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DEFORMATION PROCESSING OF PRECIPITATION-HARDENING STAINLESS STEELS

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NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

DEFORMATION PROCESSING OF PRECIPITATION-HARDENING STAINLESS STEELS

By

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ABSTRACT

This report covers the state of the art of both primary and secondary fabrication methods for the precipitation-hardenable stainless steels. Methods currently employed for primary fabrication of these alloys include rolling, extrusion, forging, and drawing of tube, rod, and wire.

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

FOREWORD

Precipitation-hardening stainless steels are potentially useful wherever corrosion resistance and high strength at high temperatures are needed. They were developed initially to meet urgent requirements in World War II, but new alloys and methods of processing have since been introduced to assist engineers concerned with missiles and space vehicles and with various applications in the field of nuclear science and technology.

The Atomic Energy Commission and National Aeronautics and Space Administration have established a cooperative program to make available information, describing the technology resulting from their research and development efforts, which may have commercial application in American industry. This publication is one of the many resulting from the cooperative effort of these agencies to transfer technology to private industry.

This survey is based on information contained in a series of reports originally prepared by Battelle Memorial Institute for the Manufacturing Engineering Laboratory of the George C. Marshall Space Flight Center. The original information has been updated and revised in writing the current, seven volume survey. These volumes were prepared under a contract with the NASA Office of Technology Utilization which was monitored by the Redstone Scientific Information Center.

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-1165(Z), in the general field of materials fabrication.

This report on practices used to deform the precipitation-hardenable stainless steels 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 106 references are included, most of which cover the period since 1959.

There are three reports issued by Defense Metals Information Center that provide a considerable amount of background information on the precipitation-hardenable stainless steels. They are:

(1) Roach, D. B., and Hall, A. M., "The Engineering Properties of Precipitation-Hardenable Stainless Steels, TML Report No. 48 (July 20, 1956).

(2) Ludwigson, D. C., and Hall, A. M., "The Physical Metallurgy of Precipitation-Hardenable Stainless Steels", DMIC Report 111 (April 20, 1959).

(3) Ludwigson, D. C., "Semiaustenitic Precipitation-Hardenable Stainless Steels", DMIC Report 164 (December 6, 1961).

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DEFORMATION PROCESSING OF PRECIPITATION-HARDENING STAINLESS STEELS

SUMMARY

The techniques used for fabricating precipitation-hardenable stainless steels are very similar to those used for the regular stainless steel grades. The PH alloys find wide use where high strength and corrosion resistance at temperatures up to 1300 F are required. Some of the alloys are widely used as springs for elevated-temperature applications where they approach the range of usefulness of more expensive alloys.

Sheet, strip, plate, and rod comprise the most popular forms of the precipitation-hardenable stainless steels in the aircraft and aerospace industries. Most of the alloys are available in rolled form. Both tubing and structural shapes have been produced by the hot-extrusion process. Sometimes the extruded shapes such as tees and angles are later cold drawn to improve tolerances and to achieve thinner webs. The superior corrosion resistance of the precipitation-hardenable stainless steels compared with the high-strength steels have made them attractive for applications in the aerospace industry at elevated temperatures where high-strength-to-density ratios are required. These alloys are readily cold drawn into tube, rod, and wire. Tubing from these alloys is extensively used for both hydraulic and deicing systems in aircraft; rod and wire are used extensively for fasteners and springs where corrosion resistance is important.

Precipitation-hardenable stainless steels can usually be formed by secondary deformation methods at room temperature. Extensive studies have shown that the formability of sheet metal can be predicted from mechanical-property measurements obtained in simple tests. However, some of these property measurements are not readily available and more or less special tests must be set up to obtain the required data. Reports of experience from various other industrial sources also have been compiled and summarized to offer assistance and guidance in performing many of the secondary deformation processes. More detailed information on any of the deformation processes is available by consulting the extensive reference list.

INTRODUCTION

The precipitation-hardenable stainless steel alloys have been used extensively in the manufacture of high-performance aircraft and missile components. Most of the alloys retain their strength to 1000 F for short terms and up to 750 F for long-term applications. They have been used for aircraft skins that have the capabilities for Mach 3 flight and for the surrounding structures near jet engines. The corrosion resistance of these alloys results in minimum maintenance of structures fabricated from them.

All of the precipitation-hardenable stainless steel alloys are iron-base alloys that are heat treatable to high strengths by a low-temperature aging treatment. They may be grouped according to the final heat-treated structure obtained, as martensitic, semiaustenitic, and austenitic types. In the annealed condition or the solution-treated condition, most of these alloys can be cold worked at room temperature. Working at elevated temperatures should be avoided because precipitation reactions will cause a considerable increase in the yield strength and reduce the ductility. The hot-working temperatures are generally above the mill-anneal temperature for the alloy. The ductility of most alloys is equivalent to that of ordinary stainless steels at room temperature so that secondary working can usually be carried out with conventional processing techniques.

The purpose of this report is to summarize the present status of primary and secondary deformation processes for precipitation-hardenable stainless steels. 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 deformation processes produce semifinished or finished parts by additional forming operations on 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 fabrication of precipitation-hardenable stainless steels.

The compositions of typical precipitation-hardenable stainless steels are given in Table I. The mechanical properties after various heat treatments also are given. As can be seen from Table I, a wide variety of mechanical properties can be attained with these alloys depending on the type of thermal treatment and the extent of deformation. Sufficient alternative processing schedules are available, however, so that acceptable mechanical properties can be obtained with almost any forming practice.

The different heat-treat designations are identified and thermal processing sequences are described in Table II. The thermal treatments may be combined with variations in deformation processing to obtain a variety of mechanical properties. This is desirable when working with deformation processes that give a uniform reduction, such as rolling, but can cause difficulties when the thermal treatment follows a process that causes nonuniform strain.

Martensitic Precipitation-Hardenable Stainless Steels. The group of martensitic precipitation-hardenable stainless steels includes 17-4 PH, Stainless W, Almar 362, 15-5 PH, and PH 13-8 Mo. These materials develop their properties by two metallurgical phenomena. The first is the transformation of austenite to martensite upon cooling from the austenizing temperature or below to room temperature. The second is the precipitation-hardening effect resulting from precipitation of elements at suitable lattice points in the material matrices. In the 17-4 PH and 15-5 PH, alloys copper is responsible for this reaction, while Stainless W depends on both aluminum and titanium. ALMAR 362 has only titanium for this reaction. PH 13-8 Mo is strengthened with the aluminum precipitate. Only a small quantity of the precipitating element, from 0.5 to 3.0 per cent, is required to provide a significant increase in hardness.

Semiaustenitic Precipitation-Hardenable Stainless Steels. The group of typical semiaustenitic precipitation-hardenable stainless steels are 17-7 PH, PH 15-7 Mo, PH 14-8 Mo, AM-350, and AM-355. The semiaustenitic stainless steels provide an unusual combination of excellent formability of the austenitic structure, high strength in the transformed martensitic condition, and good corrosion resistance. Most of the special alloying elements used in stainless steels that are austenitic at elevated temperatures lower the transformation range. The exceptions to this rule are aluminum and cobalt, which raise the transformation range. Although cobalt is generally not present in significant quantities, aluminum is an important ingredient. In such steels as 17-7 PH and PH 15-7 Mo aluminum plays an important role

TABLE I. COMPOSITIONS AND MECHANICAL PROPERTIES OF SEVERAL PRECIPITATION-HARDENABLE STAINLESS STEELS

Steel Designation	Producer	Chemical Composition, per cent bal iron											Available Forms	Tensile Properties of Sheet or Bar			
		C	Mn	Si	Cr	Ni	Mo	Al	V	Ti	N	Other		Condition[a]	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent
								Martensitic Types									
17-4 PH	Armco	0.07[b]	1.00[b]	1.00[b]	15.50	3.00	--	--	--	--	--	Cu 3.00	Bar	A	150	110	12
(Ref. 1)					17.50	5.00						5.00	Plate	H 900	195	180	13
												Cb + Ta	Wire	H 1000	180	171	14
												0.15	Forging	H 1000	170	160	14
													billets	H 1100	161	155	15
												0.45	Castings	H 1100	150	140	17
														H 1200	145	95	17
						Mill anneal 1900 F ± 25 F oil or water quench											
Stainless W	U.S. Steel	0.12[b]	1.00[b]	1.00[b]	16.00	6.00	--	1.00[b]	--	1.0	0.2[b]	--	Sheet	Mill	135	95	(c)
(Ref. 2)					18.00	8.00								annealed			
													Bar	Aged (A)	210	195	(c)
													Plate	(B)	205	190	(c)
													Wire	(C)	190	170	(c)
													Forging	Solution	135	90	(c)
													billets	annealed (D)			
														(E)	170	155	(c)
														(F)	160	145	(c)
														(G)	150	130	(c)
		Mill anneal 1850 to 1950 F for 15 minutes air cool															
ALMAR 362	Allegheny	0.03	0.30	0.20	14.5	6.5	--	--	--	0.8	--	--	Sheet	A	120	105	10
(Ref. 3)	Ludlum												Strip		140	115	20
													Bar	A 1000	150	140	15
															175	170	17
														900	188	182	13
														950	177	172	14
														1000	165	160	16
														1050	152	144	18
														1150	140	115	21
15-5 PH	Armco	0.035	0.025	0.4	15.00	4.6	--	--	--	--	--	Cu 3.3	--	H 900	195	170	11
(Ref. 4)												Co + Ta		H 1025	165	160	12
												2.7		H 1150	140	120	17
PH 13-8 MO	Armco	0.04	--	--	12.50	8.6	2.0	1.0	--	--	--	--	--	A	161	101	15.6
(Ref. 5)														H 900	214	188	15.9
														H 1000	217	200	14
														H 1050	195	187	14.7
														H 1100	173	162	17.5
								Semiaustenitic Types									
17-7 PH	Armco	0.09[b]	1.00[b]	1.00[b]	16.00	6.50	--	0.75	--	--	--	--	Sheet	A	130	40	35
(Ref. 6)					18.00	7.75	--	1.50					Plate	T	145	100	9
													Bar	TH 1050	200	185	9
														A 1750	133	42	19
														R 100	175	115	9
														RH 950	235	220	6
														C	220	190	5
														CH 900	265	260	2

TABLE I. (Continued)

Steel Designation	Producer	Chemical Composition, per cent bal iron: C	Mn	Si	Cr	Ni	Mo	Al	V	Ti	N	Other	Available Forms	Tensile Properties of Sheet or Bar: Condition[a]	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent
PH 15-7 Mo (Ref. 7)	Armco	0.09[b]	1.00[b]	1.00[b]	14.00	6.50	2.00	0.75	--	--	--	--	Sheet	A	130	55	35
					16.00	7.75	3.00	1.50					Plate	T	145	90	7
													Bar	TH 1050	210	200	7
														A 1750	150	55	12
														R 100	180	125	7
														RH 950	240	225	6
														C	220	190	5
														CH 900	265	260	2
					Mill anneal 1950 F ± 25 F air cool												
PH 14-8 Mo (Ref. 5)	Armco	0.05[b]	1.00[b]	1.00[b]	13.50	7.50	2.00	0.75	--	--	--	0.015 P	Sheet	A	125	55	25
					15.50	9.50	3.00	1.50				0.010 S	Strip	SRH 950	235	215	5
														SRH 1050	215	205	5
														H	149	63	39
AM-350 (Ref. 8)	Allegheny Ludlum	0.12[b]	0.90	0.50[b]	16.00	4.0	2.5	--	--	--	0.07	--	AMS	L	166	56	20
					17.00	5.0	3.25	--			0.13		5548-A	1375 Anneal	160	105	10
													sheet	DA	195	155	10
													AMS	R 100	200	110	12
													5548-A	SCT 850	200	170	13
													strip	CR 30	228	200	15
													AMS 5554	CR 50	275	250	13
													tubing	CR 70	339	322	11
													AMS 5745	CRT 30	227	214	18
													bars	CRT 50	272	259	12
													AMS 5745	CRT 70	335	322	11
													forgings				
AM-355 (Ref. 8)	Allegheny Ludlum	0.10	0.50	0.05[b]	15.00	4.0	2.5	--	--	--	0.07	0.01 P	AMS 5547	Annealed	187	56	29
		0.15	1.25		16.00	5.0	3.25				0.13	0.03 S	sheet	Annealed	195	60	15
													AMS 5547	DA	195	155	10
													strip	SCT	215	180	11
													AMS 5749	SCT 850	225	195	13
													plate	CR 20	210	175	23
													AMS 5743	CR 30	240	220	18
													bars	CR 40	265	260	10
													AMS 5743	CRT 20	215	165	20
													forgings	CRT 30	240	200	16
													AMS 5780	CRT 40	265	235	8
													wire	XH	350	335	1
													AMS 5781				
													tubing				

TABLE I. (Continued)

Steel Designation	Producer	Chemical Composition, per cent bal iron: C	Mn	Si	Cr	Ni	Mo	Al	V	Ti	N	Other	Available Forms	Tensile Properties of Sheet or Bar: Condition[a]	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent
AM-357 (Ref. 8)	Allegheny	0.21 0.26	0.50 1.25	0.50[b]	13.50 14.50	4.0 5.0	2.5 3.25				0.07 0.13		Developmental sheet-plate forgings	SCT 850	234	193	15
														SCT 1000	183	169	16
														CRT 24[d]	248	198	23
														CRT 33[d]	269	252	15
														CRT 65[d]	313	312	16
														CRT 89[c]	345	320	20
														CRT 25	240	215	20
														CRT 50	310	300	6
														XH	358	355	1
														SCCRT	325	315	2.5
								Austenitic Types									
A-286 (Ref. 2)	Universal Cyclops Steel Corporation	0.08[b]	2.00[b]	1.00[b]	13.50 16.00	24.00 28.00	1.00 1.50	0.35[b]	0.50[b]	1.50 2.25	--	--	Sheet-strip forging billets bar	Aged	146	100	25

(a) See Table II for heat treatment.
(b) Maximum.
(c) Ausformed.
(d) Shear formed.

TABLE II. HEAT TREATMENTS FOR PRECIPITATION-HARDENABLE STAINLESS STEEL

Alloy Designation	Heat-Treatment Designation	Thermal Treatment
17-4 PH (Ref. 1)	A	1900 F ± 25 F oil or water quench
	H 900	Anneal, age 900 ± 10 F 1 hr, air cool
	H 1000	Anneal, age 1000 ± 10 F 1 hr or 4 hr, air cool
	H 1100	Anneal, age 1100 ± 10 F, 1 or 4 hr, air cool
	H 1200	Anneal, age 1200 ± 10 F, 4 hr, air cool
Stainless W (Ref. 2)	Mill annealed	1850 to 1950 F for 15 minutes, air cool
	Aged (A)	Anneal, age 950 ± 10 F, 1/2 hr, air cool
	Aged (B)	Anneal, age 1000 ± 10 F, 1/2 hr, air cool
	Aged (C)	Anneal, age 1050 ± 10 F, 1/2 hr, air cool
	Solution annealed (D)	Anneal, solution anneal 1300 F, air cool
	Aged (E)	Anneal, solution anneal 1300 F, air cool, age 950 F for 1/2 hr, air cool
	Aged (F)	Solution anneal, air cool, age 1000 F 1/2 hr, air cool
	Aged (G)	Solution anneal, air cool, age 1050 F, 1/2 hr, air cool
17-7 PH (Ref. 6) and PH 15-7 Mo (Ref. 7)	A	Mill anneal 1950 ± 25 F
	T	1400 ± 25 F for 90 minutes, cool to 60 F in 1 hr, hold 1/2 hr
	TH-1050	1050 ± 10 F for 90 minutes, air cool
	A-1750	1750 ± 15 F for 10 minutes, air cool
	R-100	A-1750 plus -100 ± 10 F for 8 hr
	RH 950	A-1750 plus R-100, 950 ± 10 F for 60 minutes, air cool
	C	Cold rolled
	CH 900	Cold rolled, 900 ± 10 F for 60 minutes, air cool
PH 14-8 Mo (Ref. 5)	A	1825 ± 25 F
	SRH 950	1700 ± 15 F for 60 minutes, air cool, -100 ± 10 F for 8 hr, 950 ± 10 F for 60 minutes, air cool
	SRH 1050	1700 ± 15 F for 60 minutes, air cool, -100 F ± 10 F for 8 hr, 1050 ± 10 F for 60 minutes, air cool
AM-350 (Ref. 8)	H	Mill anneal 1950 ± 25 F
	L	Anneal 1710 ± 25 F, cool rapidly
	DA	L-anneal, 1375 ± 25 F for 3 hr quench, age 850 for 3 hr
	SCT 1000	L-anneal, -100 F for 3 hr, age 1000 F for 3 hr
	SCT 850	L-anneal, -100 F for 3 hr, age 850 F for 3 hr
	CR 30	Cold reduced 30 per cent
	CR 50	Cold reduced 50 per cent
	CR 70	Cold reduced 70 per cent
	CRT 30	Cold reduced 30 per cent, aged 750 to 850 F
	CRT 50	Cold reduced 50 per cent, aged 750 to 850 F
	CRT 70	Cold reduced 70 per cent, aged 750 to 850 F
AM-355 (Ref. 8)	Annealed	1875 ± 25 F
	L-annealed	1710 ± 25 F, rapid cool
	DA	L-anneal, 1375 ± 25 F for 3 hr quench, age 850 F for 3 hr
	SCT 850	L-anneal, -100 F for 3 hr, age 850 F for 3 hr
	Mill anneal	1950 ± 25 F
	SCT 1000	L-anneal, -100 F for 3 hr, age 1000 F for 3 hr
	CR 20	Cold reduced 20 per cent
	CR 30	Cold reduced 30 per cent
	CR 40	Cold reduced 40 per cent
	CRT 20	Cold reduced 20 per cent, aged 750 to 850 F
	CRT 30	Cold reduced 30 per cent, aged 750 to 850 F
	CRT 40	Cold reduced 40 per cent, aged 750 to 850 F
	XH	Cold reduced 50 per cent, aged 750 to 850 F
		L-anneal, -100 F for 3 hr, age 1000 F for 3 hr

TABLE II. (Continued)

Alloy Designation	Heat-Treatment Designation	Thermal Treatment
AM-357 (Ref. 8)	Mill annealed	1800 F
	L-annealed	1710 ± 25 F, rapid cool
	SCT 850	L-anneal, -100 F for 3 hr, age 850 F for 3 hr
	SCT 1000	L-anneal, -100 F for 3 hr, age 1000 F for 3 hr
	SA	Solution anneal 2000 ± 25 F
	CRT 24	Solution anneal, shear form at RT 24 per cent, age 850 F for 3 hr
	CRT 33	Solution-anneal, shear form at RT 33 per cent, age 850 F for 3 hr
	CRT 65	Solution anneal, shear form at RT 65 per cent, age 850 F for 3 hr
	CRT 88	Solution anneal, Ausform 75 to 90 per cent at 250 to 300 F, age at 850 F for 3 hr
	CRT 25	Solution anneal, cold roll 25 per cent, age 850 F for 3 hr
	CRT 50	Solution anneal, cold roll 50 per cent, age 850 F for 3 hr
	XH	Solution anneal, cold roll 50 per cent, age 850 F for 3 hr
	SCCRT	Solution anneal, -100 for 3 hr, cold reduce 20 to 30 per cent, age 850 F for 3 hr
A-286 (Ref. 2)	SA	1800 ± 25 F, rapid cool
	Aged	Solution treated, age 1325 ± 25 F for 16 hr, air cool

in the balance of composition as well as being a precipitation hardener.

The semiaustenitic stainless steels can be cold worked to high-strength levels or thermally treated to give high strength with good ductility. Most of the processing sequences involve forming the materials in the annealed condition followed by

(1) A high-temperature solution treatment to form austenite

(2) Deep freezing for transformation to martensite

(3) Reheating to temper the martensite while further strengthening occurs from the precipitation reaction, which proceeds simultaneously.

Sometimes the materials are formed in the solution-treated condition so that only the deep freeze and temper treatments are required. This is an advantage since the low temperatures of both treatments reduce the possibility of thermal distortion of the material.

Although the AM-350 and AM-355 steels are believed to develop their properties mainly from the transformation reaction to martensite, they are included under the precipitation-hardenable stainless steels because of the similarity in their thermal treatment and properties to the other PH steels. They are austenitic at room temperature, but care must be exercised in storage to assure that the temperature does not drop too low or partial transformation will occur with a decrease in ductility. Attempts to use these materials in the as-received, mill-annealed condition have often resulted in difficulties when the materials are exposed to low temperatures during transit. Best results are obtained by annealing in the fabricator's shop and storing at 70 F or above, prior to forming.

The thermal treatment of the precipitation-hardenable stainless steels is often accompanied by dimensional changes that must be allowed for in fabrication of close-tolerance small parts or very large parts. The materials expand significantly when martensite forms and contract slightly during tempering. Tempering after cold working results in slight contraction. Some specific values of the dimensional changes associated with thermal treatments of several alloys are given in Table III. Although the net changes may appear small, they accumulate as the size of the part increases. For instance, 20-foot-long brazed honeycomb panels made of PH 15-7 Mo will grow about 1.1 inch during heat treatment. In order to use net tooling for making parts to net dimensions, the material is sometimes given an equalizing treatments, which is simply an overaging to assure that all growth has occurred before cutting the parts to dimension.

TABLE III. DIMENSIONAL CHANGES DURING HEAT TREATMENT OF SOME SEMIAUSTENITIC STAINLESS STEELS (REF. 2)

Steel Designation	Heat-Treatment Designation	Dimensional Change, in./in.
AM-350	DA	+0.0048 L + 0.0050 T
	SCT	+0.0047
	CRT	-0.0001
AM-355	DA	+0.0059 L + 0.0054 T
	SCT	+0.0058 L + 0.0062 T
	CRT	-0.0001
	XH	-0.0001
17-7 PH	TH 1050	+0.0037 to + 0.0047
	RH 950	+0.0043 to + 0.0049
PH 15-7 Mo	RH 950	+0.0045

Austenitic Precipitation-Hardenable Stainless Steels. The austenitic precipitation-hardenable stainless steels are characterized by being austenitic in both the solution-annealed and the aged condition; A-286 is the most widely used wrought alloy of this group. These alloys are used for applications that require either nonmagnetic characteristics or high strength at elevated temperatures. Areas of an aircraft that affect the navigation systems often use such materials. Although the austenitic precipitation-hardenable steels have lower strengths at room temperature than the other precipitation-hardenable alloys, they are stronger in the temperature range of 1000 to 1200 F. They also have good toughness at subzero temperatures and excellent corrosion resistance.

A-286 develops its properties mainly by the precipitation-hardening reaction. The precipitation elements used are titanium, aluminum, and vanadium. Since there is no martensitic reaction, the thermal treatment is simpler. Another advantage is that the dimensional changes that take place during thermal treatment are relatively small. After annealing, the material must be cooled rapidly from the solution temperature to avoid precipitation. This may require a water quench depending on the thickness of the material section. The precipitation-hardening treatment is generally at a higher temperature than that for other alloys, usually in the range of 1300 to 1400 F.

PRIMARY DEFORMATION PROCESSES

This section of the report describes fabrication procedures and limitations for the rolling, forging, extrusion, and drawing of wrought precipitation-hardenable stainless steels. Table IV lists the available mill-product forms for some typical alloy compositions.

The mill practices vary considerably between the three classes of austenitic, semiaustenitic, and martensitic alloys. Since most of the details of primary deformation are considered proprietary by the steel manufacturers and are generally of minor interest to most designers and fabricators, only general descriptions of the processing practices are presented in this section. Emphasis is placed on the present capabilities of the producers in making various forms.

ROLLING

Rolled products, particularly sheet, rolled shapes, and rod are available in most of the precipitation-hardenable stainless steels. These alloys have found their largest market acceptance in the form of sheet in aircraft and aerospace applications. Except for coils of thin strip or of rods for subsequent wire fabrication, rolled products are generally supplied in flat or straight sections.

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 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 strain hardening occurs in cold rolling. Rolling develops directional mechanical properties and heavily worked grain structures.

TABLE IV. AVAILABLE MILL FORMS AND CONDITIONS OF PRECIPITATION-HARDENABLE STAINLESS STEELS

Material	Sheet	Strip	Plate	Bars and Rods	Rolled Shapes	Extrusions	Forging Billets	Tubing	Wire
AM-350 (Ref. 3)	A CRT[b]	A CRT	-- --	A[a]	A	--	--	A CRT	A
AM-355 (Ref. 3)	CRT	CRT	EOT[c]	EOT	A	EOT	EOT	--	CDT[d]
Almar 362 (Ref. 3)	A	A	A	A Aged	A	A	A	A	A
AM-357 (Ref. 3)	--	--	--	--	--	--	--	--	CDT
Stainless W (Ref. 4)	--	A	A	A	A	--	A	--	--
17-7 PH (Ref. 6)	A C	A C[e]	--	A	A	A	A	A	A
17-4 PH (Ref. 1)	A	A	--	A Aged	A	--	A	--	A
15-5 PH (Ref. 4)	A	--	--	A	--	--	A	--	A
PH 15-7 Mo (Ref. 7)	A C	A C	--	A	A	A	A	A	A
PH 14-8 Mo (Ref. 5)	A	A	--	Special order only		--	--	--	--
PH 13-8 Mo (Ref. 5)	A	A	--	Special order only		--	--	--	--
PH 14-4 Mo (Ref. 5)	--	--	--	A	A	--	A	--	CD[f]
A-286 (Ref. 2)	A[g] C	A STA[h]	A	A STA	A	A	A STA	A	A

(a) Small sheet only, less than 1 inch.
(b) CRT – cold rolled and tempered.
(c) EOT – equalized and overtempered.
(d) CDT – cold drawn and tempered.
(e) C – hard drawn.
(f) CD – cold drawn.
(g) A – may be annealed or solution treated.
(h) STA – solution treated and aged.

