-1V alloy, on the other hand, required sizing at 1450 F for 15 minutes to produce good conformity to the shapes desired.

TABLE LI. SUGGESTED SIZING CONDITIONS FOR A NUMBER OF TITANIUM ALLOYS (REFS. 56, 57, 109, 120, 121)

Alloy	Suggested Sizing Temperature, F	Time at Temperature, min	Remarks
Unalloyed	900-1000	3	Blank heated by contact with heated die
Ti-8Mn	900-1000	3	Blank heated by contact with heated die
Ti-5Al-2.5Sn	1200	15	0.032-in.-thick sheet
	1200	20	0.063-in.-thick sheet
Ti-8Al-1Mo-1V	1450	15	Ceramic dies used
Ti-3.25Mn-2.25Al	1000	3	3000 psi lateral pressure
	950	20	1500 psi lateral pressure
Ti-6Al-4V	1200	3-15	0.032-in.-thick sheet
	1200	3-20	0.063-in.-thick sheet
Ti-16V-2.5Al	600	15	0.040-in.-thick sheet
Ti-4Al-3Mo-1V	1075	20	0.037-in.-thick sheet, solution treated and aged
Ti-13V-11Cr-3Al	1100	(a)	0.065-in.-thick sheet, solution treated; aged after sizing

(a) Time at temperature not stated but presumed to be 10 to 20 minutes.

Table LII gives additional data on hot-sizing temperature and time for unalloyed titanium and five alloys. These data are in general agreement with those given in Table LI. However, Table LII also gives some post-sizing treatments used at North American Aviation (Ref. 109). The data presented in Tables LI and LII are suggested times and temperatures and might vary somewhat for the hot sizing of individual parts.

In operation, hot-sizing presses are kept at a temperature of 1000 F to reduce the possibility of distortion of the platens during heating and cooling. When dies are changed, they are preheated to the forming temperature before being placed on the hot platens to minimize thermal shock. Dies and platens are insulated along the sides to prevent excessive heat loss. The dies are maintained at the desired temperature by heat transfer from the platens and controlled by thermocouples in the platens.

Post-Sizing Treatments. Parts generally must be trimmed and deburred after sizing, and often some hand finishing is required. Parts made from non-heat-treatable alloys such as unalloyed titanium,

TABLE LII. SUGGESTED HOT-SIZING CONDITIONS FOR SELECTED TITANIUM ALLOYS (REF. 109)

Specimens heated in air atmospheres and air cooled.

Alloy	As Received Condition	Hot-Sizing Conditions			Post-Sizing Treatment		
			Time, min	Temperature, F	Treatment	Time, hr	Temperature, F
		Non-Heat-Treatable Alloys					
Titanium (unalloyed)	Annealed	Max	60	1200	Stress relief	1/2	1000
		Typical	10	1100	Ditto	1/2	1000
Ti-8Mn	"	Max	120	1050	"	1/2	1000
		Typical	10	1000	"	1/2	1000
Ti-5Al-2.5Sn[(a)]	"	Max	15	1350	"	1/2	1000
		Typical	10	1200	"	1/2	1000
Ti-8Al-1Mo-1V[(a)]	Duplex or mill annealed	Max	20	1500	"	1/4	1450
		Typical	(b)	1150-1350	"	1/4	1450
		Heat-Treatable Alloys					
Ti-6Al-4V	Solution treated	Max	30	1100	Aging	4-8	1000
		Typical	15	1050	"	4-8	1000
Ti-4Al-3Mo-1V[(a)]	Ditto	Max	10	1100	"	5-7	1050
		Typical	10	1050	"	5-7	1050

(a) These alloys were coated prior to heating to inhibit scaling.
(b) Optimum conditions have not yet been established.

TABLE LIII. EFFECT OF COLD FORMING, HOT SIZING, AND AGING ON THE PROPERTIES OF SOLUTION-TREATED Ti-4Al-3Mo-1V ALLOY (REF. 99)

Forming Temperature, F	Average Strain at Room Temperature, per cent	Average Strain at Temperature, per cent	Average Room-Temperature Compressive Yield Strength, psi	Average Room-Temperature Elastic Modulus, psi x 10^{-8}	Room-Temperature Compressive Yield Strength, per cent
80	0	0	177,950 ± 5,850	16.78	--
1000	4.2	2.8	162,300 ± 9,600	16.85	91
1100	4.9	2.9	156,150 ± 11,350	17.10	88

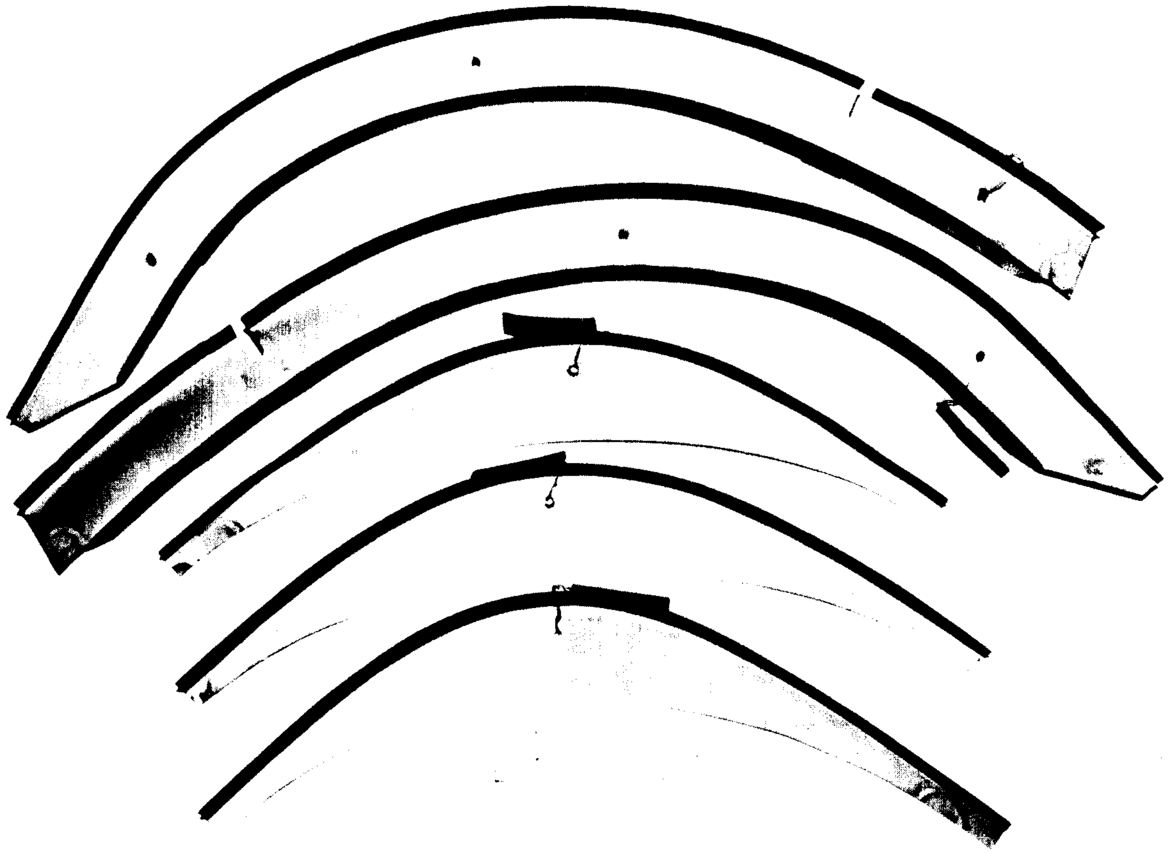


FIGURE 145. FORMERS, FIRST-STAGE FORMED ON HYDROPRESS AND HOT SIZED (REF. 55)