Rolling is often used for strain hardening to control the mechanical properties of precipitation-hardenable stainless steels.

Rolling Equipment. Detailed information on the design and operation of steel-mill rolling equipment is available elsewhere (Ref. 9); therefore, only a brief discussion of equipment and rolling nomenclature is provided here as a background for the process descriptions provided in the report.

Figure 1 shows the mill designs most commonly 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-stand two-high mills 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, round, and partially formed sections. 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 type of mill is generally used for products other than plate or sheet.

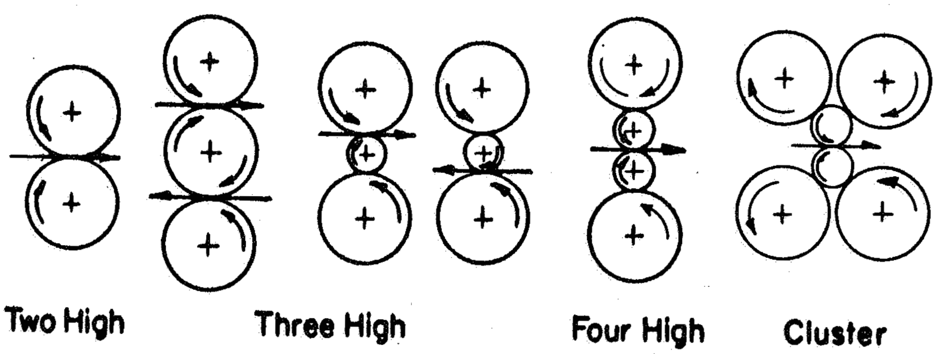


FIGURE 1. TYPICAL ROLLING-MILL DESIGNS

For rolling of narrow material where thickness control is not too critical, the two-high and three-high rolling mills described above are adequate. For rolling of wide material, four-high mills are used to achieve better roll rigidity and closer thickness control. Four-high mills are 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 Rolled Products. The rolling procedures for precipitation-hardenable stainless steels are similar to those used for the 18-8 types of stainless steels. Several important similarities exist, such as the need for frequent conditioning during processing to obtain a good surface finish, close control of working temperatures, and good control of thickness and shape during hot working to obtain close-tolerance control during subsequent cold-rolling operations.

Ingot Breakdown. After solidification, the cast ingots (weighing up to 10,000 pounds) are removed from the mold and are heated in a sulfur-free atmosphere furnace. The presence of even small quantities of sulfur will cause the material to be hot short and, possibly, to crack during rolling at elevated temperatures. The ingots either may be forged before rolling, or they may go directly to the blooming mill. The choice generally depends on the equipment available and on the initial shape of the cast ingot. The hot-working range is narrow for most of the precipitation-hardenable stainless steels so that frequent reheating is necessary during the ingot-breakdown operations.

Ingots to be used for sheet or plate processing are either forged or rolled, in a blooming mill, to rectangular slabs. If the final product is to be bar stock, ingots are forged to squares. Round shapes in diameters of 3-1/2 inches up to 6 inches are also forged.

After forging or rolling in the blooming mill, billets are surface conditioned and the hot top end is removed. Generally, the billet is ultrasonically inspected at this point. Severe flaws may require additional conditioning since it is difficult to heal defects in the stainless steels during hot rolling.

Rolling of Flat Products. The billets are hot rolled on three-high mills down to 3/8-inch-thick plate. The billets may be cross rolled to minimize directional variations in properties, although this is generally not required. Frequent heating of the billet during the rolling may be required as well as surface conditioning. At this point in the processing, the material is pickled and may be shot blasted before further rolling. The use of shot blasting should be kept to a minimum because it severely work hardens the surface.

In thicknesses ranging from 0.045 to 3/8 inch rolling is generally done on a two-high mill. The sheet may be finished hot or cold although most material is given a light cold pass to improve the flatness, straightness, and dimensional tolerances. Cold rolling enhances the mechanical properties when used in conjunction with a final tempering treatment. Rolling to thinner sheet, down to 0.001-inch-minimum thickness, is usually done cold on a cluster mill.

Rolling of Bar Products. Typical fabrication schedules for these alloys involve hot rolling of the forged bars down to 2-1/4-inch squares on a 24-inch mill, followed by surface conditioning and reheating for rolling on a 10-inch mill down to 5/16-inch-diameter rod. Rolled shapes are handled in a similar manner. Rod intended for wire production is coiled at this stage for further processing by cold drawing into wire as small as 0.001 inch in diameter.

Post-Fabrication Processing. Hot-rolled sheet and plate are generally annealed after rolling and then descaled by acid picling or vapor blasting. Following this, the material may be roller leveled and sheared to the desired length; sheet products may be stretch straightened and cut to size. Cold-rolled products may be given a temper treatment for delivery in the cold-reduced and tempered condition (CRT). The mechanical properties depend on the amount of cold reduction and the tempering temperature.

Bar products over 2-1/4 inches in diameter are generally straightened, annealed or tempered, and ground to finish size. Smaller diameter bars are straightened, ground, heat treated, descaled, and pickled prior to coiling.

Sizes and Tolerances of Rolled Products. The classification as "sheet", "strip", "foil", or "plate" depends on the relationship between width and thickness of the products. The distinction between the four for precipitation-hardenable stainless steels can be generally defined as follows:

	Dimensions, inches	
Product	Width	Thickness
Plate	Greater than 10	Greater than 0.250
Sheet	Greater than 24	Less than 0.250
Strip	Less than 24	Less than 0.250
Foil	Less than 24	Less than 0.010

Plate. The availability of plate is limited and generally requires a mill order. Because of the metallurgical characteristics of these alloys, a reduction to sheet size is generally required to develop optimum mechanical properties in these materials. AM-355 has been produced in plate thickness up to 1 inch, while PH 15-7 Mo and 17-7 PH have been limited to 1/2 inch. Plate may be produced in widths up to 36 inches and lengths up to 120 inches. Plates are generally produced to commercial AISI tolerances. One-half AISI commercial tolerances can be obtained on some alloys upon special mill order.

Sheet, Strip, and Foil. In general, the precipitation-hardenable stainless steels are available in sheet thicknesses down to 0.010 inch, widths of 24 to 60 inches, and lengths of up to 144 inches in flat or 10,000-lb coils.

Generally speaking, any of the sheet sizes can be slit into strips of any desired width.

The precipitation-hardenable stainless steel sheet, strip, and foil are generally produced to AISI commercial tolerances. However, McCann and Sack (Ref. 10) found that the thickness of about 90 per cent of the material within a coil fell within 1/4 of the full range permitted by AISI tolerances. Their study was made on A-286 and AM-350 steel produced with commercial equipments.

Flatness tolerances vary from 1/8 to 1/4 inch depending upon the alloy and alloy condition.

For aerospace applications, foil materials have been produced in thicknesses of 0.001 to 0.004 inch and widths of 24 inches from AM-350 and PH 15-7 Mo steels. These materials have been used for the manufacture of honeycomb core. A thickness tolerance of 5 per cent is easily met, and a 2 per cent tolerance is producible.

Rolled Rod and Bar. Most precipitation-hardenable stainless steel rod and bar material is shipped from the mill in the solution-treated condition. Some may also be shipped in the annealed or cold-worked condition depending on the requirements. Hot-rolled squares, rounds, and hexagons are generally available in diameters from 3/8 to 2-1/2 inches and in lengths up to 24 feet. Again, sizes vary considerably with the particular alloy. Rod and bar are generally limited to such alloys as 17-4 PH and AM-355, which do not require as great a reduction for development of their mechanical properties.

The fabrication of rolled shapes such a angles, tees, and air-foil shapes has been extensive. Figure 2 shows some typical rolled shapes that have been fabricated in lengths up to 30 feet from AM-350, PH 15-7 Mo, and A-286. Size limitations and tolerances for precision-rolled shapes as reported by Universal Cyclops (Ref. 11) are shown in Figure 3.

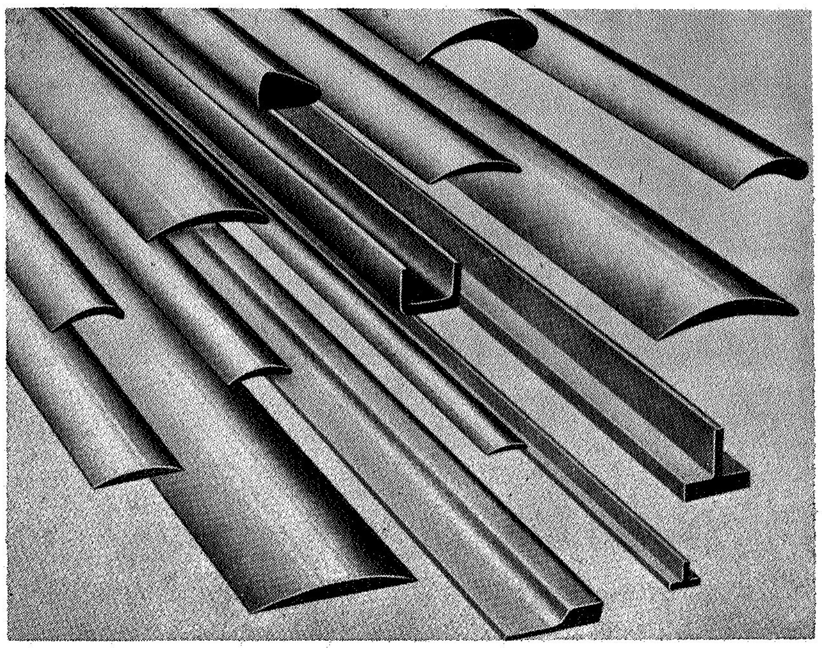


FIGURE 2. TYPICAL ROLLED SHAPES FABRICATED FOR JET- AND GAS-TURBINE ENGINES

Courtesy of D. E. Makepeace Division, Englehard Industries, Inc., Attleboro, Massachusetts.

Future Rolling Capabilities and Needs. The present capabilities and future requirements for rolling of aircraft materials, including the precipitation-hardenable steels, have been specified by a panel of the Materials Advisory Board (Ref. 12). The report indicated a need for producing rolled sheet or plate from 0.002 to 2-inch thicknesses in widths from 180 to 240 inches, with tolerances of 5 per cent or better.

EXTRUSION

The hot extrusion process has been used to produce tubing and structural shapes in the precipitation-hardenable stainless steels. Extruded shapes such as tees and angles can be cold drawn to improve tolerances and to achieve thinner gages. Tee sections with 0.062-inch-webs have been extruded in A-286 and PH 15-7 Mo alloys (Ref. 13).

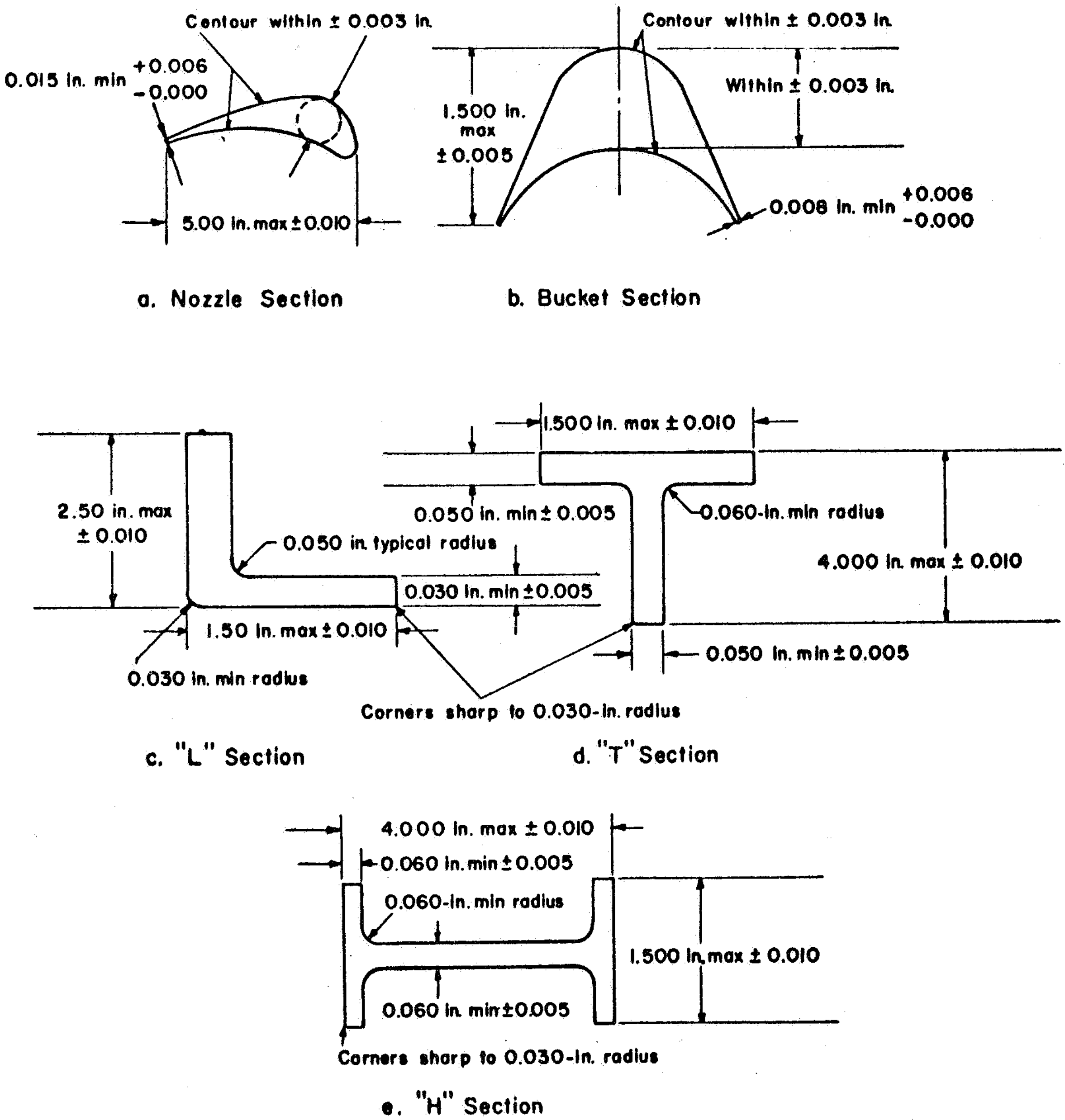


FIGURE 3. SIZE AND TOLERANCE LIMITATIONS ON PRECISION-ROLLED SHAPES (REF. 11)

The dimensions and tolerances of a Research extruded shape in PH 15-7 Mo is shown in Figure 4. The same shape was produced in A-266 with approximately twice the tolerances indicated.

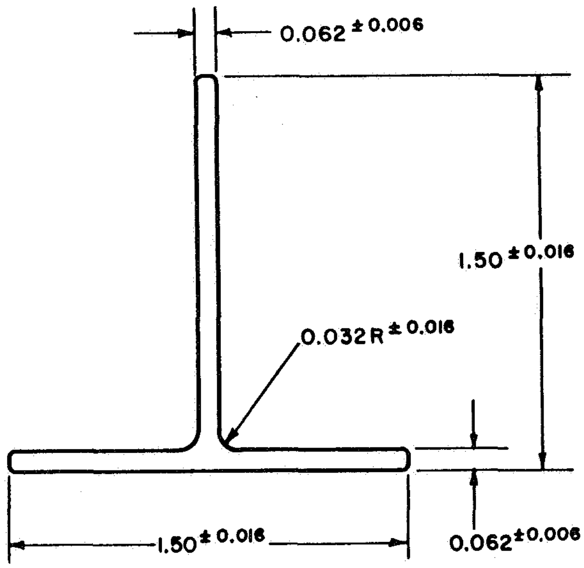


FIGURE 4. RESEARCH SHAPE FOR A-286 AND PH 15-7 Mo (REF. 13)

Extrusion is also used as a breakdown operation for materials with large as-cast grain sizes (Ref. 14). Alloys that are prone to crack during rolling or forging of the cast ingot are extruded at an extrusion ratio of 5 or 10 to 1 to eliminate the cast structures and to provide a round or rectangular section for forging or rolling. The compressive stresses characteristic of extrusion minimize cracking during hot working.

Techniques for extrusion of these alloys are very similar to stainless steel extrusion practices. The use of the Ugine-Sejournet glass-lubrication process has made extrusion possible at ratios up to 97:1 for A-286 and 37:1 for PH 15-7 Mo (Ref. 13).

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 a smaller and uniform cross-sectional area. The process can be used to produce rounds, shapes, tubes, hollow shapes, or cups.

The most common method of extrusion is referred to as direct extrusion. In this technique, the 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 5, which includes diagrams illustrating methods for tube extrusion.

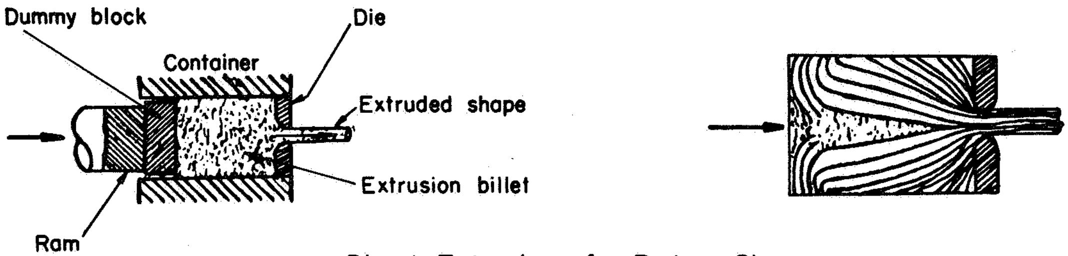
The indirect process requires lower pressures for extrusion since friction between the container and the billet is largely eliminated. The actual use of the process is not widespread, however, because of other limitations.

Extrusion Equipment and Tooling. The application of force to the billet by a ram is acutated 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.

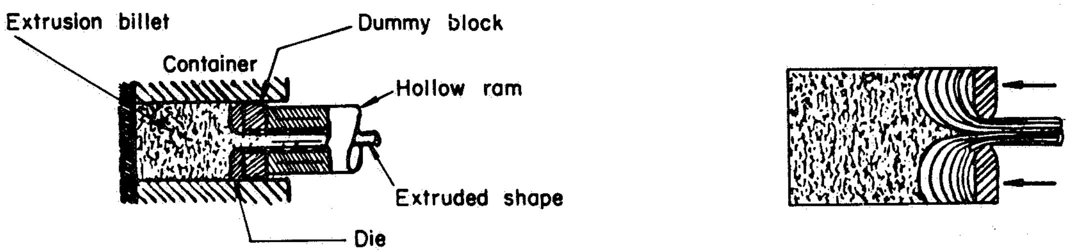
Horizontal Presses. Horizontal presses are ordinarily used for hot-extrusion operations and are available with capacities up to 14, 000 tons. The largest presses of this kind were built on the U. S. Air Force heavy-press program. Presently, there are nine of these heavy presses in the United States, ranging in capacity from 8, 000 to 14, 000 tons. The largest press equipped for 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 economy. Direct-driven pumping systems are usually more economical for comparatively small presses (Ref 16), and accumulators are used only where high ram speeds are necessary. For large presses of high capacity, e. g., 4000 tons or more, economy generally favors 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.

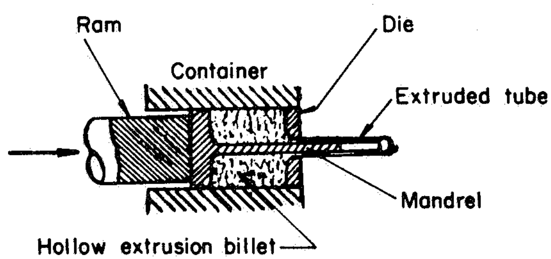
For some materials, the available ram speed becomes a deciding factor in press selection. High ram speeds are required in high-temperature extrusion to minimize heat transfer from the billet to the tools. This factor becomes increasingly critical at the billet temperatures required for precipitation-hardenable stainless steels.



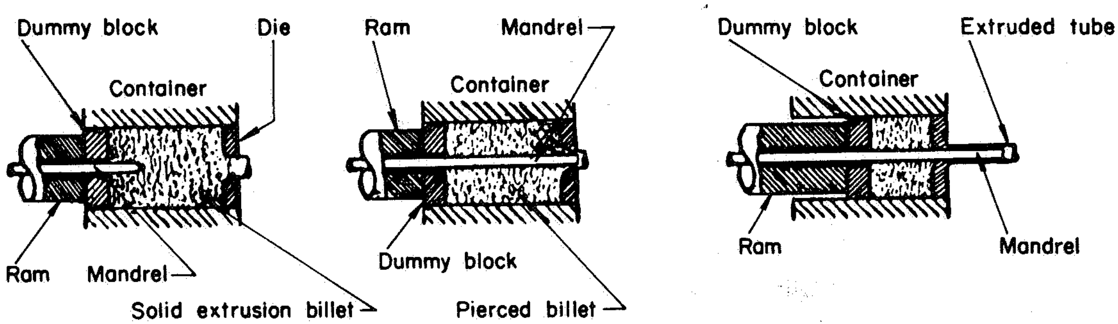
a. Direct Extrusion of a Rod or Shape



b. Indirect or Inverted Extrusion



c. Extrusion of a Tube From a Hollow Billet



d. Extrusion of a Tube From a Solid Billet

FIGURE 5. DIAGRAMMATIC REPRESENTATION OF DIFFERENT TYPES OF EXTRUSION PROCESSES (REF. 15)

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 high 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. 17). 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 Practices. The hot-extrusion process is employed for the production of long sections. All extruders employ the Sejournet glass process, using procedures similar to those developed for extruding steel. The use of glass as an extrusion lubricant was originally developed by the Comptoir Industrial d'Etirage et Profilage de Metaus, Paris, France, for extruding ferrous materials. As glasses were found that could be employed over a wide range of temperatures, the process was adopted for titanium, superalloys, precipitation-hardenable stainless steels, refractory metals, and other metals.

The practices employed by the American licensees of the Sejournet glass process for extruding precipitation-hardenable stainless steels 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.

Billets can be heated in either gas- or oil-fired furnaces, by induction or by salt-bath heating (Ref. 14). Due to the low thermal conductivity of the precipitation-hardenable stainless steels, fairly long induction heating times are required to insure uniform temperatures in the extrusion billet. The effect of temperature on the extrusion pressure of A-286 is shown in Figure 6.

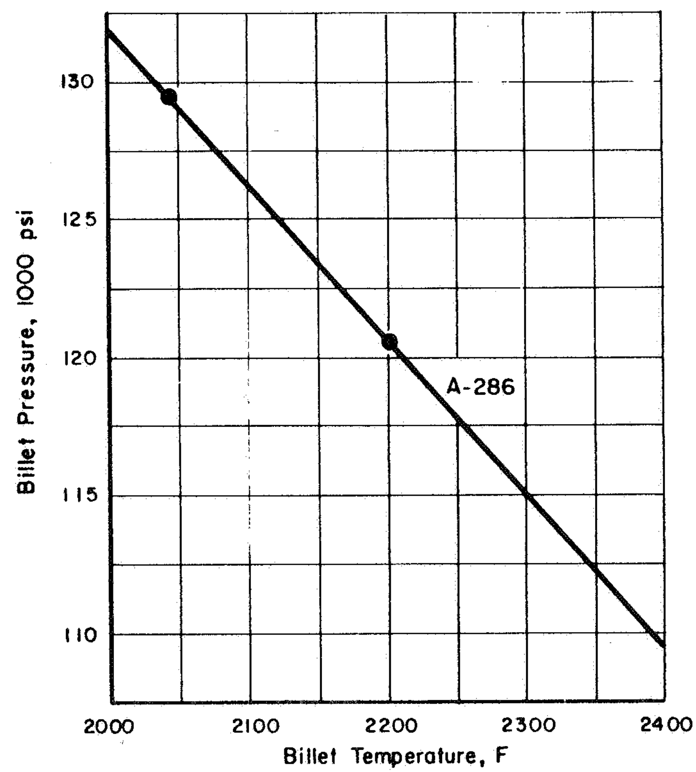


FIGURE 6. BILLET PRESSURE VERSUS TEMPERATURE FOR A-286 EXTRUDED ON A 1650-TON HARVEY PRESS IN A 5-INCH LINER (REF. 13)

The keys to the successful extrusion of these alloys are accurate temperature control and working within a narrow temperature range. Thus, transfer times between the furnace and the extrusion press must be minimized to prevent heat loss. Also, the speed of extrusion must be controlled so that overheating does not result from the heat of deformation, which is generated during extrusion.

Nickel plating of oxidized PH 15-7 Mo at Allegheny Ludlum (Ref. 13) has shown promise for obtaining thin section extrusions. Canning of A-286 in carbon steel removed some of the problems associated with chill of small billets.

Post-Extrusion Processing. Whenever possible, the extruded product is quenched after extrusion to remove any adhering glass. Quenching also prevents hardening by precipitation in some metals. However, air cooling may be required if the extruded cross-sectional area is large or if the alloy is sensitive to quench cracking.

Extrusion products usually require detwisting or straightening on hydraulic torsional stretchers or roll straighteners.

When the alloys are extruded with a metal liner, it is removed by pickling after the part is extruded.

Size Limits. A-286, 17-7 PH, AM-350, and AM-355 have been produced in a variety of shapes including tubing, angles, and tee sections. A complex shape produced in PH 15-7 Mo is shown in Figure 7. The maximum size of extrusion that presently can be made in precipitation-hardening steels fits within a circumscribed circle of 6-1/2 inches. The minimum cross-sectional area is generally determined by the extrusion ratio possible with the alloys for a given shape. For simple shapes and a small billet size of 3 inches, a minimum area might be 0.75 inch square while for a large billet size of 6-1/2 inches, a section area of 5.7 inches square or greater would be required. This condition can sometimes be corrected by extruding more than one shape at a time so that the total area being extruded is increased. High production is normally required before this is practical because the complexity of the dies required generally is not warranted.

The minimum section thickness for production is about 0.150 inch while the length of extrusion ranges from 35 to 60 feet long. Generally the length of extrusion produced is limited by the straightening equipment available rather than by the capabilities of the extrusion equipment. Corner radii between 0.031 and 0.125 inch are producible; fillet radii from 0.125 to 0.250 inch are also considered practical by commercial practice. The minimum radius is generally a function of the shape complexity. Structural angles can be held to a tolerance of ±2 degrees with a camber of 1/8 inch in 5 feet. The twist in small widths of 1.50 inches or less ordinarily does not exceed 0.125 inch in 5 feet. For widths up to 4.00 inches, the twist should not exceed

0.187 inch in 5 feet. The flatness can generally be maintained as 0.010 inch per inch of width. Surface finishes of 63 rms microinches have been obtained although production finishes of 200 to 250 rms are more practical. Tube concentricity of ±10 per cent of the wall thickness can be obtained in production.

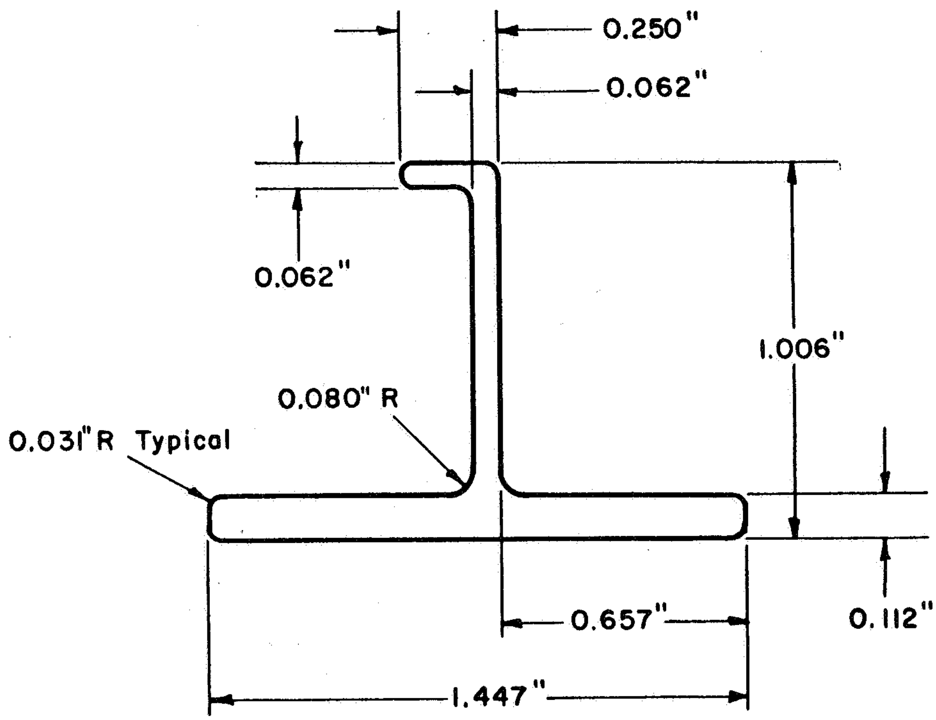


FIGURE 7. CONFIGURATION OF EXTRUDED SHAPE PRODUCE IN PH 15-7 Mo STEEL (REF. 13)

Mechanical Properties of Extrusions. It is difficult to assign minimum properties to precipitation-hardenable stainless steel extrusion because of the limited production and many variations of extrusion techniques. Some of the mechanical property data that has been compiled on typical precipitation-hardenable stainless steel extrusions is shown in Table V.

In general, it has been found that the mechanical properties of extruded alloys are similar to the properties of rolled shapes. In some cases, the transverse properties of the extruded shapes were better than those of rolled shapes.

Extrusion of Powder Compacts. Some recent work at Clevite Corporation (Ref. 19) and IIT Research Institute (Ref. 20) have indicated the feasibility of extruding PH 15-7 Mo starting with a powder compact. Toaz at Clevite found that resistance heating of a

TABLE V. TENSILE PROPERTIES OF EXTRUDED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 18)

Material	Condition	Direction	Extruded Section	Yield Strength (0.29% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Elongation, per cent	Reduction in Area, per Cent
AM-350	1710 F, -100 F 850 F	Longitudinal	Angle	176.0	200.0	30.0	--
AM-355	1710 F, -100 F 850 F	Longitudinal	Shape	173.5	206.0	23.0	49.2
				179.5	210.0	21.0	50.0
AM-355	SCT	Longitudinal	T shape 0.375 x 2.5 x 2	170.7	209.8	18.0	40.0
				186.5	210.3	16.0	41.0
AM-355	SCT	Transverse	T shape 0.375 x 2.5 x 2	163.9	213.9	12.0	31.0
				178.6	213.5	11.0	23.0
17-7 PH	TH 1050	Longitudinal	Angle 1/2 to 1 inch	176.6	190.5	12.0	42.0
		Longitudinal	Angle 1/2 to 1 inch	166.0	185.1	15.0	41.0
		Transverse	Angle 1/2 to 1 inch	185.0	194.0	10.0	31.0
		Transverse	Angle 1/2 to 1 inch	163.2	206.0	10.0	28.0
	TH 950	Longitudinal	Angle 1/2 to 1 inch	110.0	176.2	25.0	35.0
			Angle 1/2 to 1 inch	125.5	188.8	21.0	38.0
		Transverse	Angle 1/2 to 1 inch	165.4	206.5	13.0	32.0
		Transverse	Angle 1/2 to 1 inch	185.6	195.0	15.0	33.0
A-286	1800 F, water quench, 1325 F	--	--	119.5	162.0	29.0	45.2
		--	--	105.0	130.7	27.3	51.0
	1650 F, water quench, 1310 F	Longitudinal	--	85.6	148.5	25.0	42.4
		Transverse	--	88.8	147.4	24.0	33.7
	1750 F, water quench, 1300 F	Longitudinal	Tube 10.7 OD x 6.0 ID	85.8	147.0	25.0	31.0
		Longitudinal	Tube 10.7 OD x 6.0 ID	83.1	145.0	22.0	27.0
		Transverse	Tube 10.7 OD x 6.0 ID	85.0	150.0	26.0	37.0
		Transverse	Tube 10.7 OD x 6.0 ID	82.9	131.0	15.0	20.0

hydrostatically compacted billet of PH 15-7 Mo to 2000 F gave the best results. Glass was found to be superior to the $PbO-SiO_2$ compound as a lubricant at temperatures of 2000 F and above. A reduction ratio of 16:1 was found to give the best yield for the PH 15-7 Mo alloy. The tensile ultimate and yield strength of the extrusions was found to be lower than for wrought material but the ductility was considerably better.

FORGING

Introduction. Forged precipitation-hardenable alloys have found wide acceptance in the aerospace industry for applications at elevated temperatures requiring materials with a high-strength to density ratio. The superior corrosion resistance of these materials compared with the high-strength steels also makes them attractive from the standpoint of maintenance. Some of the alloys are now produced by vacuum-melting techniques to reduce the level of gaseous elements such as nitrogen, which contributes to poor workability and ductility. By suitable metalworking practices, relatively complex shapes can be forged and close tolerances can be held.

Ingots, billets, and bars for forging are generally produced by practices used for conventional austenitic stainless steels. Since the requirements for forging billets are relatively small, the mill suppliers stock a few standard sizes and either cog or hot roll them to the sizes specified by the customer.

Most of the alloys have been produced by arc melting. A recent trend is toward the production of ingots by consumable-electrode, arc-melting practice. Most forging billets are supplied in the overaged condition, which is developed by holding solution-treated material at 1150 F for several hours. The overaging treatment reduces the possibility of stress-corrosion cracking during storage and makes the billets easier to machine. Overaged material must be solution treated prior to precipitation hardening. If the billets are supplied in the solution-treated condition, they may be precipitation hardened directly after forging. A study by Berry, Watmough, and Glassenberg (Ref. 21) has indicated the feasibility of forging a 17-4 PH castings to improve their properties. A recent study by Marschall, Gehrke, Sabroff, and Boulger (Ref. 22) has shown the advantages of using ausforging techniques to secure higher strengths and good toughness in AM-355.

Forgeability. Because of the composition of these alloys, some delta ferrite is usually present in cast ingots. The temperature used in initial ingot breakdown may either increase or decrease the amount of delta ferrite. The semiaustenitic alloys may contain as much as 10 to 20 per cent delta ferrite while the martensitic alloys under proper forging conditions should contain no delta ferrite. The presence of delta ferrite is undesirable because of its mechanical properties.

The range of permissible forging temperatures is generally limited on the low side by a drop in forgeability due to carbide precipitation. For most alloys, this reaction starts at about 1750 F. The formation of additional delta ferrite on heating sets the upper temperature limit. An increase in delta ferrite results in a reduction of ductility. Consequently, the amount of retained delta ferrite determines the forgeability of the alloys. The final properties of the forgings (particularly the transverse ductility) are also degraded by larger amounts of delta ferrite.

The relative forgeability ratings of some of the precipitation-hardenable stainless steels are shown in Table VI. The use of lower forging temperatures and greater stiffness of these alloys requires 30 to 50 per cent higher forging loads than would be required for a typical alloy steel such as AISI 4340. The precipitation-hardenable stainless steels are much less sensitive to decarburization than the high-carbon low-alloy steels. Since scaling is less severe, it is possible to use some precipitation-hardenable stainless steel forgings with as-forged surfaces.

Forging Practice. The basic composition of the precipitation-hardenable stainless steels are similar to the 18-8 grades so that the general forging conditions are not too different. Differences in forging practices will be emphasized.

TABLE VI. RELATIVE FORGING BEHAVIOR OF TYPICAL PRECIPITATION-HARDENABLE STAINLESS STEELS (REFS. 23-25)

Variables	Alloys					
	17-7 PH	AM-355	17-4 PH	AM-350	PH 15-7 Mo	A-286
Forging temperature	2150 F	2150 F	2150 F	2150 F	2100 F	2150 F
Decarburization	Low	Low	Low	Low	Low	Low
Scale	Low	Low	Low	Low	Low	Low
Grain-size control	Fair	Fair	Good	Fair	--	Fair
Forgeability	Fair	Good	Good	Good	Fair	Fair
Forging pressure (relative)[a]	1.4	1.4	1.4	--	--	--
Thermal cracking	None	Low	Medium	Low	None	None
Die wear	Medium	Medium	Medium	--	--	--

(a) AISI 4340 considered as 1.

Alloys such as PH 15-7 Mo and 17-7 PH contain two phases (martensite and carbide), a characteristic that affects forgeability. At temperatures above 1700 F, they behave like the 18-8 grades of stainless and have good forgeability, but at lower temperatures the forgeability is poorer because of carbide precipitation.

Forgeability characteristics of the martensitic grades of precipitation-hardenable alloys are about the same as those of the 12 to 14 per cent chromium stainless steels such as Type 410. Alloys such as 17-4 PH can be forged with excellent reproducibility of shape and mechanical properties provided care is taken to avoid overheating at the center of heavy sections from excessively heavy or rapid reductions. Thermal cracking may occur if overheating is not prevented.

The semiaustenitic precipitation-hardenable stainless steels (17-7 PH, PH 15-7 Mo, and AM-350) are susceptible to cracking during forging, and consequently require more forging steps than the other alloys to permit surface conditioning between steps. These alloys have a tendency to retain the austenitic structure at room temperature after forging at or above 2000 F. Grain refinement is obtained by heating the forgings at about 1400 F to promote the austenite transformation to martensite. Care should be exercised in the use of this treatment, however, since it causes carbide precipitation, makes the austenite less stable, and may result in complete transformation to martensite on cooling to room temperature. This condition is favorable for subsequent heat treatment and grain refinement.

Since the delta ferrite contents of these alloys may range from 0 to 15 per cent at room temperature, it is common practice to determine the content before forging. Stringers of ferrite on the surfaces of the billet may cause rupture during forging depending on the amount of reduction. Delta ferrite in other locations of the billet has little effect on forgeability but may reduce the transverse ductility of the forgings.

A number of factors should be considered when selecting the temperature for forging the precipitation-hardenable stainless steels. The rate and amount of deformation, grain growth, transformation, to delta ferrite and type of subsequent heat treatment should be considered. Temperatures higher than the initial forging temperature can be developed in the billet by excessively fast or heavy reductions. High temperatures result in larger amounts of delta ferrite. Consequently, delta ferrite cracking may occur even though the initial billet temperature was below the delta ferrite formation temperature. The forging temperature should be lowered 100 F when fast reductions are used.

Alloys that retain austenite to room temperature do not respond to grain-refining heat treatments. Care must therefore be taken to avoid forging temperatures that will cause excessive grain growth. This is especially true when only light reductions are taken. A limit of approximately 2100 F for forgings with light reductions has been used.

Forging temperatures recommended for some of the precipitation-hardenable stainless steels are given in Table VII. The effect of per cent reduction on the initial forging temperature is shown by the decrease in forging temperature with increasing per cent reduction.

Billets of precipitation-hardening steels are usually preheated at 1200 to 1400 F for a time sufficient to equalize the temperature before they are charged into a furnace at the forging temperature in order to avoid internal cracks. A section thickness of 8 to 10 inches could be preheated to a maximum temperature of 1600 F while a billet thickness of 4 inches or less might be charged directly into a furnace at the forging temperature. The time required for the temperature of a billet to equalize is dependent on the billet thickness. When heating directly to the forging temperature, 1/2 hour should be allowed for each inch of billet thickness. A billet of 3-inch thickness or greater should have a soaking time at temperature of 1 hour minimum before forging.

TABLE VII. FORGING TEMPERATURES RECOMMENDED FOR PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 23)

Alloy	Maximum Forging Temperature, F	Recommended Temperatures for Forgings Receiving Given Nominal Amounts of Reduction, F: Light (Up to 15 Per Cent)	Moderate (15 to 50 Per Cent)	Severe (Over 50 Per Cent)	Variable[a]
		Austenitic			
A-286[Ref. 24]	2150	1800	2100	2150	2100
		Semiaustenitic			
AM-350	2150	2100	2150	2150	2100
AM-355	2200	2000	2150	2150	2000
17-7 PH	2200	2050	2150	2200	1950
PH 15-7 Mo	2250	2000	2100	2150	2000
		Martensitic			
Stainless W	2250	2050	2200	2200	2050
17-4 PH	2200	2100	2150	2150	2100

(a) Variable reduction – This refers to forgings receiving widely differing reductions. End upsets, for example, receive large reductions on the upset end while the shaft may remain essentially undeformed.

When a hot-forging billet is placed in a cold die, the surface of the billet is chilled very rapidly to a lower temperature. Consequently, the time required to complete the forging operation is going to have a significant effect on the final forging temperature and the forging pressure. The effect of forging time on the pressure required and of the final temperature on the forging billet is shown in Figure 8 for A-286. An assumed cooling rate of 200 F per second was used in establishing the temperature curve.

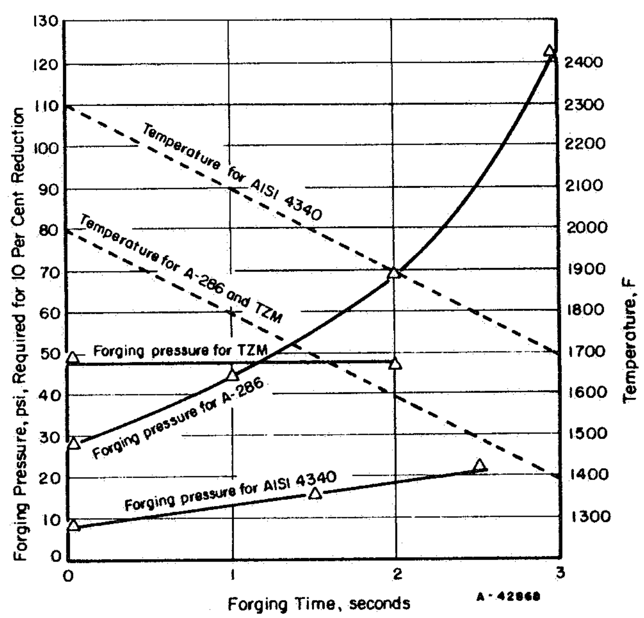


FIGURE 8. EFFECT OF DIE QUENCHING ON FORGING-PRESSURE REQUIREMENTS FOR A-286 (REF. 26)

Control of the cooling rate after forging is essential to avoid cracking. The martensitic types are more susceptible to cracking upon cooling than the other types due to the transformation to martensite. General practice is to return sections thicker than 3 inches, and smaller intricate forgings, to the heating furnace for equalizing at the forging temperature prior to cooling. Large sections should be cooled slower than the thinner sections. This is sometimes accomplished by covering the forgings with a thin steel sheet to prevent drafts from hitting the part.

The heating of the precipitation-hardenable steels in a reducing atmosphere should be avoided to prevent pickup of nitrogen or carbon. Heating in an atmosphere of cracked ammonia should also be avoided. An oxidizing atmosphere should be used for all heating. Although this will result in some scale, the scale can be removed by pickling in a nitric-hydrofluoric acid mixture or by grit blasting. In pickling for the removal of scale, care should be taken to avoid intergranular corrosion by limiting the time in the pickling solution. A part with high residual stresses is susceptible to intergranular corrosion. When a part is forged to final shape, it is best to remove scale by vapor blasting. Before a billet is heated for forging, all carbonaceous lubricants should be removed from its surface. The presence of foreign materials can cause carburization of the material or nitrogen pickup. Carburization or nitrogen pickup produces a more stable austenite.

The lubrication practices for the precipitation-hardenable stainless steels are the same as those used for the austenitic stainless steels. The lubricant should be controlled by placing only a smooth, thin coating on the billet to reduce surface-metal flow when forging parts with thin webs. Large surface deformations that might occur in some areas if the lubricant is not uniform will exaggerate rupturing from the presence of delta ferrite on the surface.

Cold Forging. No specific information on the cold-forgeability of precipitation-hardenable stainless steels has been found. Based on forging experience with 18-8 grades of stainless steel, reductions in the neighborhood of 20 per cent would be possible with the semiaustenitic and austenitic alloys. Coining to close-dimensional tolerances is possible because the soft austenitic structure of these materials has a relatively low strength before final heat treatment. The semiaustenitic steels, however, are susceptible to transformation from cold work. When these alloys are forged to final dimensions, a growth factor of about 0.004 inch per inch must be allowed for in the design of the dies. This growth occurs during final heat treatment.

The martensitic types should not be cold forged due to the reduced ductility of the martensitic structure.

Forging Tolerances. The forging tolerance obtained depends to some extent on the type of forging operation. When surfaces of a forging are to be left without any machining, a closed-die type of forging generally is used. With this type of forging, the size, complexity, forging properties, and economy factors affect the dimensional tolerances. Sharp fillets, wide thin webs, and high ribs, or bosses are difficult to forge. A machining allowance must also be considered when establishing the design and tolerances required. Typical fillet radii and machining allowances for A-286 and 17-7 PH are given below (Ref. 25):

	Fillet Radii, inch		Machining Allowance, inch	
Alloy	Preferred	Minimum	Conventional	Close Tolerance
A-286	1/2 to 3/4	1/4 to 3/8	0.015 to 0.06	--
17-7 PH	1/4 to 1/2	3/16	0.015 to 0.06	0.015

The fillet radii values are for 1-inch-high ribs; corner radii can be about half as large. The machining allowance is for each surface.

Such other factors as die-closure tolerance, draft-angle tolerance, and dimensional tolerance should also be considered. The draft angles and tolerances recommended by the ASM Committee on Drop Forgings (Ref. 27) are listed in Table VIII. The dimensional tolerances increase with the area and the weight of the forging. Dimensional, mismatch, and die-wear tolerances for steel forgings, which apply to the precipitation-hardenable stainless steels, are given in Table IX. As the tolerances build up on a forging, so does the excess weight and the amount of material that must be removed by machining. Closer tolerances increase forging costs. The total effect on the cost of a finished component depends on the material and machining costs as well as the tooling costs. This is shown schematically in Figure 9 for a particular lot size. Proceeding from a "blocker" forging to a precision forging results in lower material and machining costs but increases the tooling costs. Total cost for close-tolerance forging is generally lower but increases for precision forging, depending on the cost of material and the relative difficulty of forging and machining operations. The costs also depend, to a considerable extent, on the total production quantity involved.

TABLE VIII. DRAFT AND DRAFT TOLERANCES FOR STEEL FORGINGS (REF. 27)

Height or Depth of Draft, in.	Commercial Standard Draft, deg	Commercial Standard Tolerance Plus[a], deg	Special Standard Draft deg	Special Standard Tolerance Plus[a], deg
		Outside Draft		
1/4 to 1/2	--	--	3	2
3/4 to 1	5	3	--	--
Over 1/2, up to 1	--	--	5	2
Over 1, up to 3	7	3	5	3
Over 3	7	4	7	3
		Inside Draft		
1/4 to 1	7	3	5	3
Over 1	10	3	10	3

(a) The minus tolerance is zero.

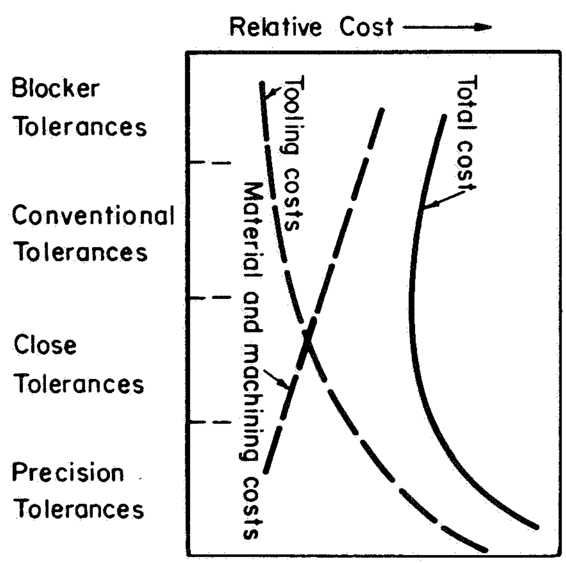


FIGURE 9. SCHEMATIC DIAGRAM OF THE EFFECT OF TOLERANCES ON THE COST OF PRODUCING A FORGING (REF. 26)

TABLE IX. RECOMMENDED COMMERCIAL TOLERANCES FOR STEEL FORGINGS (REF. 25)

Forging Size		Tolerance, inch			
Area, sq in.	Weight, lb	Plus	Minus	Mismatch (Plus)	Die Wear (Plus)
5.0	1.0	0.031	0.016	0.016-0.031	0.031
7.0	7.0	0.062	0.031	0.016-0.031	0.062
10.0	1.5	0.031	0.031	0.016-0.031	0.031
12.0	12.0	0.062	0.031	0.010-0.031	0.062
20.0	2.0	0.062	0.031	0.016-0.031	0.062
20.0	30.0	0.062	0.031	0.020-0.040	0.062
38.0	4.5	0.062	0.031	0.016-0.031	0.062
38.0	80.0	0.062	0.031	0.025-0.050	0.062
50.0	8.0	0.062	0.031	0.020-0.040	0.062
50.0	60.0	0.062	0.031	0.020-0.040	0.062
50.0	100.0	0.062	0.031	0.025-0.050	0.062
95.0	11.0	0.062	0.031	0.020-0.040	0.062
132.0	17.0	0.062	0.031	0.025-0.050	0.062
166.0	73.0	0.094	0.031	0.030-0.060	0.094
175.0	150.0	0.094	0.031	0.030-0.060	0.094
201.0	40.0	0.062	0.031	0.025-0.050	0.062
240.0	51.5	0.094	0.031	0.030-0.060	0.094
250.0	250.0	0.094	0.031	0.030-0.060	0.094
265.0	60.0	0.094	0.031	0.030-0.060	0.094
275.0	65.0	0.125	0.031	0.047-0.094	0.125
300.0	75.0	0.125	0.062	0.047-0.094	0.125
300.0	350.0	0.094	0.031	0.030-0.060	0.094
375.0	450.0	0.125	0.031	0.047-0.094	0.125
415.0	306.0	0.125	0.062	0.047-0.094	0.125
525.0	750.0	0.125	0.062	0.047-0.094	0.125
900.0	1000.0	0.125	0.062	0.047-0.094	0.125

Properties of Stainless Forgings. The properties of precipitation-hardenable stainless steel forgings depend on the final temperature of forging and reduction as well as the final heat treatment given the materials. Many properties are obtainable by variations in the processing sequence. Some of the typical mechanical properties obtained in several alloys after different heat treatments are given in Table X.