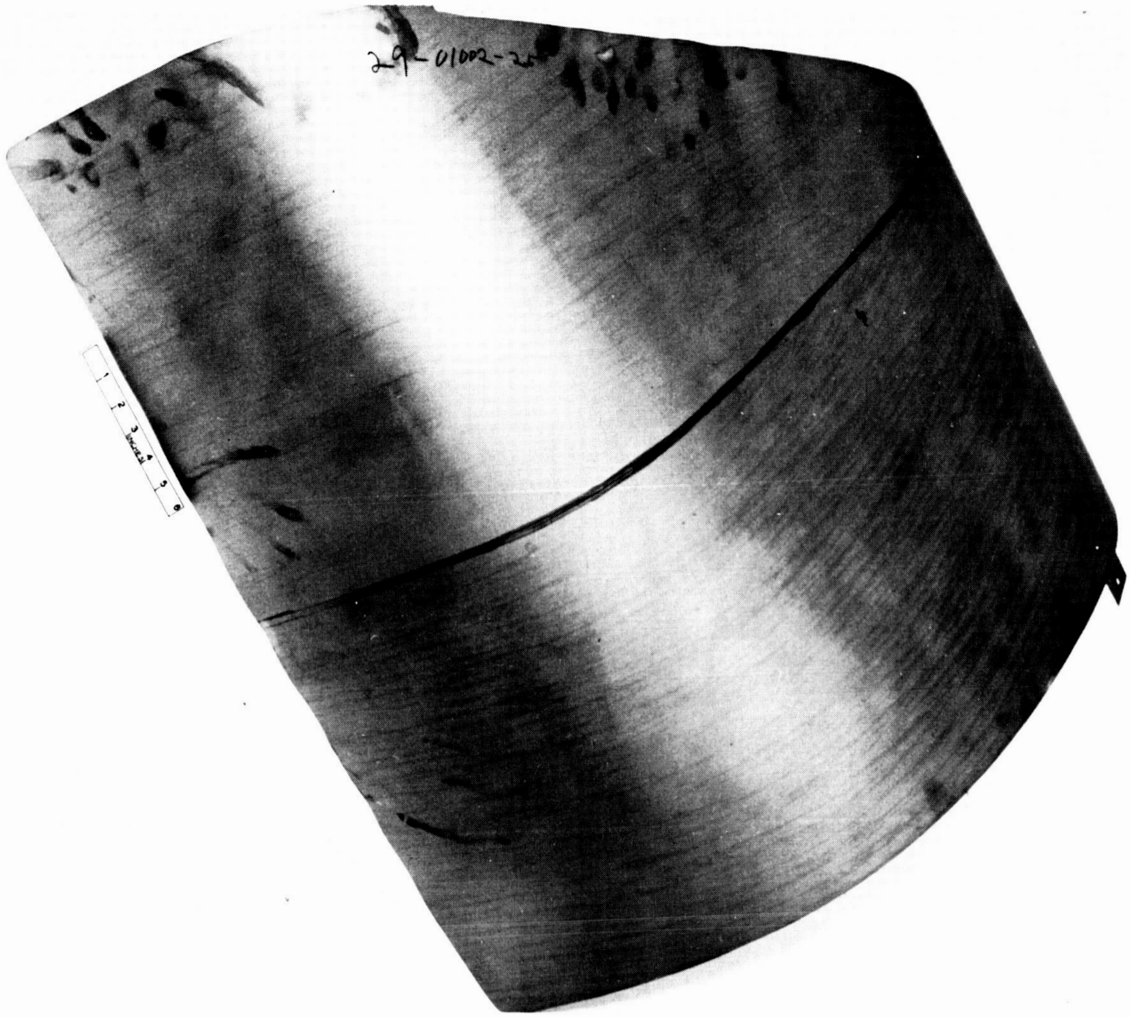


FIGURE 146. FUSELAGE TAIL-CONE SKIN (REF. 55)

Formed on Tool Shown in Figure 143
Ti-4Al-3Mo-1V Alloy

the Ti-8Mn, Ti-5Al-2.5Sn, and Ti-8Al-1Mo-1V alloys may be stress relieved. The heat-treatable alloys such as Ti-6Al-4V, Ti-4Al-3Mo-1V, and Ti-13V-11Cr-3Al are aged after hot sizing. These alloys are preformed and hot sized in the solution-treated condition. The aging may be done with the part placed free of restraint in the furnace, or the part may be held in fixtures to minimize warping during aging. Sometimes, the aging treatment is made part of the hot-sizing cycle since the heat-treatable alloys are sized and aged in the solution-treated condition.

Some post-sizing heat treatments are shown in Table LII. After sizing and heat treatment, the parts are pickled and then are ready for use.

A few typical titanium alloy parts produced by forming and hot sizing are shown in Figure 145. These particular parts were preformed on the Hydropress and then hot sized and finished.

Figure 146 shows a part made using the combination skin form and sizing tooling shown in Figure 143. This method of sizing appears to be a useful way of producing rather large sheet parts having generous radii and curvature.

Properties of Hot-Sized Titanium. Peterson and Young (Ref. 99) obtained data on the compressive yield strength and elastic moduli for the Ti-4Al-3Mo-1V age-hardenable alloy as solution treated, and after forming at 1000 and 1100 F followed by aging. Their data are shown in Table LIII. This alloy retained 91 and 88 per cent of its room-temperature compressive yield strength when aged after hot sizing at 1000 and 1100 F, respectively. These test results indicate that the solution-treated Ti-4Al-3Mo-1V alloy may be easily formed between matched heated dies into large panels with mild contours. Aging fixtures are not necessary in order to retain the hot-sized contours.

Data were obtained at McDonnell Aircraft Corporation (Ref. 121) on the tensile properties of the Ti-13V-11Cr-3Al alloy, rubber formed at room temperature in the solution-treated condition and then hot sized at about 1100 F followed by aging at 900 F for 60 hours in air. The tensile data, shown in Table LIV, indicate that both yield and tensile strength of this alloy could be maintained at about 97.3 per cent of the strength that might be expected if the hot-sizing step at about 1100 F had been omitted. However, the 60-hour aging treatment after sizing is necessary to maintain strength since apparently only a negligible amount of aging occurs during the hot-sizing cycle at 1100 F.