Examples of Stainless Forgings. Some typical examples of precipitation-hardenable stainless steel forgings are shown in Figures 10 and 11. Figure 10 shows a 17-4 PH forging after machining and heat treatment. The forging was obtained in the annealed

TABLE X. MECHANICAL PROPERTIES OF TYPICAL PRECIPITATION-HARDENABLE STAINLESS STEEL FORGINGS (REF. 26)

Alloy	Size of Stock	Direction of Test	Heat Treatment	Tensile Strength, 1000 psi	0.2% Offset Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Ferrite Content, per cent
17-4 PH	8-in. square	T	Annealed plus H 925	188.0	171.0	5.0	5.4	--
		T	Homogenized plus annealed plus H 925	188.0	170.0	12.5	33.2	--
17-4 PH	4-in. slab	L	Annealed plus H 925	194.8	--	17.0	53.5	--
		T	Annealed plus H 925	195.0	--	4.5	5.0	--
		T	Homogenized plus annealed plus H 925	195.2	--	10.5	26.0	--
AM-355	--	T	Not given	178.0	--	22.0	--	0
17-7 PH	--	T		184.0	--	19.0	--	0
		T		180.0	--	5.0-8.0	--	0 to 2
		T		180.0	--	0-3	--	Over 2
15-7 Mo	--	T		205.0	--	1-4	--	Above 2
		T		195.0	--	4-9	--	Above 2

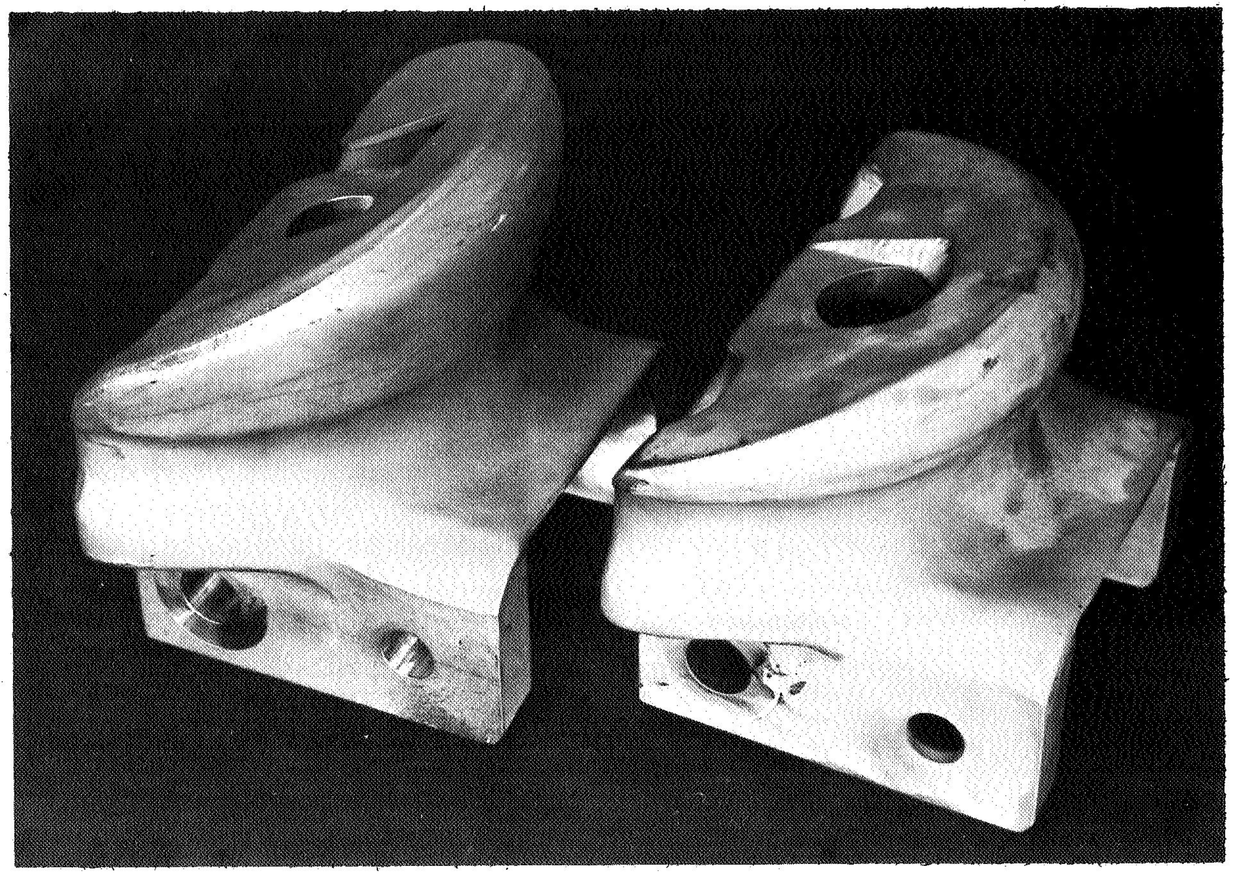


FIGURE 10. FORGED 17-4 PH ARRESTING GEAR HOCK FOR THE RA5 AIRCRAFT

Courtesy of North American Aviation, Inc., Columbus, Ohio.

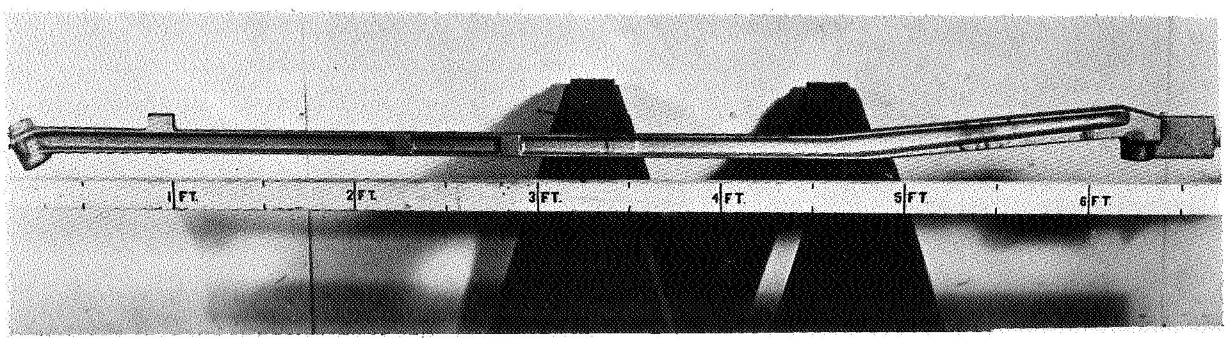


FIGURE 11. FORGED A-286 ARRESTING GEAR ARM FOR THE T2B

Courtesy of North American Aviation, Inc.,
Columbus, Ohio.

Material - A-286
Weight - 41.2 lb.

condition and machined prior to heat treatment. The arresting gear arm shown in Figure 11 was forged from A-286. It also was machined in the annealed condition and hardened after finishing. Both of these parts were made from precipitation-hardenable stainless steel because they are subjected to high temperature near the engine exhaust on jet aircraft. The corrosion resistance of the material is also of advantage since they are heated and cooled in a salt-water environment.

DRAWING

Drawing is a cold-working process in which the cross section of a long workpiece is reduced by pulling it through a die. Semi-finished shapes are cold drawn into rod, wire, and tube products for a variety of applications. Drawing is capable of producing products with better finishes, closer tolerances, and thinner sections than hot-working processes. Cold-drawn products made from precipitation-hardenable stainless steels have a variety of applications. For instance, helical, high-temperature compression springs are produced from the 17-7 PH, PH 15-7 Mo, AM-350, and AM-355 alloys. The limiting service temperature of these springs is 100 to 150 F higher than that of Type 302 stainless steel springs, bringing their useful operating temperature to within about 50 F of the more costly Inconel X-750 nickel-base alloy. Springs from these precipitation-hardening alloys are not subject to hydrogen embrittlement after pickling, as are the low-alloy steels or hardened standard stainless steels.

The 17-7 PH and the PH 15-7 Mo grades as well as Stainless W are extensively used as fasteners for jet engines and other aircraft, and missile applications where high strength and corrosion resistance are important. Some of the alloys such as A-286, AM-350, 17-7 PH, and PH 15-7 Mo are used as tubing for both hydraulic and deicing systems on aircraft.

Rod and Wire Drawing. Introduction. Large-diameter rod is cold drawn in straight lengths on a standard drawbench. Individual bull blocks are used for drawing 1/2 to 1-inch-diameter rod. A block is a drum, ordinarily driven by an individual motor, that pulls the rod or wire through the die and produces a coil.

Hot-rolled wire rod approximately 0.25 inch in diameter is annealed and pickled prior to the start of cold drawing. The techniques for drawing the precipitation-hardening stainless steels are very similar to those used for the regular grades of stainless steels except that intermediate annealing generally must be more frequent. This is because the precipitation-hardenable grades usually have higher work-hardening rates. Where the regular stainless grades can be reduced about 75 per cent in area between anneals, many of the precipitation-hardenable grades must be annealed after a 50 per cent reduction (Ref. 28). Reductions per pass average about 20 per cent and the drawing of hot-rolled rod is normally done on multiple-pass machines.

In-process annealing may be done in either a gas-fired furnace or in a salt bath, and a typical annealing temperature for grades such as AM-350 or AM-355 is 1900 F. Best drawing properties are obtained with these grades by a duplex anneal consisting of (Ref. 28)

(a) Heating at 1425 F for 2 hours and air cooling

(b) Heating at 1100 F for 2 hours and air cooling.

An exception among the precipitation-hardenable stainless steels, with regard to their high work-hardening rates, is Almar 362. This maraging grade has a low work-hardening rate, and wire has been drawn as much as 98 per cent without annealing (Ref. 29). Thus, it can be processed by techniques used for the regular stainless grades.

Coatings. A number of coating materials have been used as carriers to facilitate lubrication during drawing (Ref. 30). These include lead, lime, borax, and oxalate. Lead, applied by dipping the cleaned wire into molten lead using a flux, has performed well for many years. However, lead fumes are toxic and the need for good ventilation has brought about a gradual shift to other coatings. Lime coatings usually in conjunction with borax and other materials are also used. The oxalate coatings appear to have some advantages over lime and lead because they are simple to apply and remove and give a better surface to the finished product, especially when used in a plug draw. These coatings are gaining acceptance especially by spring manufacturers, one of the principal users of lead coatings.

Equipment. Rods and wires generally are pointed by swaging. Drawing of the stainless steels is usually done on multiple-die machines with dry-soap lubricants. Figure 12 shows schematic drawings of two types of machines used to draw stainless steel wire with dry lubricants. In the first type of machine, shown in Figure 12a, the wire is drawn and stored on accumulator blocks before passing to the next die. A single motor is used to drive all the blocks that mechanically engage and disengage the main drive shaft. Capstans and blocks usually are air cooled.

The second type of machine as shown in Figure 12b, is characterized by individual, variable-speed, direct-current motors whose speeds are regulated by a dancer arm that controls the speed at which the capstan revolves. Both air and water cooling is utilized with this type equipment. Wires drawn to about 0.050-inch diameter are drawn with dry-soap lubricants.

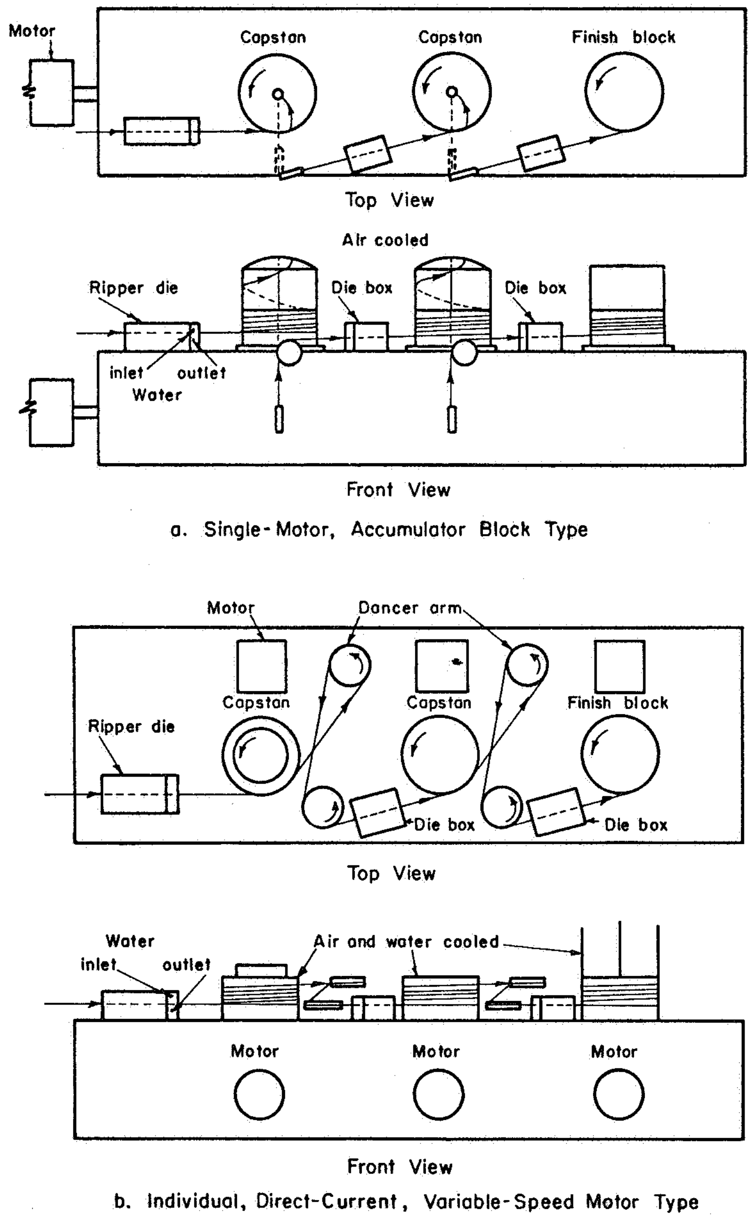


FIGURE 12. SCHEMATIC DRAWINGS OF TWO TYPES OF WIRE-DRAWING MACHINES (REF. 30)

Dies having 12-degree approach angles well blended into a bearing of 25 to 50 per cent, which in turn is blended into a relief angle of 90 degrees, are used for drawing stainless steel rod and wire (Ref. 30). For wire sizes smaller than about 0.050-inch diameter, wet-wire-drawing techniques are used. Figure 13 shows a schematic drawing of one type of machine used with this practice. The wire is first passed through a ripper die where it is drawn with a dry-soap lubricant. The wire then is passed into the wire-drawing tub and is alternately passed from one capstan through the die to the other capstan and then back to the first capstan. The capstans either may be stepped, as shown, or tapered. This cycle is repeated to achieve the desired number of reductions. The drawing tub is filled with a liquid lubricant, which may contain vegetable soaps and emulsions as lubricants. After passing through the finish die, the wire is straightened on the "killer" or straightener and then spooled.

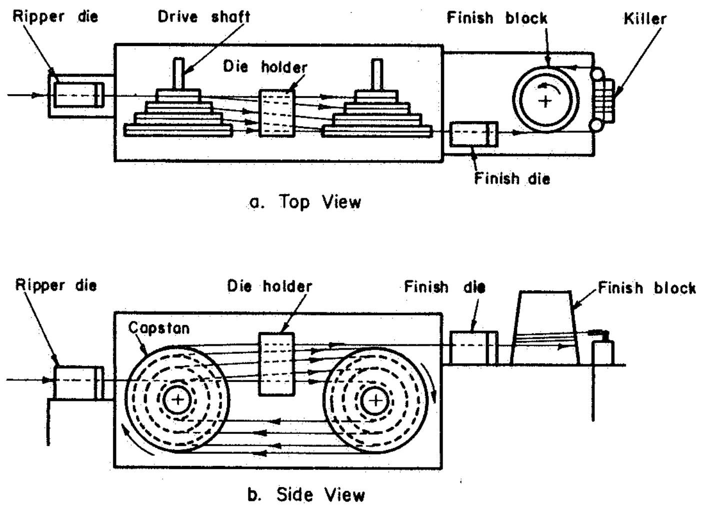


FIGURE 13. SCHEMATIC DRAWING OF WET-WIRE-DRAWING MACHINE (REF. 30)

Both dry and wet lubricants may contain molybdenum disulfide or other additives. Copper coatings frequently are used on wire or rod that is to be used for the cold heading of fasteners (bolts, rivets, etc.).

Figure 14 is a photograph of a versatile wire-drawing machine designed to draw wire having a maximum diameter of 0.037 inch either wet or dry. The machine has a self-contained lubricant tank and pump for circulating the liquid lubricants. Machines of this type, containing up to about 20 dies, are available.

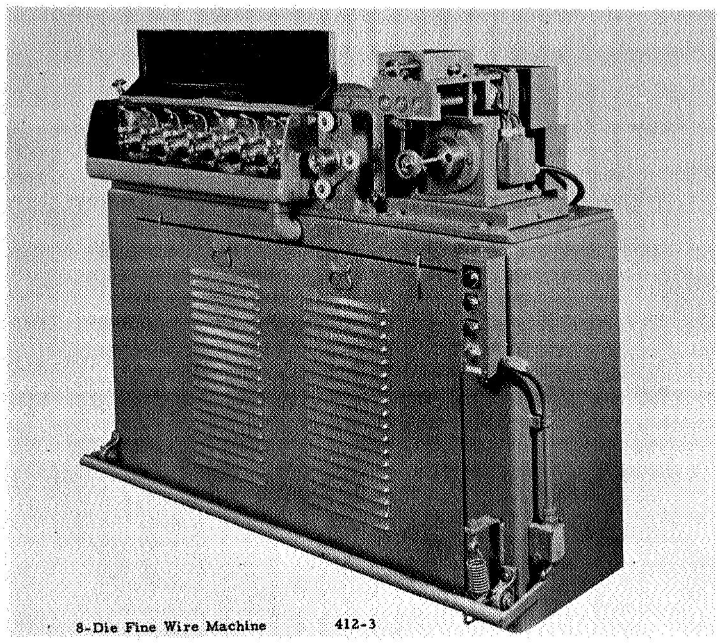


FIGURE 14. EIGHT-DIE FINE-WIRE MACHINE

Courtesy of the Vaughan Machinery Company, Cuyahoga Falls, Ohio.

Properties of Drawn Wire and Rod. Tables XI, XII, and XIII give properties of 17-7 PH, Almar 362, and AM-350 stainless steel wire in various diameters after cold drawing, and after various aging treatments. These data indicate the high strengths that can be developed in these alloys. These values are considered typical of the strengths that can be obtained in some of the other grades of precipitation-hardenable stainless steel wire.

Table XIV gives short-time tensile data for 1/8-inch-diameter wire of the AM-350 alloy at temperatures from room to 850 F. A gradual decrease in strength occurs with increasing test temperature. However, the ductility of the wire does not increase with decreasing strength and increasing test temperature as might be expected.

Table XV gives typical tensile strengths for AM-350 and AM-355 bar stock when tempered after drawing at 800 to 1100 F. Slightly higher strengths are shown for AM-355 than for AM-350. Higher strengths in each grade are produced by tempering at 850 F.

TABLE XI. SPECIFICATION REQUIREMENTS FOR 17-7 PH STAINLESS STEEL WIRE (REF. 31)

Wire Diameter, inch	Condition C[(a)], 1000 psi range	Condition CH 900[(b)], 1000 psi range
0.030-0.041[(c)]	260-290	320-350
0.042-0.051[(c)]	255-285	310-340
0.052-0.061[(c)]	250-280	305-335
0.062-0.071	242-272	297-327
0.072-0.086	240-270	292-322
0.087-0.090	230-260	282-312
0.091-0.100	227-257	279-309
0.101-0.106	223-253	274-304
0.107-0.130	221-251	272-302
0.131-0.138	215-245	260-290
0.139-0.146	213-243	258-288
0.147-0.162	211-241	256-286
0.163-0.180	209-239	254-284
0.181-0.207	207-237	252-282
0.208-0.225	203-233	248-278
0.226-0.306	198-228	242-272
0.307-0.440	192-222	235-265

(a) Solution treated and cold drawn.
(b) Cold-drawn wire (Condition C) heated at 900 ± 10 F for 1 hour and air cooled to room temperature.
(c) Produced in coils only.

TABLE XII. TENSILE PROPERTIES OF ALMAR 362 COLD-DRAWN WIRE CONTAINING 0.88 PER CENT TITANIUM IN THREE DIAMETERS AGED AFTER DRAWING (REF. 29)

Wire Diameter, inch	Cold Reduction, per cent	Aging Treatment		Yield Strength (0.2% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Reduction in Area, per cent
		F	Hours			
0.111	88	None	--	165	185	20
		800	4	210	225	25
		850	4	215	230	30
		900	4	210	225	45
		950	4	205	220	40
0.083	10	None	--	131	136	70
		900	4	192	194	58
	75	900	4	196	202	47
	89	900	4	201	205	50
0.009	80	None	--	210	235	--
		800	1	256	257	--
		850	1	250	251	--
		900	1	250	250	--
		950	1	240	240	--

TABLE XIII. TENSILE PROPERTIES OF 1/8-INCH-DIAMETER AM-350, COLD-DRAWN STAINLESS STEEL WIRE AFTER VARIOUS AGING TREATMENTS (REF. 32)

Values are averages of triplicate tests.

Cold Reduction, per cent	Aging After Annealing at 1900 F: Temp, F	Aging After Annealing at 1900 F: Time, min	Hardness, R_C[(a)]	Yield Strength (0.2% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Per Cent Elongation in 1/2-Inch Gage Length	Reduction in Area, per cent	Modulus of Elasticity, 10^6 psi
30	None		44.5	200	227	15	49	28.4
50	None		47.5	249	275	13	46	29.3
70	None		52.5	321	338	11	47	28.3
30	750	10	45.0	216	232	15	56	29.6
50	750	10	48.0	258	272	14	52	29.4
70	750	10	53.0	324	340	12	51	29.2
30	750	180	44.0	217	231	17	55	30.9
50	750	180	48.5	264	279	14	55	29.4
70	750	180	54.0	334	344	12	51	28.9
30	800	10	43.5	217	231	18	55	31.0
50	800	10	48.0	256	271	15	56	29.4
70	800	10	53.0	330	339	11	52	29.0
30	850	10	45.0	213	226	18	55	28.3
50	850	10	48.5	259	272	12	55	30.0
70	850	10	53.0	321	335	11	54	29.5
30	900	10	44.0	215	230	18	54	30.2
50	900	10	47.5	253	268	14	55	29.4
70	900	10	53.5	329	339	11	55	28.9
30	900	180	41.5	205	218	17	59	29.1
50	900	180	46.5	248	260	14	56	29.3
70	900	180	51.5	310	330	13	55	29.1

(a) Converted from R_{45N} readings.

TABLE XIV. ELEVATED-TEMPERATURE TENSILE PROPERTIES OF 1/8-INCH-DIAMETER COLD-DRAWN AM-350 STAINLESS STEEL WIRE (REF. 32)

Wires aged for 10 minutes at 750 F after drawing.

Cold Reduction per cent	Test Temperature, F	Hardness, R_C[(a)]	Yield Strength (0.2% Offset), 1000 psi	Ultimate Strength, 1000 psi	Per Cent Elongation in 1/2-Inch Gage Length	Reduction in Area, per cent	Elastic Modulus, 10^6 psi
30	RT	45.0	216	232	15	56	29.6
50	RT	48.0	258	272	14	52	29.4
70	RT	53.0	324	340	12	51	29.2
30	200	42.0	201	216	8	48	29.1
50	200	50.0	245	266	3	40	28.5
70	200	54.0	305	319	--	37	27.8
30	400	47.0	182	209	16	45	30.7
50	400	50.0	221	249	--	39	27.2
70	400	54.0	295	309	--	30	27.3
30	600	45.0	177	214	11	39	26.6
50	600	49.0	221	252	10	38	25.9
70	600	54.0	270	302	--	28	27.3
30	650	47.0	172	208	15	40	26.0
50	650	48.0	223	248	--	39	22.7
70	650	53.0	263	293	4	32	25.9
30	700	49.0	164	205	16	45	25.0
50	700	50.0	197	238	10	34	25.3
70	700	54.0	263	286	6	21	20.9
30	800	46.0	163	203	14	44	25.6
50	800	48.0	191	232	--	39	25.3
70	800	41.0	226	274	--	19	26.6
30	850	41.0	157	187	12	19	22.8
50	850	49.0	192	221	11	39	25.3
70	850	55.0	221	262	--	10	23.4

(a) Converted from R_{45N} readings.

than by tempering at 1000 or 1100 F. The merits of vacuum melting or inert-atmosphere melting of the AM-355 grade compared with air melting are shown by both higher transverse strengths and higher ductility values.

TABLE XV. EFFECT OF TEMPERING TEMPERATURE ON ROOM-TEMPERATURE PROPERTIES OF AM-350 AND AM-355 BAR STOCK (REF. 33)

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Per Cent Elongation in 2-Inch Gage Length	Reduction in Area, per cent	Hardness, RC
			AM-350		
850	162	198	15.0	49.0	47
1000	150	164	22.0	53.0	40
1100	108	151	20.0	50.0	35
			AM-355 (Longitudinal)		
850	182	216	19.0	38.5	--
1000	171	186	19.0	57.0	--
			AM-355 (Transverse)		
850(a)	185	220	11.5	20.5	--
1000(a)	169	184	14.8	39.5	--
850(b)	168	207	5.3	7.6	--

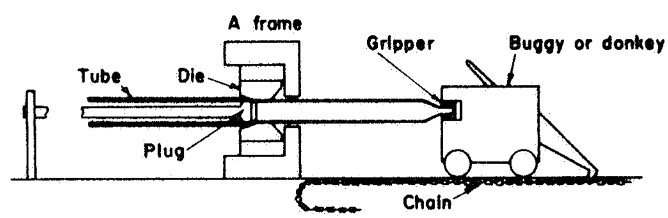
(a) From bar stock that was consumable electrode remelted in argon or vacuum.
(b) From bar stock that was arc melted in air atmosphere.

Table XVI gives typical tensile properties of AM-355 stainless steel bar stock at temperatures up to 1000 F. These are short-time properties and are not typical of the properties that might be attained during long-time exposures at the test temperatures. Although both yield and ultimate tensile strength drops with increasing temperature of test, no corresponding increase in ductility is evident. The change in reduction in area values also are not linear with variations in testing temperature.

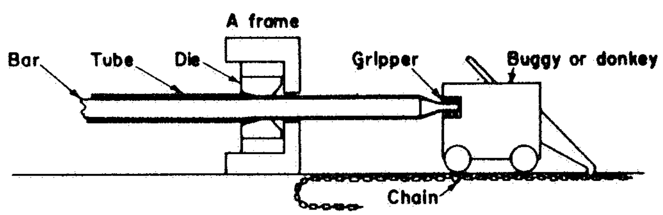
Tube Drawing. Tube drawing consists of reducing the diameter or wall thickness, or both, of a hollow cylinder by using a drawbench and suitable dies and lubricants. The tube blank can be produced by (a) hot extrusion, (b) hot rolling and piercing a billet, or (c) welding of a roll-formed strip or sheet. Figures 15a and 15b

TABLE XVI. EFFECT OF TESTING TEMPERATURE ON THE TENSILE PROPERTIES OF AM-355 BAR STOCK[a] (REF. 33)

Testing Temperature, F	Tempering Temperature, F	Yield Strength 0.02% Offset, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Ultimate Tensile Strength, 1000 psi	Per Cent Elongation in 2 Inch-Gage Length	Reduction in Area, per cent
70	850	142	182	216	19.0	38.5
	1000	147	171	186	19.0	57.0
400	850	123	163	207	15.5	45.0
	1000	128	152	166	16.0	59.5
600	850	110	152	210	11.5	35.5
	1000	123	143	159	14.0	49.0
800	850	98	139	198	11.0	35.5
	1000	107	128	140	15.0	53.5
1000	850	65	97	144	16.0	57.0
	1000	70	96	115	19.0	65.0



a. Drawbench Using Plug



b. Drawbench Using Bar

FIGURE 15. SCHEMATIC DRAWING OF TUBE DRAWBENCH (REF. 30)

show a tube drawbench that uses a plug mandrel and a solid-bar mandrel, respectively. Sometimes the tube is sized by drawing through a die without a plug or mandrel supporting the inside diameter. Such tube drawing is called tube sinking.

The tube blank is pointed by hot forging, rotary swaging, or squeezing to permit passing the reduced end through the tungsten carbide drawing die and grasping it with the gripper. As for bar and wire drawing, oxalate coatings also have largely replaced lead coatings. Often liquid lubricants such as chlorinated oils or greases are used both in conjunction with coatings and without prior coatings.

Tubes of most grades of precipitation-hardenable stainless steels cannot be reduced as heavily as the regular stainless steel grades between anneals. All drawing lubricants and coatings must be removed after drawing; this may be accomplished in an alkali cleaner followed by rinsing and then pickling in nitric acid. Tubes may be solution treated after drawing or they may be merely hardened by precipitation treatments. Sometimes the tubes are both solution treated and aged after tube drawing.

Table XVII lists available sizes of precipitation-hardenable stainless steel mechanical aircraft tubing supplied by one producer. Most of these high-strength tubes are available in straight lengths up to 24 feet. Many sizes are also available in coils. The AM-350 and Almar 362 grades also can be obtained in tube form. Table XVIII gives tensile data on cold-drawn seamless Almar 362 tubing after various percentages of cold reduction prior to aging. Larger reductions produce higher strengths with only little decrease in ductility.

SECONDARY DEFORMATION PROCESSES

The primary wrought products (sheet, plate, bar, tubing, extrusions) can be converted to more useful shapes by secondary deformation processes. All of the conventional techniques used for that purpose have been applied successfully to precipitation-hardenable stainless steels. Descriptions of many of the common sheet- and tube-forming processes and the limits imposed by the characteristics of the materials of interest are covered in this section of the report.

The severity of deformation required to produce a part depends on the relative shapes and dimensions of the blank or

TABLE XVII. SIZE LIMITS OF PRECIPITATION-HARDENABLE STAINLESS STEEL TUBING AVAILABLE FROM ONE PRODUCER[(a)]

A-286 Seamless Standard			17-7 PH Welded Special			PH 15-7 Mo Welded Special		
Outside Diameter, in.	Wall Thickness, in. Min	Max	Outside Diameter, in.	Wall Thickness, in. Min	Max	Outside Diameter, in.	Wall Thickness, in. Min	Max
0.012	0.002	0.004	0.012	0.002	0.004	0.012	0.002	0.004
0.0312	0.002	0.010	0.0312	0.002	0.010	0.0312	0.002	0.010
0.0625	0.003	0.028	0.0625	0.003	0.020	0.0625	0.003	0.015
0.0937	0.004	0.042	0.0937	0.004	0.028	0.0937	0.004	0.020
0.125	0.004	0.049	0.125	0.004	0.035	0.125	0.004	0.028
0.1875	0.004	0.065	0.1875	0.004	0.042	0.1875	0.004	0.035
0.250	0.005	0.083	0.250	0.005	0.049	0.250	0.005	0.035
0.3125	0.005	0.109	0.3125	0.005	0.049	0.3125	0.005	0.035
0.375	0.005	0.125	0.375	0.005	0.065	0.375	0.005	0.042
0.4375	0.005	0.125	0.4375	0.005	0.065	0.4375	0.005	0.042
0.500	0.005	0.125	0.500	0.005	0.065	0.500	0.005	0.049
0.5625	0.006	0.125	0.5625	0.006	0.065	0.5625	0.006	0.049
0.625	0.006	0.125	0.625	0.006	0.065	0.625	0.006	0.049
0.750	0.006	0.035	0.750	0.006	0.035	0.750	0.006	0.035
0.875	0.006	0.035	0.875	0.006	0.035	0.875	0.006	0.035
1.000	0.007	0.035	1.000	0.007	0.035	1.000	0.007	0.035
1.125	0.008	0.035	1.125	0.008	0.035	1.125	0.008	0.035

(a) Data taken from Bulletin No. 43, "A Guide to the Selection and Application of Superior Tubing", Superior Tube, Norristown, Pennsylvania.

TABLE XVIII. TENSILE DATA ON ALMAR 362 SEAMLESS COLD-DRAWN TUBING (REF. 29)

Condition	Outside Diameter, in.	Wall Thickness, in.	Yield Strength (0.2% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Per Cent Elongation in 2-Inch Gage Length
As hot extruded plus 1500 F, 1 hr, air cool plus 900 F, 8 hr, air cool	1.750	0.200	172	180	15
Cold drawn 27.4 per cent plus 900 F, 8 hr, air cool	1.615	0.154	185	186	8
Cold drawn 62 per cent plus 900 F, 8 hr, air cool	1.350	0.094	187	200	7
Cold drawn 70 per cent plus 900 F, 8 hr, air cool	1.000	0.059	--	205	10
Cold drawn 87 per cent plus 900 F, 8 hr, air cool	0.987	0.041	206	206	11

preform and the completed object. The properties of the workpiece material determine whether the desired change in shape can be accomplished successfully. Failures in forming are caused by rupture, buckling, or a combination of these. Rupture results from lack of ductility under imposed tensile stresses; excessive compressive loading causes elastic or plastic buckling. Methods for predicting the formability of sheet materials from their mechanical properties in simple tests were developed during an extensive study for the U.S. Air Force by Ling-Temco-Vought, Incorporated (Refs. 34, 35). That investigation indicated that failures in conventional-forming operations result from the mechanisms shown in Table XIX (Ref. 36). The table also shows the mechanical properties found to correlate with limiting deformations in different types of forming operations. Higher values of the parameters indicate better formability. The mechanical properties needed to calculate the formability parameters for a particular material can be determined from tensile and compressive tests conducted at the desired forming temperature. Other organizations are also investigating the correlations between standard mechanical properties and the performance of materials in specific forming operations. As information of this kind is collected and systematized, it will become easier to predict the response of metals to deformation processing.

The forming limits set by necking or splitting correlate with ductility measurements in tensile tests. Deformation limits set by buckling failures correlate with the ratios of elastic modulus to the yield strength of the metal. Since changes in deformation temperature affect all of those mechanical properties, formability varies with temperature. Unfortunately, the information needed for predicting the effects of higher temperatures on formability are not ordinarily available for many materials of interest.

Precipitation-hardenable stainless steels are generally formed at room temperature. The exception to this rule are such alloys as AM-350 and AM-355, which may undergo a phase change during forming at room temperature. Warm forming of these alloys at 300 F avoids this difficulty. Experiments at Ling-Temco-Vought indicated that the ductility parameters for PH 15-7 Mo, AM-350, and A-286 alloys are better in the temperature range from room temperature to 500 F than at higher temperatures unless very high temperatures around 2000 F are considered. The effects of higher temperatures on the buckling parameters were variable but generally favorable near 1000 F. The optimum deformation temperatures for the splitting and buckling parameters are given in Table XX (Ref. 36).

TABLE XIX. TYPES OF FAILURES IN SHEET-FORMING PROCESSES AND MATERIAL PARAMETERS CONTROLLING DEFORMATION LIMITS[a] (REF. 36)

Process	Cause of Failure: Splitting	Cause of Failure: Buckling	Ductility Parameter[b]	Buckling Parameters[c]
Brake forming	x		ε in 0.25 in.[d]	
Dimpling	x		ε in 2.0 in.[e]	
Beading				
Drop hammer	x		ε in 0.5 in.[d]	
Rubber press	x		ε in 2.0 in. (d_u)	
Sheet stretching	x		ε in 2.0 in.	
Joggling	x	x	ε in 0.02 in.	E_c/S_{cy}
Liner stretching	x	x	ε in 2.0 in.[f]	E_t/S_{ty}
Trapped rubber, stretching	x	x	ε in 2.0 in.[g]	E_t/S_{ty}
Trapped rubber, shrinking		x		E_c/S_{cy} and $1/S_{cy}$
Roll forming		x		E_t/S_{ty}[h] and E_c/S_{cy}[i]
Spinning		x		E_c/S_{cy} and E_t/S_u
Deep drawing		x		E_c/S_{cy} and S_{ty}/S_{cy}

(a) The parameters can be determined in tensile and compressive tests.

(b) ε indicates natural or logarithmic strain; the dimensions indicate the distance over which it should be measured.

(c) E_c = modulus in compression; E_t = modulus in tension; S_{cy} = compressive yield strength; S_{ty} = tensile yield strength; S_u = ultimate tensile strength.

(d) Corrected for lateral contraction.

(e) For a standard 40-degree dimple.

(f) The correlation varies with sheet thickness.

(g) The correlation is independent of sheet thickness.

(h) For roll forming heel-in sections.

(i) For roll forming heel-out sections.

TABLE XX. OPTIMUM DEFORMATION TEMPERATURES FOR SPLITTING AND BUCKLING PARAMETERS OF PH 15-7 Mo, AM-350, AND A-286 (REF. 36)

Parameter[a]	Temperature Range	Optimum Deformation Temperature PH 15-7 Mo	AM 350	A-286
ε in 0.25	RT to 1000 F	RT	RT	RT
	1000 to 2000 F	1600 F	2000 F	2000 F
ε in 2.0	RT to 1000 F	500 F	500 F	RT
	1000 to 2000 F	Poorer	2000 F	2000 F
$1/S_{cy}$	RT to 1000 F	1000 F	1000 F	1000 F
	1000 to 2000 F	2000 F	2000 F	Poorer
$(E_c/S_{cy})(S_{ty}/S_{cy})$	RT to 1000 F	500 F	500 F	1000 F
	1000 to 2000 F	Poorer	Poorer	Poorer
E_c/S_{cy}	RT to 1000 F	1000 F	800 F	1000 F
	1000 to 2000 F	Poorer	Poorer	Poorer
E_t/S_{ty}	RT to 1000 F	1000 F	1000 F	500 F
	1000 to 2000 F	2000 F	2000 F	2000 F
E_t/S_u	RT to 1000 F	1000 F	1000 F	RT
	1000 to 2000 F	2000 F	2000 F	2000 F

(a) Parameters defined in footnotes to Table XIX.

BLANK PREPARATION

Introduction. Blanks for deformation processes are produced by cutting, preforming, or welding to the desired size and shape. The size of the blank depends on whether the parts are to be formed to final dimensions or 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 necessary with precipitation-hardenable stainless steels in processing are emphasized.

In general, techniques used for the preparation of blanks from austenitic 300 series stainless steels may be used on the precipitation-hardenable alloys. Most of the materials are prepared for forming in the annealed or solution-treated condition. Scaling and growth during heat treatment require some additional planning during blank preparation, and a knowledge of the forming and thermal-processing sequence is needed prior to the preparation.

Layout of Blanks. When more than one part is to be obtained from a sheet of material, the positioning of the blanks on the sheet has a marked influence on the scrap loss. The amount of blanking scrap generally is determined by the dimensions of the sheet and blank, the shape of the formed part, and the ingenuity of the layout man. The choice of sheet dimensions can be important. The normal procedure is to first determine the method of blank preparation and the clearance required around the blank. A pattern is then made that includes allowance for growth, tooling, and trimming. Several arrangements of the pattern on a sheet are then tried, and the one requiring the least material is selected. The selection of the sheet size may depend on ease of handling, scrap loss, or blank-preparation method. Where a large or complex-shape blank is required, it may be feasible and economical to weld smaller blanks together to obtain the shape desired. This procedure can be carried one step further by producing a preformed blank to reduce the amount of forming required.

Shearing. Shearing is generally the most economical method of blank preparation and, therefore, is widely used. Conventional shearing equipment suitable for the 300 series stainless steels can be used with most precipitation-hardenable stainless steels in either the annealed or solution-treated condition. Shearing the material in a harder condition requires more force but may produce a smoother sheared edge.

When thicknesses above 0.125 inch are sheared, some difficulty may be expected from edge roughness. This can be minimized by using thick shear blades to minimize deflection. Heavy hold-down pressures will also help maintain a smooth cut. The cutters should be sharp and free of nicks to assure a smooth edge. Blades made from W2 steel are considered satisfactory.

The shearing load required for the various alloys can be determined from the following formula (Ref. 37):

$$P = \frac{K(L \times T \times S)p}{2000} \quad ,$$

where

P = total shearing load, tons

L = total cut length, inch (perimeter)

T = material thickness, inch

S = shear strength of material (between 60 and 70 per cent of ultimate strength)

p = per cent penetration (expressed as a decimal) (about 39 per cent)

K = factor for friction, dull tools, incorrect clearance (K = 1.5 approximately).

The ultimate strengths for the various alloys and conditions of heat treatment were given in Table I.

Blanking. Blanking is normally performed on a punch press to produce a blank with the desired shape in one operation. The precipitation-hardenable stainless steels are generally blanked in the annealed or solution-treated condition required for subsequent forming operations. Blanking techniques are widely used for materials of 0.125-inch thickness or less; heavier materials can be blanked but the tool life is considerably less. The press size required for blanking can be determined from the equation given for shearing.

Dies for blanking precipitation-hardenable stainless steels should be rigid and guide pins should be used to insure proper alignment. This requirement becomes more important for thicker sheet. Insufficient stiffness in the tooling causes die failure and ragged edges on the blanks. The cutting edge of the tools must be sharp and free of irregularities. The die clearance may vary between 5 and 8 per cent of the material thickness. The smaller clearance will give a smoother edge but may result in problems in stripping the material from the punch.

The tolerance obtainable in sheared blanks depends on the shape and size of the blank as shown in Figure 16. The tolerance may be improved by operations such as shaving or by using a new blanking process known as fine-line blanking (Ref. 38). Shaving is an extra operation involving the removal of a small amount of material from the edge of the blank to remove the taper generally associated with blanking and shearing operations (Ref. 37). Since it is an extra operation, this step is generally only warranted where very precise tolerances of ±0.010 inch or less are required. The fine-blanking process is capable of holding tolerances of ±0.001 inch and of producing parts with a square edge (Ref. 38). The process requires the use of a triple-action hydraulic press, which preloads the material to be blanked before the blank is sheared from the parent material.

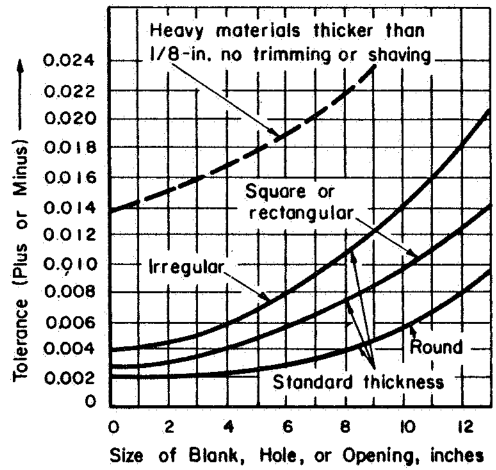


FIGURE 16. EFFECT OF SIZE AND SHAPE OF BLANK ON TOLERANCES (REF. 39)

The practical production tolerances for punching holes in materials including the precipitation-hardenable stainless steels are given in Table XXI. The tolerance for hole punching varies with the thickness of the material and the size of the hole.

TABLE XXI. PRACTICAL PRODUCTION TOLERANCES FOR PUNCHED HOLES (REF. 39)

Hole Diameter, in.	Practical Tolerance, in.
Light Materials (Up to 0.031 In.)	
Up to 1.000	Plus or minus 0.002
1 to 10	Plus or minus 0.005
10 to 20	Plus or minus 0.010
Medium Thickness Material (Up to 0.109 In.)	
Up to 1	0.005
Up to 10	0.012
Up to 20	0.020
Heavy Materials (1/8 In. Plus)	
Up to 1	0.015
Up to 10	0.025
Up to 20	0.035

Sawing. The precipitation-hardenable stainless steels may be sawed by low- or high-speed (friction sawing) bands, and by hacksawing methods. Many of the difficulties associated with machining the precipitation-hardenable stainless steels are encountered in sawing. They include galling, work-hardening, and high cutting temperatures. These difficulties are minimized by selecting a high-quality machining tool, correct saw blade, saw pitch, feed, lubricant and coolant, and cutting speed for the material and the material thickness.

A comparison of various sawing methods used on stainless steels is given in Table XXII, which lists the advantages and disadvantages of each process. Although there have been little data published about the sawing of the precipitation-hardenable stainless steels, their properties are similar to the 300 series stainless steels. Suggestions on bandsaw blades used in cutting the Type 300 stainless steels are given in Table XXIII. Operational data including saw speed and cutting rate for several thicknesses are given in Table XXIV. Cutting rates for friction sawing stainless steel are shown in Table XXV. For the same thickness of material the cutting rate for friction sawing is approximately ten times faster than band sawing because the heat generated from the friction cutting continuously anneals the material ahead of the blade.

Hacksaws are normally used in cutting bar stock. When using automatic-feed hacksaws for cutting precipitation-hardenable stainless steels, between 40 and 50 strokes per minute with a feed rate of 0.003 inch per stroke should give satisfactory results. Higher cutting speeds will generally result in shorter blade life.

Slitting and Hand Shearing. Slitting and hand shearing is used to prepare long, narrow, thin blanks or to cut circles. When contour changes are not too sharp, hand shearing may also be used for irregularly shaped blanks. The hand process is generally limited to 0.040-inch-thick material or less in the annealed condition.

Conventional slitting equipment has been used for preparing precise, straight cuts in PH 15-7 Mo material. Cuts up to 20 feet long have been made successfully by this technique. For best results, the equipment should be of rigid construction and the tooling should be maintained in a sharp condition.

TABLE XXII. COMPARISONS OF VARIOUS SAWING METHODS (REF. 40)

	Band Sawing			
	Low Speed			
Characteristics	Conventional Band Sawing	Power Band Sawing	High-Speed Friction Sawing	Hacksawing
How Used	Straight-line cutting	Cut-off operations (bars, tubing, etc.)		Primarily cutoff
	Cutting contours Blanking work Trimming work		Up to 3/8 inch thick	Low output production
	Up to 1-inch stack cutting		Most common method for trimming small quantities of parts	Tool-room work Maintenance work
			Particularly suitable for cutting out blanks in 1/4-hard and harder tempers	
Advantages	Makes duplicate parts with minimum chip waste	The width of cut (karf) is about 1/2 that of hacksawing	No detrimental thermal penetration as in hot cutting.	A good all-around cut-off tool
	Cuts any contour		Tends to anneal the metal rather than work-harden it.	
	Makes internal or external cuts			
	Length of cut not limited by table dimensions or stroke	Saw band moves only in one direction - no back stroke to waste time	High speed cutting reduces any tendency toward stress cracking.	

TABLE XXII. (Continued)

Characteristics	Band Sawing: Low Speed: Conventional Band Sawing	Band Sawing: Low Speed: Power Band Sawing	Band Sawing: High-Speed Friction Sawing	Hacksawing
Advantages			Fastest method to cut stainless steel	
Limitations	Not suitable for cutoff		Not suitable for cutting stacked, flat pieces	Not suitable for sawing light-sheet sections
	On bars over 1-inch diameter, best to use power band sawing or hacksawing			

TABLE XXIII. PRECISION SAW BANDS USED FOR STAINLESS STEEL (REF. 40)

Width, in.	Thickness, in.	Pitches – Raker Set							Pitches – Wave Set				
		6	8	10	12	14	18	24	8	10	12	14	32
		Nominal Set and Code							Nominal Set and Code				
1/8	0.025	--	--	--	--	0.043	0.042	0.042	--	--	--	--	--
3/16	0.025	--	--	0.044	--	0.043	0.042	0.042	--	--	--	--	0.042
1/4	0.025	--	--	0.044	0.043	0.043	0.042	0.042	--	--	--	--	0.042
3/8	0.025	--	0.045	0.044	--	0.043	0.042	0.042	--	--	--	--	--
1/2	0.025	0.045	--	0.044	--	0.043	0.042	0.042	--	0.044	--	0.043	--
5/8	0.032	--	0.055	0.055	--	0.054	0.052	0.050	--	0.057	--	0.057	--
3/4	0.032	0.055	0.055	0.055	0.054	0.054	0.052	--	0.057	0.057	0.057	0.057	--
1	0.035	0.058	0.058	0.058	--	0.057	--	--	--	0.063	--	--	--

TABLE XXIV. OPERATIONAL DATA FOR BAND SAWING STAINLESS STEEL[a, b] (REF. 40)

Thickness, in.	Pitch, teeth/in.	Speed, fpm 303,416 Stainless Steels	Speed, fpm Other Stainless Steels	Cutting Rate, in.^{2}/min
1/32	24-32	140	100	2.5-4
1/16	18-24	140	100	1-2.5
1/4	14	125	75	0.75-1.0
1/2	10	110	70	
1	6-10	100	60	0.5-0.75
3 and over	3-8	75	50	0.1-0.50

(a) Saw set = 0.042-0.065, depending on saw width.

(b) Saw width = 3/16 to 1 inch, depending on a straight or radius cut.

TABLE XXV. SAW VELOCITY AND CUTTING RATES USED FOR FRICTION SAWING STAINLESS STEELS (REF. 40)

Work Thickness, in.	Saw Pitch, teeth/in.	Saw Velocity, fpm	Linear Cutting Rate, ipm
1/16	18	3,000-7,000	120
1/8-3/16	14	3,000-7,000	75
1/4-7/16	10	6,000-10,000	55-60
1/2-11/16	10	9,000-13,500	15-30
3/4-15/16	10	12,000-15,000	8-10
1	10	12,000-15,000	6

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 precipitation-hardenable stainless steels makes the process limited in application.

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 generally require smoothing if the blank will not be trimmed after forming. Short tool life and high maintenance costs are normally associated with this type of blank preparation. It has the same thickness limitations as shearing.

Thermal Cutting. For cutting precipitation-hardenable stainless steels thicker than 1/4 inch, a thermal-cutting process may be more efficient than sawing, depending on the alloy and its condition. Such processes as carbon arc, iron-powder flame-cutting, gas metal-arc, or plasma arc are more satisfactory than an acetylene torch. Some specific data on powder cutting of stainless steels are given in Table XXVI. Sometimes a wire instead of powder is fed to the heated area in the gas metal-arc process. Curves for the rate of cutting at various energy input levels and material thicknesses are shown in Figure 17. Although these processes can be used for cutting the precipitation-hardenable stainless steels less than 1/4 inch in thickness, they normally are applied to the thicker materials. As the material thickness increases the thermal-cutting methods become faster and less costly per linear cut than sawing. The breakeven point on cost is about 1 inch.

As might be expected, the thermal-cutting processes cause some grain growth near the face of the cut, and the cut surface is relatively ragged and rough. They also may deplete this area of some of the necessary age-hardening elements. Most of the heat-affected area should be removed by grinding after cutting. The rough surface is generally smoothed at the same time. Since grinding is generally a slow handwork operation, the thermal processes are used mainly for preparation of bar stock or plate shapes that are to be subsequently machined or welded.

Edge Conditioning. The precipitation-hardenable stainless steels should be deburred to minimize damage to the forming tools and to assure safety in handling. Most of the alloys are not

TABLE XXVI. POWDER-CUTTING DATA FOR STAINLESS STEEL (REF. 41)

Steel Thickness, in.	Diameter of Cutting Oxygen Orifice, in.	Oxygen Pressure, psi	Cutting Speed, ipm	Gas Consumption, ft^3/hr Oxygen	Gas Consumption, ft^3/hr Acetylene	Powder Flow, oz/min	Steel Thickness, in.
1/2	0.040	50	14	125	15	4	1/2
1	0.060	50	12	225	23	4	1
2	0.060	50	10	300	23	4	2
3	0.080	50	9	550	32	5	3
4	0.100	50	8	675	38	6	4
5	0.120	60	7	800	45	7	5
6	0.140	60	6	900	63	8	6
8	0.140	70	4	1000	63	8	8
10	0.160	75	3.5	1100	75	8	10
12	0.160	75	3	1200	75	8	12

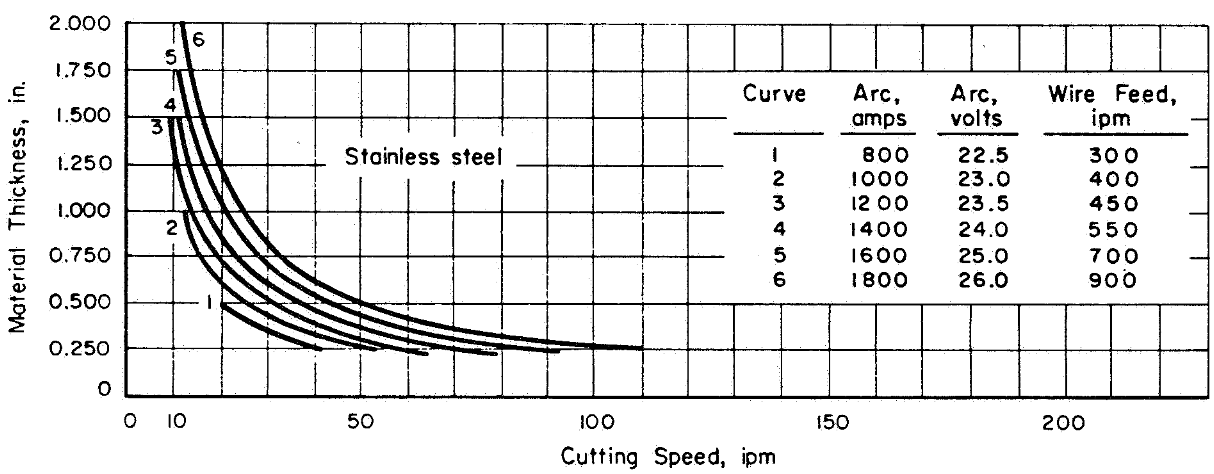


FIGURE 17. OPERATING DATA FOR CUTTING STAINLESS STEEL WITH THE GAS METAL-ARC PROCESS (REF. 41)

notch sensitive in the annealed or solution-treated condition, but they may be susceptible to stress-corrosion cracking at the stress risers. When the blanks are to be trimmed after forming, scratches on the edge of the blanks are acceptable since they have very little effect on formability. Sharp edges, however, should be removed from the blank to prevent damage to the forming tools. The edges of blanked holes and cut-outs as well as pilot holes should be deburred on both sides for maximum tool life.