TABLE LIV. TENSILE PROPERTIES OF THE SOLUTION-TREATED Ti-13V-11Cr-3Al ALLOY (REF. 121)

Rubber Formed and Then Creep Formed Within the Aging Temperature Range of the Alloy.

Test No.	Rubber Formed at Room Temperature	Creep-Forming Temperature, F 1080	1100	Aged 900 F, 60 hr in air	Tensile Yield Strength, psi	Ultimate Tensile Strength, psi	Per Cent Elongation, 2-inch gage length
1	x			x	176,000	197,500	11
2	x			x	176,500	196,500	8
3	x	x			131,000	136,000	20
4	x		x		129,000	133,000	22
5	x		x	x	171,000	191,000	10
6	x	x		x	172,000	192,000	9

The two examples cited indicate that for the age-hardenable alloys, strengths of over 90 per cent of the age-hardened strength can be produced by hot sizing the solution-treated alloys and then aging. Those alloys that cannot be strengthened by heat treatment are usually formed in the annealed condition. The addition of a hot-sizing cycle after preforming to obtain more precise contours would not be expected to severely alter the strength and probably would render the part slightly more ductile. Here, the hot sizing might serve as a stress-relieving treatment.

Future Use of Hot Sizing. Up until recently most of the applications for titanium parts in aircraft were limited to rather small sizes up to about 2 or 3 feet long and 1 foot wide such as are shown in Figure 145. Presently, the possibility for using titanium alloys as skin for aircraft is being investigated actively and, indeed, some skins are being used for this purpose. One modest size experimental fuselage tail-cone skin is shown in Figure 146. The increased demand for large formed skins should accelerate the development and use of the ceramic tools, either of the mating type or combination skin form and sizing type. Both of these techniques are being used to produce contoured skin sections as large as about 3 x 5 feet and perhaps even much larger. This type of application should grow as the increased speed and range of aircraft will demand lighter, stronger, and more heat-resistant skin materials.

The proposed supersonic transport plane is perhaps the most publicized application of these higher speed aircraft. The military needs for aircraft also will swell the demand for producing sizable precisely shaped skin sections from the titanium alloys. While these developments are taking place, the need for the smaller titanium-alloy components presently being produced would be expected to continue. These smaller units then can be assembled by welding techniques to form the spars, stiffeners, and ribs that comprise the airframes that will support the skins.

CONCLUSIONS AND RECOMMENDATIONS

Various types of research are expected to advance the art of deformation processing of titanium and its alloys. Developments in any of the areas mentioned below are expected to increase productivity and decrease the costs of components fabricated from titanium.

Some of the recommendations for research on primary deformation processes by Panels of the Materials Advisory Board (Refs. 122, 123) are the following:

(1) Hot Rolling

(a) Development of equipment capable of rolling wider sheet (Ref. 122)

(b) Development of methods for improving control of sheet thickness and shape (Ref. 122)

(c) Development of better methods for preventing surface contamination during heating (Ref. 122)

(d) Development of processes for producing desirable anisotropic properties in flat-rolled titanium products

(2) Cold Rolling

(a) Development of techniques for handling wide, thin sheet (Ref. 122)

(b) Development of equipment for straightening wide sheet and plate (Ref. 122)

(3) Forging

(a) Investigations on lubricants and methods of applying them (Ref. 123)

(b) Development of dies that can be used at temperatures between 1000 and 1500 F (Ref. 123)

(c) Development of techniques or equipment for producing larger parts and large parts of greater complexity

(4) Extrusion

(a) Investigations on lubrication to decrease die wear and improve surface quality (Ref. 123)

(b) Develop extrusion practices that will permit use of titanium parts with as-extruded surfaces (Ref. 123)

(c) Develop practices for extruding thinner structural sections.

Two types of effort should be particularly worthwhile for secondary deformation processes.

(1) Collection of information on the mechanical properties that control the performance of sheet and plate in forming operations. The parameters of greatest importance are not ordinarily measured in routine tensile and compression tests. Knowledge of typical values and their normal range for commercial products would permit better predictions of formability limits. Data should be obtained at various temperatures and for appropriate conditions of heat treatment.

(2) Development work should also be directed toward improving equipment and tooling for forming titanium alloys by conventional processes at elevated temperatures. Some effort on new techniques for forming titanium also seems justified. Major improvements in forming some types of objects from sheet and tubing may result from applying a counterpressure to minimize tensile stresses developed at the surface during forming. Drawing and flanging operations are possible examples.

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DEFORMATION PROCESSING OF TITANIUM AND ITS ALLOYS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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