Deburring and polishing can be done by draw filing or belt grinding on blanks up to 0.040 inch thick. For thicker sheet materials, a grinding wheel or machining operation such as milling should be considered.

Surface Preparation. Surface imperfections such as scratches may act as stress risers and may cause stress-corrosion cracking of the precipitation-hardenable alloys in service. Also a surface layer contaminated by iron can cause the part to lose its corrosion resistance.

It is a good practice to remove oil, grease, and other soluble materials from the surfaces of blanks before heating them. There are a number of cleaning processes that have been developed for the precipitation-hardenable stainless steels. During forming operations, these consist of vapor degreasing or caustic degreasing. The same type of operations are generally used before any thermal treatment to reduce the possibility of nonuniform scale formation.

The removal of scale from material that has been thermally treated is complicated by the possibility of intergranular corrosion if strong pickling acids or prolonged pickling times are used. Some companies prefer to use mechanical methods of scale removal. Blast cleaning with ironfree, clean shot or grit may be employed. Traces of scale that may be left on the surface after mechanical cleaning should be removed by brief exposure to warm 15 per cent nitric - 3 per cent hydrofluoric acid bath. A pickling procedure that has been used successfully on AM-355 strip is (Ref. 42):

After Annealing	After Tempering
15% HNO_3	15% HNO_3
3% HF	3% HF
130 F temperature	130 F temperature
3 minutes	1 minute

The A-286 alloy, after solution treatment, has been descaled by a two-stage treatment: (1) immersion in an oxidizing salt bath at 900 F followed by a 5-minute neutralization in a 20 per cent sulfuric acid bath. (2) 35 to 40 per cent nitric acid - 4 per cent hydrofluoric acid bath for 20 minutes (Ref. 43).

Heat treatment of materials that have been cleaned and processed in an inert atmosphere will often reduce the time required to descale the material and in some cases may eliminate this step entirely. Also protective coating materials are available that will reduce the scale formation and make the scale that does form easier to remove. The suppliers of heat-treat materials should be consulted for specific recommendations in this area.

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. Heavy-wall welded pipe and tubing also is made by brake-forming techniques. Handworking or sizing operations are usually required to produce parts with closer dimensional tolerances.

The springback allowance for the annealed or solution-treated, precipitation-hardenable stainless steel alloys is normally less than 10 degrees. When the aged alloys are bent, the springback may be as high as about 30 degrees. If the bend radii are sufficiently large, no unusual problems are encountered.

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 18 for two typical brake-forming setups. In air bending, 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 18 depends on the sheet thickness, T, and the punch radius, R. According to Wood (Ref. 44), the practical limits for brake bending lie between:

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

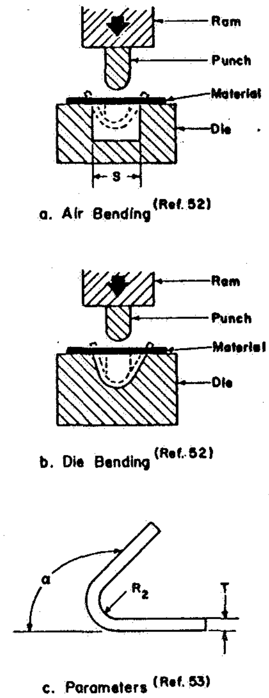


FIGURE 18. TYPICAL BRAKE-FORMING SETUPS AND PARAMETERS

Those 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.

Presses Used for Brake Forming. A press brake is a single-action press with a very long and narrow bed. Its chief purpose is to form long, straight bends in pieces such as channels and corrugated sheets.

Brake presses are commercially available having capacities ranging from about 8 to 2000 tons. Figure 19 shows a typical brake press having a capacity of 60 tons. For the bending of relatively thin sheet metal, the press capacity can be relatively small and hand operated.

Table XXVII lists the capacities and other pertinent information on brake presses available from one manufacturer.

TABLE XXVII. CAPACITIES AND OTHER TYPICAL INFORMATION ON BRAKE PRESSES[a]

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 Horsepower	Range of Shipping Weight, pounds: Largest	Smallest
							Mechanical Press Brakes								
1B-15	--	15	10	4	2	20-50	4 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[b]	--	14	12	--	--	--	25	50,000	26,500
HD-300	--	300	18-2/3	8-2/3	12	25[b]	--	--	16	8	--	--	30	52,600	29,000
HD-400	--	400	18-2/3	8-2/3	12	26[b]	--	--	--	12	6	--	40	67,000	33,000
HD-500	--	500	18-2/3	8-2/3	12	25[b]	--	--	--	14	9	--	40	85,500	50,000
HD-600	--	600	24	10	12	25[b]	--	--	--	16	10	--	50	119,000	59,800
HD-750	--	750	24	14	12	21[b]	--	--	--	22	14	10	60	120,000	79,500
HD-1000	--	1000	24	14	18	21[b]	--	--	--	--	18	14	75	204,000	102,000

(a) Data taken from Booklet 203C and Bulletins 89F and 91 from Niagara Machine and Tool Works, Buffalo, New York.
(b) Normal press speed gives rated capacity. High press speeds along with press tonnage ratings are 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.

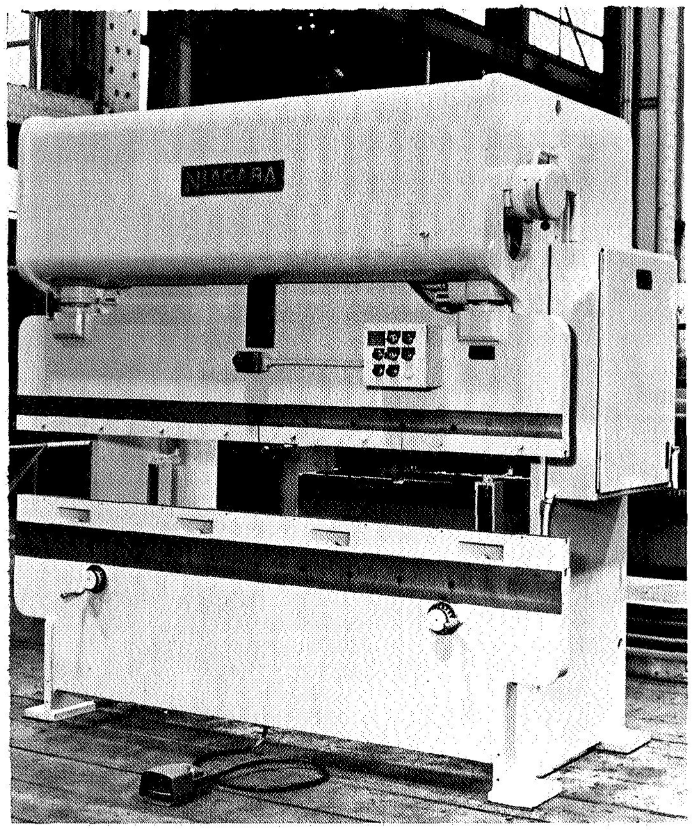


FIGURE 19. 60-TON MECHANICAL PRESS BRAKE

Courtesy of Niagara Machine and Tool Works, Buffalo, New York.

Tooling. Figure 20 shows a group of typical press-brake bending and forming dies (Ref. 45). The dies pictured include 90-degree and acute-angle forming dies (a and b), gooseneck dies (c), offset dies (d), hemming dies (e and f), seaming dies (g), radius dies (h), beading dies (i), curling dies (j), tube- and pipe-forming dies (k and l), four-way die blocks (m), channel-forming dies (n), U-bend dies (o), box-forming dies (p), corrugating dies (q), multiple-bend dies (r), and rocker-type dies (s).

Materials used as dies and punches for brake-press forming the precipitation-hardening stainless steels are generally the same as those used for the 300 series stainless steels. As a basic principle, the larger the differential in hardness between the tooling and the workpiece, the greater the resistance to galling (Refs. 46, 47). Brake-press tooling is made from a variety of materials and the choice of tooling for a specific application depends on the size of the part, the number of parts to be formed, and the complexity of the required bends. When only a small number (250 to 1000) parts are required, cold-rolled steel often is used as a die material. Zinc-alloy (Kirksite) tooling also may be used to produce small quantities of parts (usually less than 50). Meehanite cast iron is used for punches and dies at temperatures up to 1400 F.

When the quantity of parts to be produced is large (1,000 to 10,000), punches and dies made of hardened carbon steel or low-alloy steels such as SAE 3140 and 4340, tool steels such as H-11, and aluminum bronze are used intensively. In this connection, laboratory tests indicate that hardened 17-4 PH stainless steel has excellent resistance to galling when used against solution-treated 17-4 PH stainless steel and should prove to be an excellent die material (Ref. 47). Chromium plating on the punches and dies and aluminum-bronze dies are often used to minimize galling. For the production of very large quantities of parts (over about 10,000), the extra cost involved in using cemented carbide punches and dies may be warranted as a result of their durability. However, the cemented carbides should not generally be used in conjunction with lubricants containing sulfur and chlorine because the nickel- or cobalt-alloy binder may be embrittled, thus, causing the tool to crumble.

Sometimes beryllium copper is used for forming dies, especially for relatively short-production runs. This material can be precisely cast to shape and for many applications requires no further machining. Thus, economy in die costs can be achieved over other methods and materials.

Punches of any of the alloys are made to the desired bend radii. The female die may be a V die or a channel die. For brake forming at room temperature, a hard-rubber insert sometimes is placed in the channel die to avoid scratching the formed parts. The surface of the punch must be free of defects such as nicks where it contacts the blank.

In recent years, urethane pads also have been used as universal female dies for some brake-forming applications. Figure 21 shows some press-brake dies in which urethane has been used. These dies are most useful where set-up time, flexibility, and prevention of scratching and marring of parts are important factors. Only the punch needs to be machined for each separate application since the urethane behaves like a solid liquid under the confined conditions.

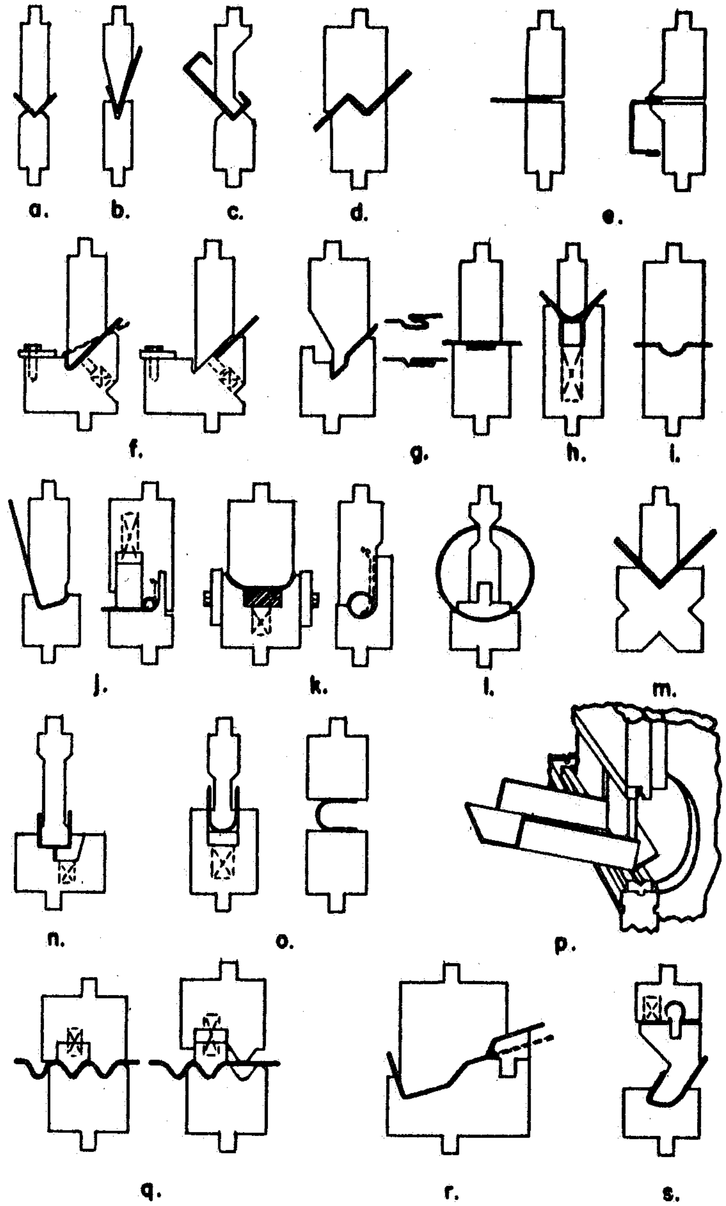


FIGURE 20. TYPICAL PRESS-BRAKE-BENDING AND FORMING DIES (REF. 45)

Derived or adapted from the Verson Allsteel Press Company, Chicago, Illinois (a, f, g, h, i, k, l, n, o, q, r, s); The Cincinnati Shaper Company, Cincinnati, Ohio (b, d, m, p); and Dreis and Krump Manufacturing Company, Chicago, Illinois (e, j). Courtesy of American Society of Tool and Manufacturing Engineers.

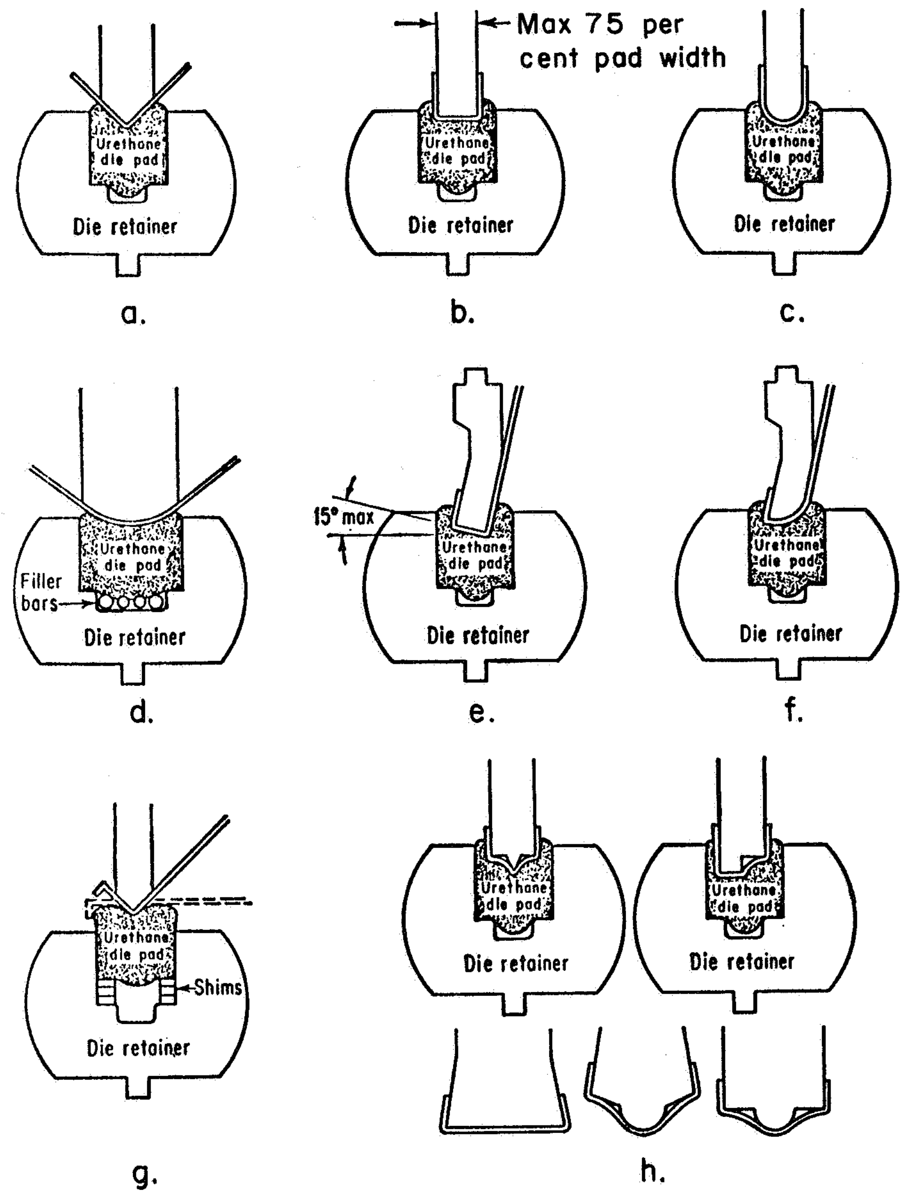


FIGURE 21. PRESS-BRAKE DIES USING URETHANE AS THE LOWER DIE (REF. 44)

Courtesy of the American Society of Tool and Manufacturing Engineers.

Figure 21 shows the following press-brake applications of urethane dies: V- and U-forming applications (a, b, and c); radius-forming applications (d); forming with gooseneck punches (e and f), forming reverse bends (g), and contour forming with concave areas (h). For these latter applications, the lighter the sheet thickness, the sharper the definition.

Bending Procedures. Blanks of the precipitation-hardenable stainless steels for bending on a press brake are prepared by methods described in the section on blank preparation. Normally these alloys are bent in the annealed (solution treated) condition at room temperature. Some of the alloys, notably AM-350 in the annealed condition, can be more severely formed at 300 F than at room temperature because little or no martensite formation occurs.

The precipitation-hardenable stainless steels usually require lubrication to insure good die life and good surface finishes. For mild-forming operations, polar lubricants such as castor oil, lard oil, and sperm oil may be used. Severe deformations require the use of surface-active compounds such as sulfurized or sulfochlorinated mineral oils and paraffins, and metallic soaps. These can be pigmented or diluted with neutral thinning oils as required. If parts are to be heat treated after bending, care must be taken to completely remove oil and other contaminants prior to heat treating. Their presence would result in carburization on the surface of the part and affect the hardening response. Cleaning may be accomplished with a suitable solvent or, more thoroughly, with a vapor degreaser or alkaline cleanser after forming.

Bending Limits. Failures in bending always occur by splitting in the outer fibers. Through the years, minimum bend radii have usually been determined by trial and error using the experience gained from similar materials as guidelines. More recently, a number of engineering methods have been developed for predicting the minimum radius to which a material may be bent without fracture (Refs. 44, 48). These methods usually are based on the assumption that the material is bent in plane strain and that the strain at which a workpiece splits in bending is equal to that strain at fracture in a tensile specimen. The natural or logarithmic strain in the outer fiber of a bent structure is

$$E = \ln \left(\sqrt{1 + T/R}\right) , \qquad (2)$$

where

T = thickness, inches

R = inner bend radius, inches.

In tensile tests

$$E = \ln \frac{100}{100\ A_R} \quad , \tag{3}$$

where

A_R = reduction in area expressed in per cent.

Datsko and Yang (Ref. 48) showed that the minimum bend radii for various materials could be predicted fairly accurately by the following relationships:

$$\frac{R_{min}}{T} = \frac{50}{A_R} - 1 \text{ (for } A_R < 20) \tag{4}$$

$$\frac{R_{min}}{T} = \frac{(100 - A_R)^2}{200 - A_R{}^2} \text{ (for } A_R > 20) \quad . \tag{5}$$

The differences between Equations (4) and (5) arose from taking into account a displacement of the neutral axis during bending. Datsko (Ref. 48) considered the displacement to be significant in materials exhibiting large reduction-in-area values. The equations may be used to estimate minimum safe bending radii from tensile-property data found in handbooks. It is safer, of course, to determine the values on materials of interest on flat specimens.

Wood and his associates (Ref. 44) determined the limiting tensile strain by measuring the elongation in a gage length of 0.25 inch and correcting it for width strain. This is equivalent to the strain based on reduction-in-area values for biaxial stress, but is affected by specimen geometry. To use their approach, tension tests are made on specimens marked with a grid of 1/4-inch squares. Then the data are used for the equations given in Table XXVIII to construct a formability diagram like that shown in Figure 22. Their analysis takes bend angle as well as critical bend radius into account. Figure 22 is based on a material with a corrected limiting plane-strain value of $E = 0.4$. The curve would move to the right for materials exhibiting better ductility in plane-strain tensile tests.

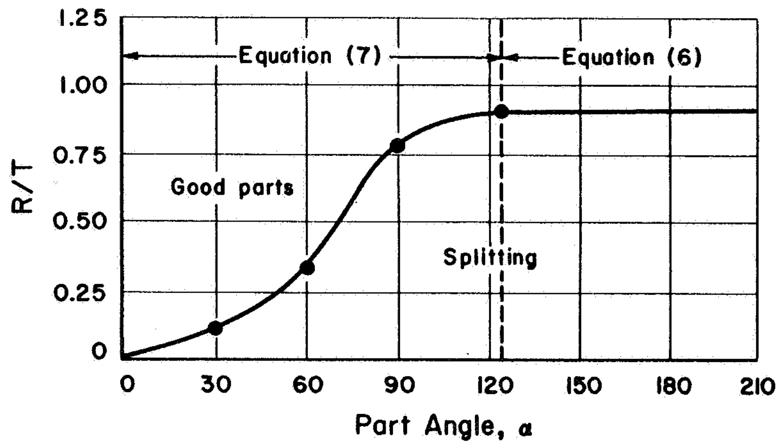


FIGURE 22. EXAMPLE OF A SPLITTING-LIMIT CURVE FOR BENDING (REF. 34)

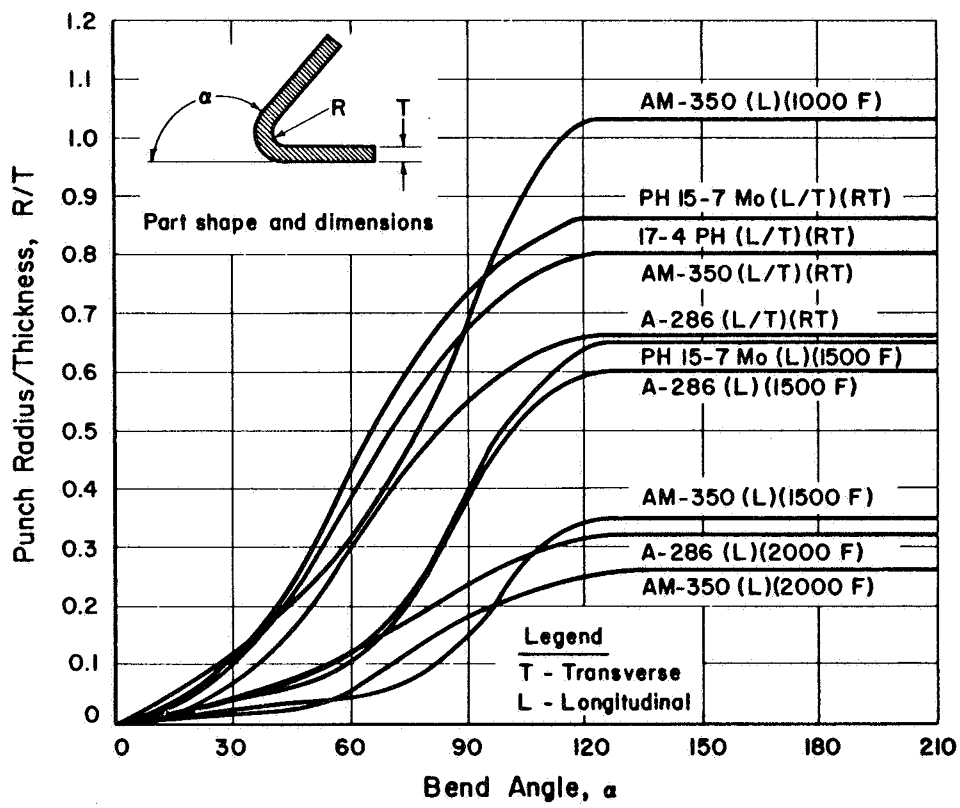


FIGURE 23. COMPOSITE BRAKE-BEND-LIMIT CURVES FOR FOUR PRECIPITATION-HARDENABLE STAINLESS STEEL ALLOYS (REFS. 33, 34)

TABLE XXVIII. EQUATIONS FOR CONSTRUCTING SPLITTING-LIMIT DIAGRAMS FOR BRAKE FORMING (REF. 44)

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 22)

θ = angle of interest ranging from 0 to 180 degrees

E = corrected value of maximum strain based on 0.25-inch gage length.

Equations:

where

$$\alpha => \phi$$

$$R/T = 1/(2.718)^{2E} - 1$$

where

$$\alpha < \phi$$

$$R/T = 0.5\,[R/T \text{ from Equation (6)}]\,[\,1 + \text{Sin}\,(\theta - 90\text{ deg})]$$

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

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

$$R/T = 0.5\left[\,2.718^{2E} - 1\right]^{-1}\left[\,1 + \text{Sin}\left(\frac{15.21\,\alpha}{11.4 - 2.718^{2E} - 1)^{-1}} - 90\text{ deg}\right)\right]. \quad (10)$$

Figure 23 shows such curves for four precipitation-hardenable stainless steels. These curves were drawn on the basis of tests ranging from room temperature to 2000 F. The experimental data also are shown in Table XXIX (Refs. 33, 34). All of the alloys appear to bend equally well when tested longitudinally or transverse at room temperature to the rolling direction of the sheet. The A-286 alloy was the most easily bent at room temperature and the PH 15-7 Mo alloy was difficult to bend. The AM-350 grade was more difficult to bend at 1000 F than at room temperature, because precipitation occurred when the alloy was heated to 1000 F. The three alloys, PH 15-7 Mo, A-286, and AM-350, were all easier to bend at 1500 F than at room temperature, apparently having overaged and softened when heated. Still less bending effort was required in bending the A-286 and AM-350 alloys at 2000 F. However, the difficulties in obtaining tooling that will withstand these high temperatures is usually not worth the effort since most of the precipitation-hardenable-stainless steels can readily be bent at room temperature or slightly elevated temperatures such as 300 F.

TABLE XXIX. BRAKE-BENDING LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REFS. 33, 34)

Alloy	Grain Direction, L/T	Bending Temperature, F	Critical Bend Angle, α, degrees	Critical Bend Limits, R/T	Bend Limits, R/T, for Various Angles, α, Below Critical: 30	45	60	75	90	105	120
17-7 PH	L/T	RT	122	0.80	0.10	0.22	0.37	0.54	0.66	0.75	0.79
PH 15-7 Mo	L/T	RT	121	0.86	0.11	0.23	0.42	0.60	0.72	0.80	0.84
PH 15-7 Mo	L	1500	126	0.65	0.05	0.08	0.12	0.20	0.38	0.55	0.63
AM-350	L/T	RT	122	0.80	0.10	0.22	0.37	0.54	0.66	0.75	0.79
AM-350	L	1000	123	1.03	0.12	0.20	0.33	0.48	0.68	0.90	1.03
AM-350	L	1500	131	0.35	0.02	0.03	0.04	0.07	0.15	0.28	0.35
AM-350	L	2000	135	0.26	0.01	0.02	0.04	0.12	0.17	0.22	0.24
A-286	L/T	RT	124	0.66	0.07	0.15	0.29	0.43	0.54	0.62	0.65
A-286	L	1500	128	0.60	0.04	0.06	0.10	0.20	0.38	0.52	0.59
A-286	L	2000	128	0.32	0.04	0.07	0.12	0.18	0.24	0.28	0.31

In addition to the data of Wood et al., given in Table XXIX, other data in the literature on minimum radii for bending the precipitation-hardenable stainless steels are shown in Figure 30.

The PH 15-7 Mo stainless steel was reported to have better overall bending characteristics than either the 17-7 PH or the AM-355 alloys in one experimental investigation (Ref. 49). Edge roughness does not noticeably affect bending results obtained with the 17-7 PH, PH 15-7 Mo, AM-355, or A-286 stainless steels in laboratory tests (Refs. 49, 50).

The data in Table XXX show that the A-286 alloy can be bent at room temperature a little more easily than 17-7 PH, PH 15-7 Mo, AM-350, and AM-355. This observation is especially true for the solution-treated and aged condition. Most difficult of the five stainless steels considered with regard to bendability is the PH 15-7 Mo alloy.

The values of bend radii most useful to design people are the design bend radii, not the minimum bend radii. Values for design radii used by two aircraft manufacturers for four of these precipitation-hardenable stainless steels are shown in Table XXXI. In the

TABLE XXX. BRAKE-BENDING LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS

Alloy	Condition(a)	Sheet Thickness, in.	Grain Direction to bend(b)	Bending Temperature, F	Minimum Bend Radius(c), XT	Bend Angle, degrees	Springback, degrees	Remarks	Reference
17-7 PH	ST	0.025	--	RT	0.65	130	6		49
17-7 PH	ST	0.063	--	RT	0.5	130	2		49
17-7 PH	STA (1050)	0.025	--	RT	6.	130	15-18		49
17-7 PH	STA (1050)	0.063	--	RT	6.5	130	--		49
PH 15-7 Mo	ST	0.025	--	RT	0.65	130	8		49
PH 15-7 Mo	ST	0.063	--	RT	0.3	130	-1		49
PH 15-7 Mo	STA (1050)	0.025	--	RT	6.0	130	19-27		49
PH 15-7 Mo	STA (1050)	0.063	--	RT	4.5	130	18-20		49
PH 15-7 Mo	ST	0.080	--	RT	0.8	130	3-5	120 in. x 240 in.-sheet	50
PH 15-7 Mo	ST	0.025	--	RT	1.2	130	8	Standard sheet	50
PH 15-7 Mo	ST	0.063	--	RT	0.4	130	-1	Ditto	50
PH 15-7 Mo	STA (1050)	0.080	--	RT	7.2-8.6	130	23-29	120 in. x 240 in.-sheet	50
PH 15-7 Mo	STA (1050)	0.025	--	RT	6.2	130	19-26	Standard sheet	50
PH 15-7 Mo	STA (1050)	0.063	--	RT	4.8	130	18-19	Ditto	50
PH 15-7 Mo	ST	0.060	L/T	RT	0(d)	90	0		51
PH 15-7 Mo	ST (50 CW)	0.030	L/T	RT	2.0	90	8-9		51
PH 15-7 Mo	ST (50 CW) A(900)	0.030	L/T	RT	2.0	90	11		51
AM-350	SCT	--	L/T	RT	3.0	180	--		52
AM-355	ST	0.025-0.063	--	RT	0.75	130	3		49
AM-355	STA (850)	0.063	--	RT	3.5	130	18		49
A-286	ST	0.025	--	RT	1.2	130	3.5-6		50
A-286	ST	0.059	--	RT	0.5	130	-1		50
A-286	STA	0.025	--	RT	2.0	130	9-12		50
A-286	STA	0.059	--	RT	1.5	130	6-8		50
A-286	ST	0.030	--	RT	1.6	130	2-6	Wide sheet	53
A-286	ST	0.080	--	RT	0.4	130	0-3	Ditto	53
A-286	ST	0.025	--	RT	1.2	130	4-5	Standard sheet	53
A-286	ST	0.063	--	RT	0.5	130	-1	Ditto	53
A-286	STA	0.030	--	RT	1.6	130	7	Wide sheet	53
A-286	STA	0.080	--	RT	1.6	130	2-6	Ditto	53
A-286	STA	0.025	--	RT	1.3	130	7-12	Standard sheet	53
A-286	STA	0.063	--	RT	1.8	130	6-8	Ditto	53

(a) ST = solution-treated or annealed condition.
STA ( ) = solution-treated and aged condition, with aging temper indicated in parentheses.
ST (CW) A ( ) = solution treated and cold worked indicated percentage, followed by aging at indicated temperature.
SCT = solution treated, subzero cooled and aged at 850 or 1000 F.

(b) L = bend parallel with grain direction
T = bend perpendicular or transverse to grain direction.

(c) Minimum radius of pin divided by thickness of sheet - also called bend factor; radius of pin determined by multiplying bend factor by sheet thickness.

(d) Bent flat on itself.

TABLE XXXI. DESIGN STANDARD BEND RADII USED FOR BRAKE FORMING

17-7 PH (STA)[a]				17-7 PH (ST)[a]		AM-350 (ST)[b]	AM-355 (ST)[b]	PH 15-7 Mo (ST)[b]	17-7 PH (ST)[b]
Sheet Thickness, T, in.	Bend Radius, in.	Bend Factor, R/T[c]	Tolerance in Bend Radius, in.	Bend Radius, in.	Bend Factor, R/T[c]	Bend Factor, R/T[c]	Bend Factor, R/T[c]	Bend Factor, R/T[c]	Bend Factor, R/T[c]
0.012	0.13	11.0	±0.03	0.03	2.5	2[d]	2[d]	1[d]	2[d]
0.016	0.13	8.0	±0.03	0.03	1.9				
0.020	0.16	8.0	±0.03	0.06	3.0				
0.025	0.16	6.4	±0.03	0.06	2.4				
0.032	0.25	7.8	±0.03	0.06	1.9				
0.036	0.25	7.0	±0.03	0.09	2.5				
0.040	0.31	7.8	±0.06	0.09	2.25				
0.045	0.34	7.6	±0.06	0.09	2.0				
0.050	0.38	7.6	±0.06	0.13	2.6				
0.056	0.47	8.4	±0.06	0.13	2.3				
0.063	0.50	8.0	±0.06	0.13	2.0				
0.071	0.56	8.0	±0.09	0.16	2.25				
0.080	0.63	8.0	±0.09	0.16	2.0				
0.090	0.75	8.3	±0.09	0.19	2.1				
0.100	--	--	--	0.22	2.2				
0.112	--	--	--	0.22	1.96				
0.125	--	--	--	0.25	2.0				
0.140	--	--	--	0.28	2.0				
0.160	--	--	--	0.34	2.1				
0.180	--	--	--	0.38	2.1				
0.190	--	--	--	0.38	2.0				

(a) Material and Condition; McDonnell Aircraft Corporation, St. Louis, Missouri, Design Handbook section on "Standard Bend Radii", Code No. 76301, 6M39.
(b) Material and Condition; "Sheet metal and Extrusion Standard Detail", Lazaroff, S. T., North American Aviation, Inc., Columbus, Ohio, Specification No. HA012-002 (April 8, 1964) (RSIC 0491).
(c) To obtain bend radius, Multiply R/T value in table by thickness.
(d) Indicated bend factor used for all thicknesses of sheet.

annealed condition, a design-bend-radius value of about 2T appears satisfactory. In the age-hardened condition, the 17-7 PH alloy has a design bend radius that ranges for the instance cited in Table XXXI, from bend factors of about 6.5 to 11.0.

Springback. The annealed (solution treated) precipitation-hardenable stainless steels show much less springback than the same alloys in the solution-treated and aged condition as shown in Figure 30. Lowest springback among the aged alloys is shown for the A-286 alloy; highest for the PH 15-7 Mo alloy.

In production operations, an allowance for springback can be made by overbending and then permitting the bend to return to the desired angle. Handworking operations may be employed to produce exact shapes. Hot-forming methods are not used much with these alloys because they are hardened by precipitation during heating. However, a method of clamping the alloys during transformation is being used and this will be discussed in more detail in the hot-sizing section of this report.

Figure 24 illustrates the brake forming of a bead in AM-355 CRT flat stock. Using a laminated punch as shown, beads in sheet thicknesses up to 0.014 inch were successfully formed. Figure 25 shows a brake-formed bead in an AM-355 CRT hat section. The hat section was brake formed using a die layout template. The following two-stage operation was used to form the beads:

(1) Two open-angle bends were preformed into the part. The bends are located on the centerlines of the beads.

(2) Beads were finish formed by placing a length of drill rod into the preformed angle and bottoming in the female die using a flat punch.

Post-Forming Treatments. The usual requirements for post-forming operations might include deburring; thorough cleaning by vapor degreasing, and alkaline-cleaning methods; visual or penetrant inspection for cracks; shearing length or width when required; and pickling, washing, protective wrapping, and identifying. Often the parts also are annealed after the final bending operation.

Sometimes parts are aged after they have been formed in the solution-treated condition to obtain the desired strength properties. Such aging is done usually above 850 F and generally is followed by suitable pickling, washing, and wrapping of parts. Since most of the precipitation-hardenable stainless steels work harden to a greater extent than the austenitic stainless steels, intermediate anneals may be required especially if the final part shape requires extensive bending. These anneals are accomplished by heating in air at the solution-treating temperature to restore full ductility to the part. Such anneals must usually be followed by a pickling treatment to remove the scale that formed during the anneal.

If the dimensions and accuracy of the finished piece make the final anneal impractical, the following alternative procedure may be used:

(1) Form to as near completion as possible, preferably a minimum of 90 per cent of the finished shape

(2) Anneal at the solution-treating temperature

(3) Pickle

(4) Perform final sizing operations.

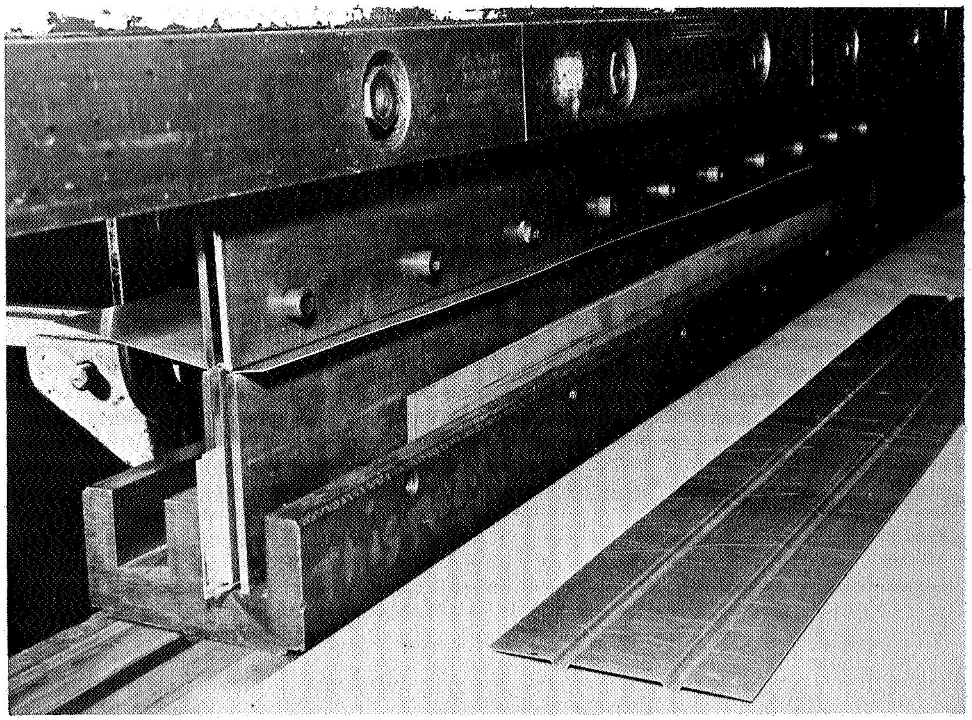


FIGURE 24. BRAKE FORMING A BEAD IN AM-350 CRT FLAT STOCK

Courtesy of The Boeing Airplane Company, Seattle, Washington.

FIGURE 25. BRAKE-FORMED BEAD IN AN AM-355 CRT HAT SECTION

Courtesy of The Boeing Airplane Company, Seattle, Washington.

Introduction. Deep drawing is a process used to produce cylindrical or 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. 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 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.

Precipitation-hardenable stainless steels normally are deep drawn at room temperature. Cups, domes, cones, and boxes are produced 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 blank-holder pressure on mechanical presses than on hydraulic presses. For these reasons, the use of mechanical presses is 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 sometimes an advantage in deep drawing depending on the particular alloy. 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 2500 psi for precipitation-hardenable stainless steels in the annealed condition, 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 XXXII. Figure 26 shows an 800-ton hydraulic press equipped with a 600-ton die cushion used in forming sinks from stainless steel.

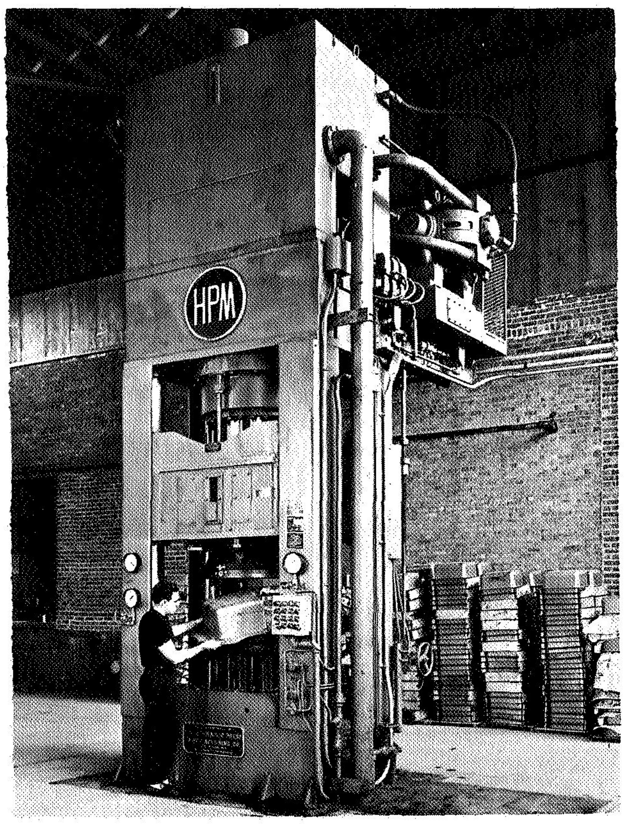


FIGURE 26. 800-TON PRESS EQUIPPED WITH A 600-TON DIE CUSHION USED FOR DRAWING STAINLESS STEEL SINKS

Courtesy of The Hydraulic Press Manufacturing Company, Mt. Gilead, Ohio.

TABLE XXXII. CHARACTERISTICS OF TYPICAL DEEP-DRAWING PRESSES

Manufacturer		Platen Size, in.	Tonnage
E. W. Bliss Company	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
The Hydraulic Press Manufacturing Company	Hydraulic triple- or 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.

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. 54):

$$P = d\,T\,S\pi\,(C - 1 + D/d) \tag{11}$$

where

P = punch load, pounds

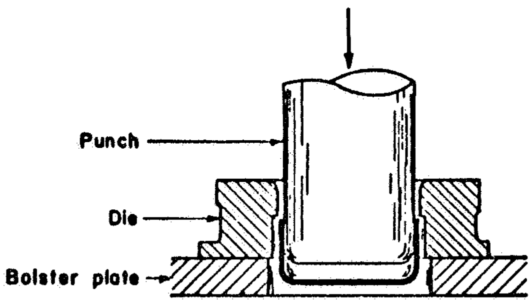
D = blank diameter, inch

d = punch diameter, inch

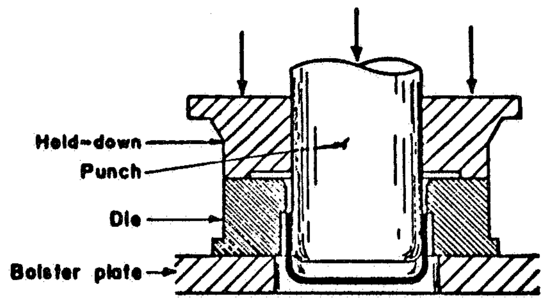
T = blank thickness, inch

S = maximum stress in metal, psi

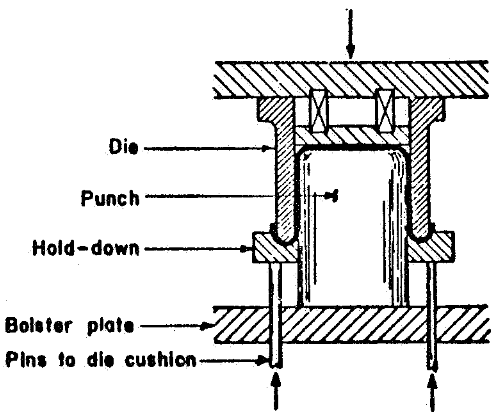
C = an empirical constant to take bending and blank holding loads into account; approximate 0.35 for precipitation-hardenable stainless steels.



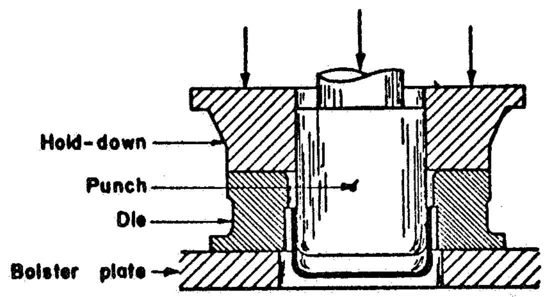
a. Single Action Without Hold-Down



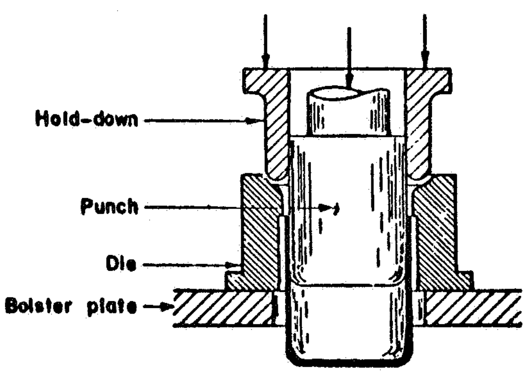
b. Double Action With Recessed Hold-Down



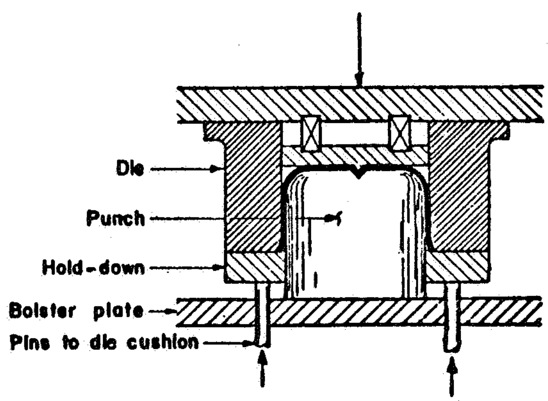
c. Single Action Inverted With Die Cushion Hold-Down Reverse Redraw



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 27. TYPES OF DEEP-DRAWING OPERATIONS (REF. 55)

Tooling for Deep Drawing. The design of the tooling used in deep drawing depends on the type of press to be used. Some of the typical tooling arrangements for drawing or redrawing are shown in Figure 27. 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 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 as shown in Figure 28. When the depth of draw to the blank-diameter ratio is small, it is sometimes possible to form without the use of a hold-down ring.

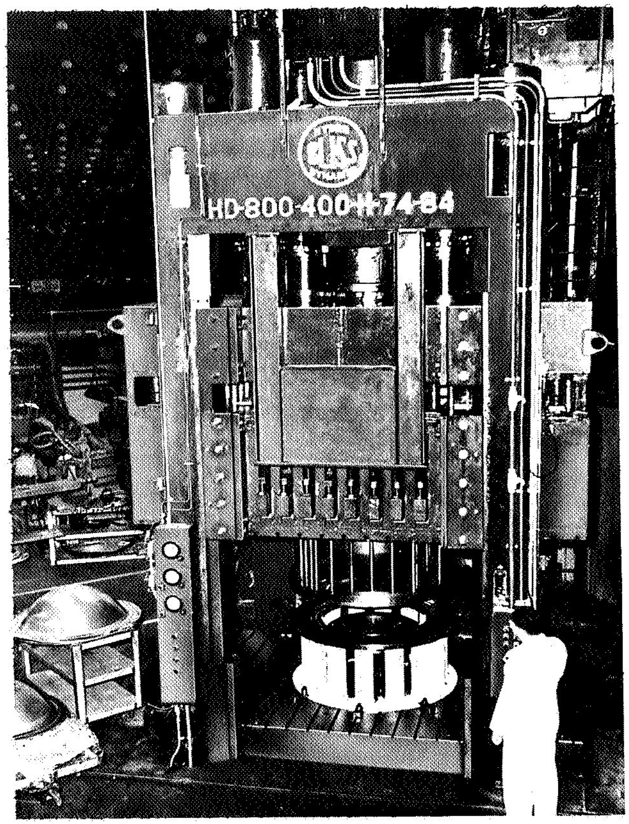


FIGURE 28. 800-TON PRESS EQUIPPED WITH SPRING-LOADED DIE CUSHION USED FOR DRAWING 52-INCH-DIAMETER ALUMINUM DOMES

Courtesy of E. W. Bliss Company, Canton, Ohio

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 Sachs (Ref. 56), the gap should be 25 to 50 per cent smaller than the thickness developed as the edge of the flange moves from its origin to final position. This amount of thickening is given by the equation

$$T/T_1 = D/D_1 \tag{12}$$

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 Equation (12). Experiments indicate that conical blank holders result in lower drawing loads than other types (Ref. 56).

A number of tooling materials have been used for deep drawing precipitation-hardenable stainless steels at room temperature. Alloy tool steels are normally used for the dies in deep drawing the PH steels. Some of the steels that have been used include 3C-1Cr-1Mo-12V composition heat treated to 64-66 R_C, and high-carbon high-chromium die steel heat treated to 60-62 R_C (Ref. 57). Cast-iron dies have been used for small-production runs while cemented carbide dies may be used for large-production quantities.

Clearances between the punch and die must be controlled to prevent galling, rupture, or buckling in the cup wall. The selection of the clearance between the punch and draw ring depends to some 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. Clearances for deep drawing precipitation-hardenable stainless steels should be about the material thickness of the blank plus 40 to 45 per cent of this thickness (Ref. 58). These alloys generally possess higher physical properties than drawing-quality steel and have greater resistance to wall thinning.

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 allowed 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 four to eight times the thickness of the metal (Ref. 58). Excessively large radii, in excess of about 10 T, may cause the parts to pucker. For severe operations, the punch radius should exceed four times the sheet thickness. When multiple-stage drawing is to be performed, large draw-ring radii should be used on the initial die stages. The radius can be reduced on the final stages until the desired radius is obtained.

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 increase. In most drawing operations, compressive stresses in the circumferential direction tend to buckle or wrinkle the rim of the blank. Shallow wrinkles should be prevented from forming by adjusting the force on the hold-down ring. Attempts to iron out wrinkles should be avoided due to the rapid work hardening of the metal. For the 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 thicknesses 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 set of dies. The general practice is to take a smaller reduction in redrawing operations than that used for the previous operation. A 35 to 40 per cent diameter reduction on cupping should be reduced to 15 to 25 per cent on redraw.

The depth to which the precipitation-hardenable stainless steels can be drawn for making rectangular shapes in one press stroke is a function of the corner radius and part dimensions. The corner radius should exceed 10 per cent of the minimum part dimension (Ref. 58). The depth of draw for precipitation-hardenable stainless steels should be limited to two to five times the corner radius. Such factors as the shape of the part, whether it has straight or tapered sides, and the thickness of material affect the limiting depth of draw. As the sheet thickness decreases below 0.050 inch, the permissible depth also decreases.

The draw-ring radius should be more generous for drawing rectangular shapes than for cylindrical shapes. A factor of five to seven times the thickness of the material should be used.

Rectangular shapes can be redrawn to sharpen the corners or to stretch out wrinkles along the sides. When the depth of draw is greater than that possible in one operation, it is sometimes possible to draw about two-thirds of the depth in the first pass, anneal the part, and complete the part in the same die. This practice is also used to avoid wrinkling.

Due to the rapid work-hardening rate of the precipitation-hardenable stainless steels a low drawing speed should be used. Speeds from 10 to 20 feet per minute should be satisfactory for PH 15-7 Mo and 17-7 PH. The speed may be lower or higher for the other precipitation-hardenable stainless steels depending on their rate of work hardening and sensitivity to strain rate. The austenitic types such as A-286 can probably be formed at a higher speed while the martensitic types like 17-4 PH and Almar 362 should be drawn at a lower speed.

Lubrication of the blanks in deep drawing is necessary to obtain maximum drawability. Lubricants minimize the energy required to overcome friction between the blank and the tooling and reduce the possibility of galling or seizing.

A heavy bodied or mineral oil of the chlorinated or sulfurized type should be used for heavy press work (Ref. 58). For light pressure forming, light oils and soap solutions may be used. The lubricants are applied to the blanks by dipping, spraying, or swabbing. The various manufacturers of lubricants should be contacted for specific recommendations for a given alloy and type of drawing. All lubricants should be thoroughly removed before any thermal treatment of precipitation-hardenable stainless steels to prevent surface contamination.

In some cases, applying the lubricant to only certain portions of the blank or tooling may assist in obtaining maximum formability. For instance, a lubricant between the blank and the die and the 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 that cause stretching, and sometimes rupture, at those locations. Therefore, benefits are sometimes obtained from rough or unlubricated punches. (Ref. 59)

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 precipitation-hardenable stainless steels, pertinent data 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:

$$R = \frac{\ell n\ W_o/W}{\ell n\ T_o/T} \quad , \qquad (13)$$

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 zero, 45, and 90 degrees from the rolling direction. The component of normal anisotropy can be defined as

$$R = 1/4\ (R_{zero} + 2\ R_{45} + R_{90}) \quad . \tag{14}$$

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

$$\frac{Z}{X} = \sqrt{\frac{1 + R}{2}} \quad . \tag{15}$$

A completely isotropic material would have R values of 1, for tests in all directions, and a uniform strength in the thickness and plane of the sheet.

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 29. The deep-drawing properties of materials are often compared on the basis of the maximum reductions they will withstand under standardized conditions. The ratings may be 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, and if no stretching or ironing occurs, can be calculated from the relationship

$$H/d = 1/4\,[(D/d)^2 - 1] \quad . \tag{16}$$

When there is a flange on the cup, the relationship changes since the restraining force caused by the flange shrinkage must be considered. The use of a flange, although wasteful of material, may eliminate wall splitting in a part. The ratio of the diameter or radius to the thickness of the blank may also affect success in deep drawing. In any case, the friction resulting from the hold-down pressure becomes an appreciable part of the load in drawing comparatively thin blanks.

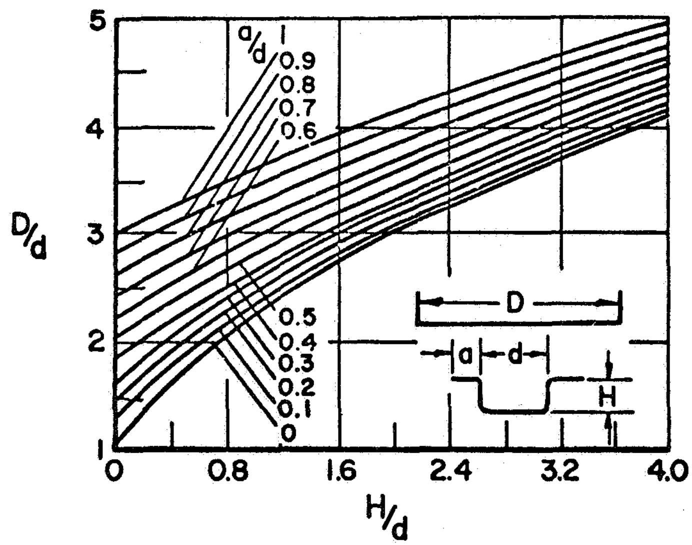


FIGURE 29. THEORETICAL RELATIONS BETWEEN DIMENSIONS OF A SHARP-RADIUSED CYLINDRICAL PART AND BLANK DIAMETER (REF. 56)

<u>Deep-Drawing Limits</u>. Success in deep-drawing operations is influenced by mechanical properties and hence by prior processing history. Hamilton and Meredith found that tank ends could be successfully deep drawn from 0.090-inch-thick 17-4 PH sheet when the material was in the overaged condition (H 1200), but could not be made when it was in the solution-annealed condition (Ref. 60).

Wood and associates (Ref. 33) have shown that drawability of the material can be predicted from the following forming index:

$$\frac{E}{Y_c} \times \frac{Y_c}{Y_t} = \text{Deep-Drawing Formability Index,} \qquad (17)$$

where

E = Young's elastic modulus, psi

Y_c = compressive yield strength, psi

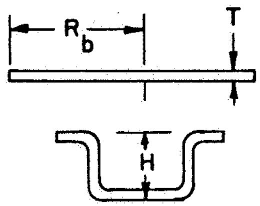
Y_t = tensile yield strength, psi.

An increase in index indicates an increase in formability in deep drawing. Using this index for a particular material and material condition, a relationship between the flange-width-to-part-radius ratio and flange-width to material-thickness ratio can be determined and forming limits envelope, as shown in Figure 30, can be constructed. Both of the alloys shown appear to have better drawability at 500 F than at room temperature; the formability decreases at higher temperatures because of precipitation reactions. Most of these materials, however, are drawn at room temperature since only the most difficult draws would warrant the use and expense of elevated-temperature tooling.

The drawability of the Almar 362 alloy with different types of punches is shown in Figure 31. The drawability of this alloy is slightly poorer than that of the 400 series stainless steels.

An example of a deep-drawn tank end is shown in Figure 32. This part was made by explosive-forming techniques until the production requirements justified the use of deep drawing. The part is shown after assembly with a collar.

Before deep drawing any of the precipitation-hardenable stainless steels, they should be in the most ductile condition. Since material purchased in the annealed (solution treated) condition may harden during transportation and storage, the material should be annealed prior to forming as a precaution. Sometimes the precipitation-hardenable stainless steels are overaged prior to drawing to put them in a softer condition.



Part shape and dimensions

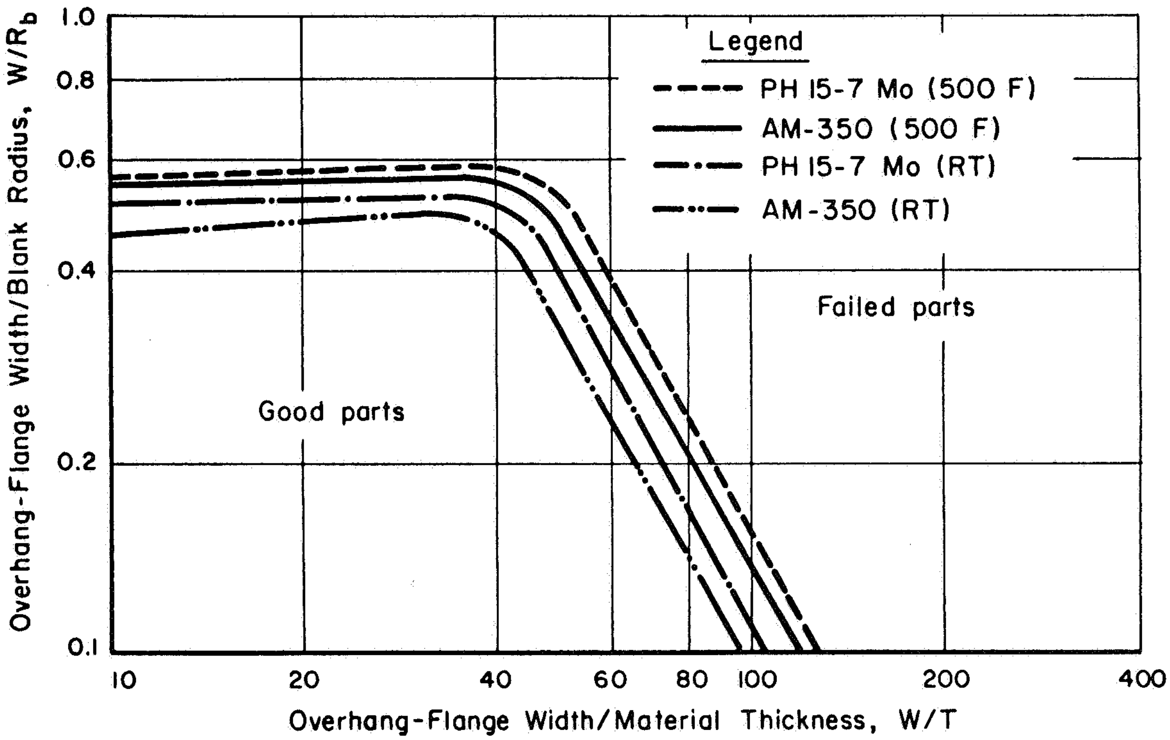


FIGURE 30. DEEP-DRAWING-LIMIT CURVES FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 33)

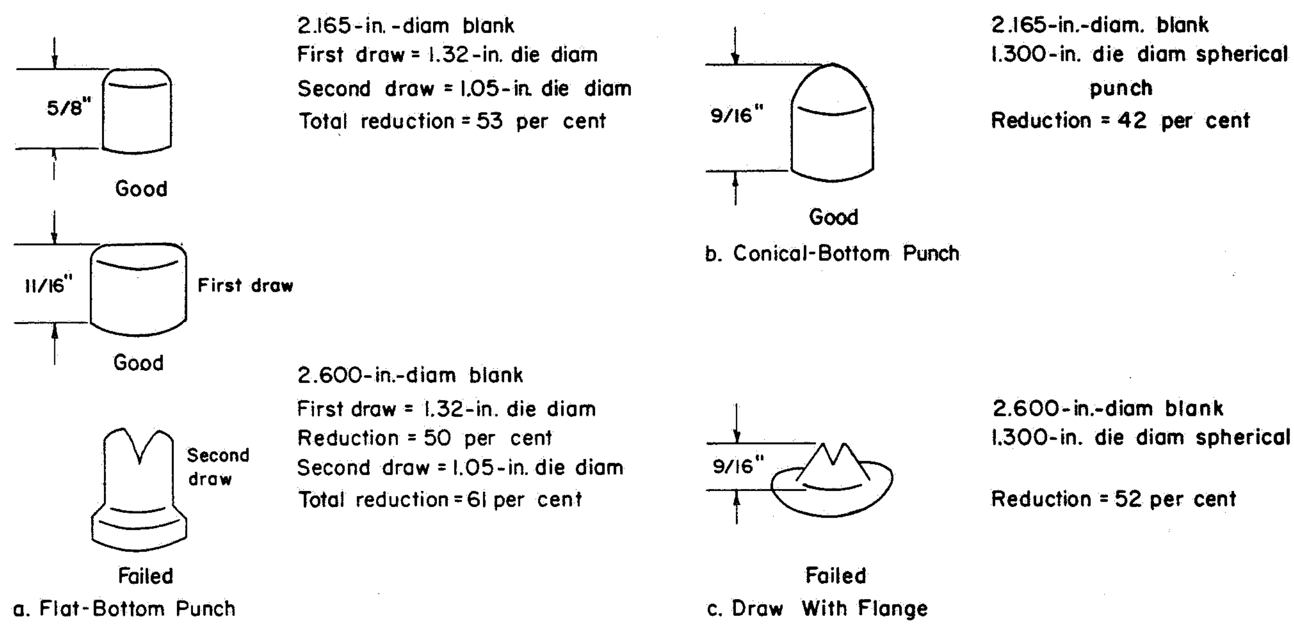


FIGURE 31. DEEP-DRAW TEST OF ANNEALED ALMAR 362 (REF. 60)

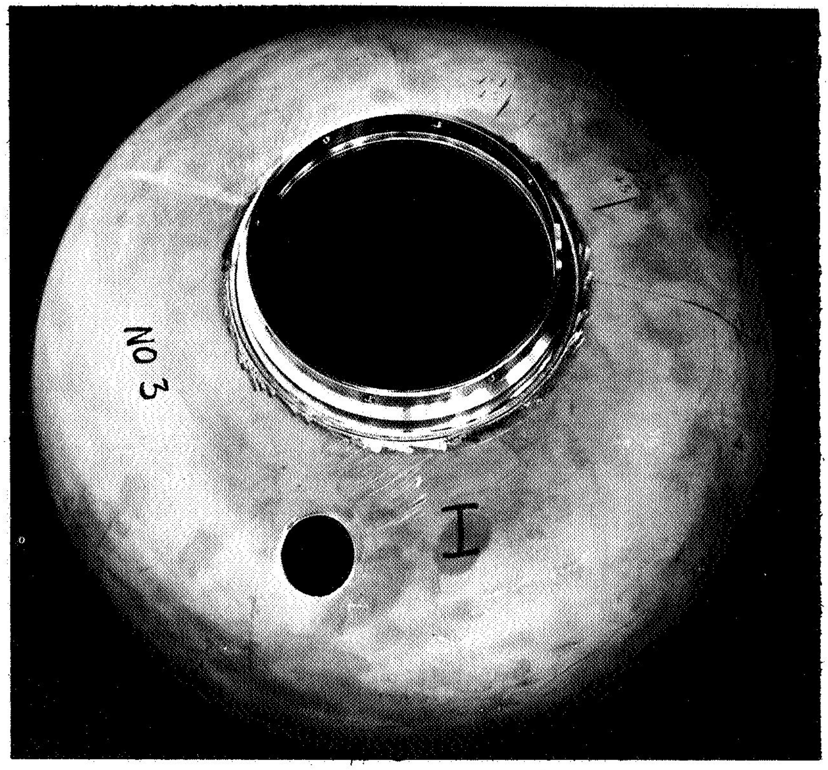


FIGURE 32. DEEP-DRAWN AM-350 TANK END

Starting material was 0.040 inch thick and the completed part was 4-inches deep. Part was formed in the annealed condition at room temperature and heat treated in a sizing fixture. Courtesy of North American Aviation, Inc., Columbus, Ohio.

Care should be taken to assure that the tooling is clean and free of defects. The surface of the blanks should also be clean to prevent abrasion of the tooling. Surface scratches should be prevented or removed, and the edges of the blanks should be deburred and free of any cracks.

Post-Forming Treatments. Since these materials work harden very rapidly and some types transform to martensite during forming, the parts should be given a thermal treatment soon after forming, preferably within 24 hours. The residual stress in the material from the forming operation may be sufficiently high to cause delayed cracking or stress-corrosion cracking if the parts are exposed to a corrosive atmosphere. Generally, these materials are given a thermal treatment before use to avoid a gradual change of part dimensions or mechanical properties with time.

Lubricants from the drawing operation must be removed completely from the part before it is given any thermal treatment. The lubricants can be removed in a trichloroethylene degreaser; insoluble materials may require an acid etch.

SPINNING AND SHEAR FORMING

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 differs from spinning principally because it produces reductions in thickness. A number of trade names have been used to describe the shear-forming process since its development. 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 because it appears to be emerging as the most accepted name for the process.

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 33, is limited to thin (less than 1/16 inch thick) low-strength (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, such as the precipitation-hardenable stainless steels.

Spinning differs from most metalworking processes in that the material is deformed at a point rather than over a broad area and 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 34.

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

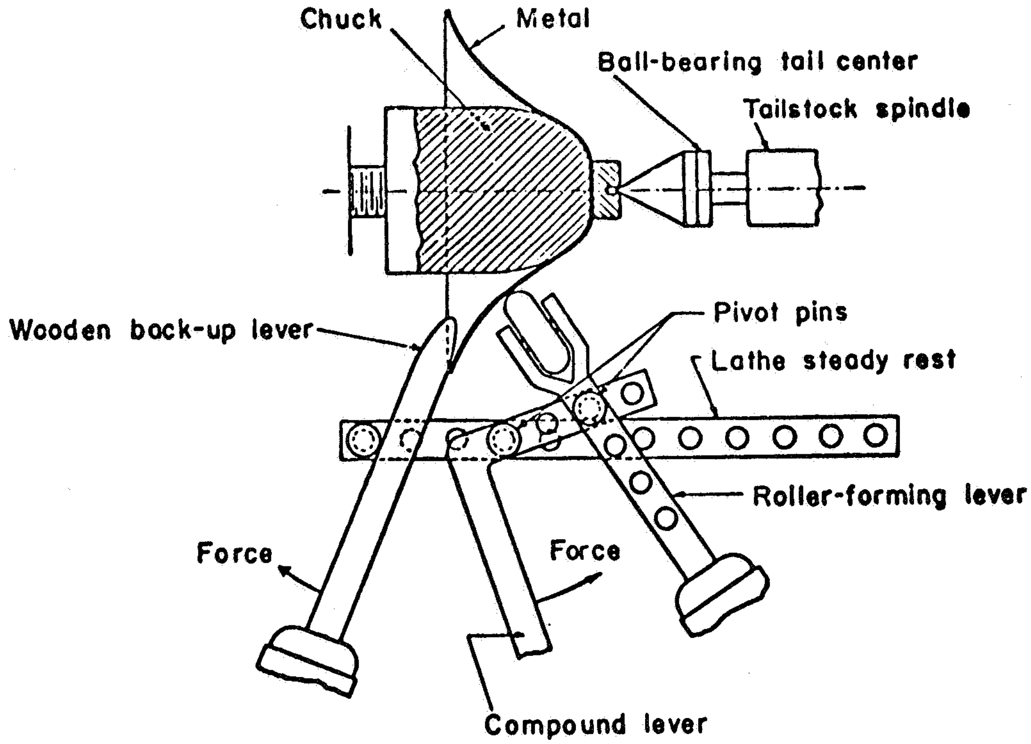


FIGURE 33. MANUAL SPINNING (REF. 55)

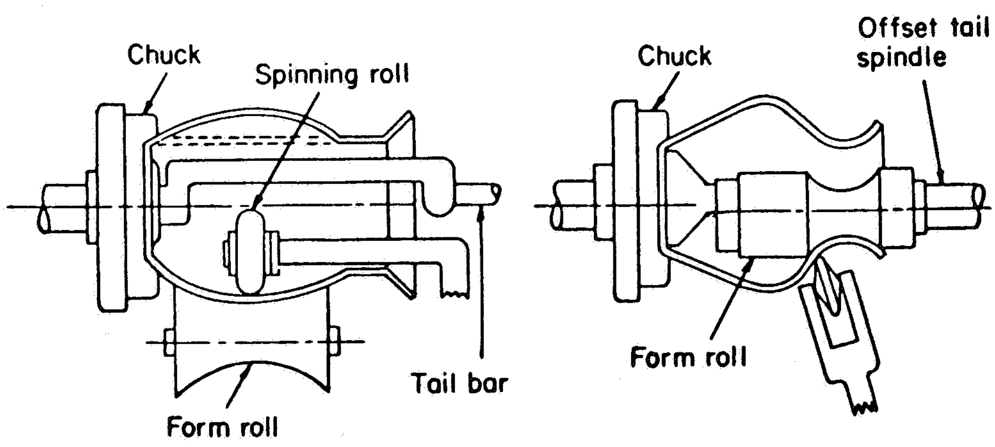


FIGURE 34. INTERNAL SPINNING TECHNIQUES (REF. 61)

great. The limits are related to the ratio of compressive modules of the material to the compressive yield (Ref. 33). Elastic buckling occurs in the unspun flange of the part as shown in Figure 35.

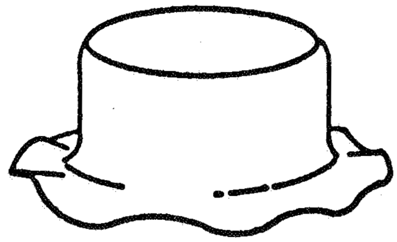


FIGURE 35. ELASTIC BUCKLING IN A SPUN PART (REF. 33)

The ratio of depth to diameter of parts that can be produced by spinning is limited by plastic buckling. Buckling limits are related to the ratio of tensile modulus to the tensile ultimate strength of the workpiece material (Ref. 33). Since plastic buckles are very difficult to remove, they should be prevented by limiting the amount of deformation in one operation to that permitted by the characteristics of the material. The precipitation-hardenable stainless steels may be spun at room temperature or elevated temperatures up to 500 F. Attempts to spin at higher temperatures may lead to reduced ductility in the temperature range of 600 to 1500 F, depending on the alloy.

Exceeding the formability limits can cause shear splitting or circumferential splitting, as shown in Figure 36. 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 tensile ultimate strength of the material in the axial direction.

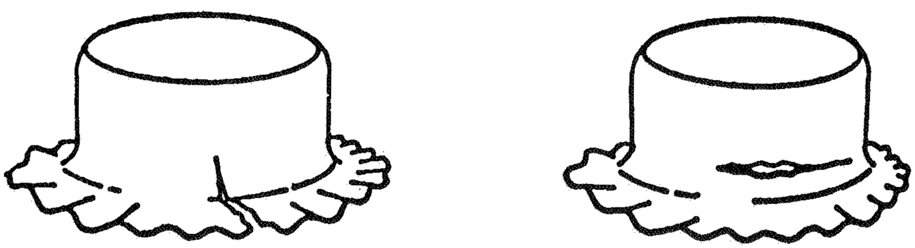


FIGURE 36. SHEAR SPLITTING AND CIRCUMFERENTIAL SPLITTING (REF. 33)

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. Since the precipitation-hardenable stainless steels work harden very rapidly only a single tooling pass should be made between anneals.

Principles of Shear Forming. Shear-forming processes can be broken down into cone and tube shear forming; other shapes can be considered as modified cones.

A typical example of cone shear forming is shown in Figure 37. The blank, a circular disk, 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. This figure shows a progression of the forming sequence starting with Step (1). The rolls are not driven, but rotate due to contact with the rotating blank.

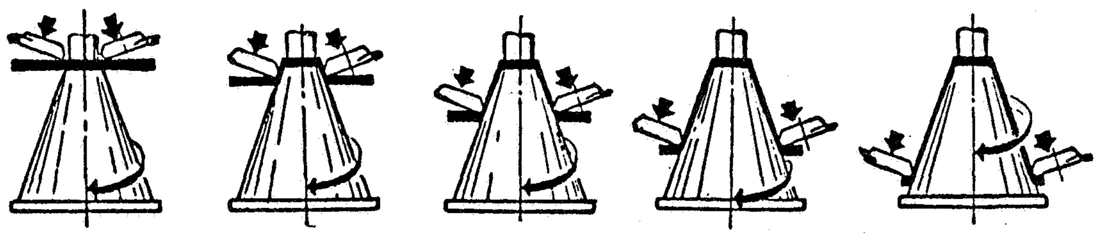


FIGURE 37. STEPS IN SHEAR FORMING A CONE (REF. 62)

Cone Shear Forming. The percentage reduction of material thickness during cone shear forming is a function of the part shape. Figure 38 shows the geometric measurements that are important for shear forming a cone. The final thickness is related to the initial thickness of the blank by the sine of the half angle of the cone.

$$T = T_b(\sin a/2) . \tag{18}$$

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 half angle as

$$R = 100(1 - \sin a/2) \quad , \tag{19}$$

where

R = the per cent reduction.

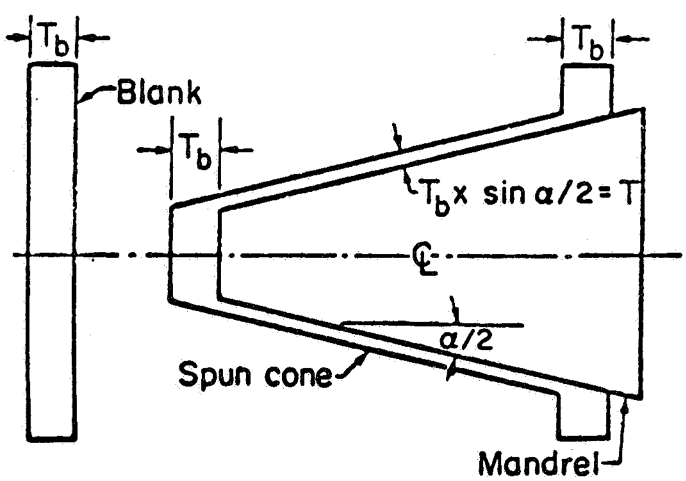


FIGURE 38. GEOMETRIC RELATIONS IN CONE SHEAR FORMING (REF. 63)

The same rule applies to shapes other than a cone with the final thickness at any given point along the part being determined by the angle the part makes with the axis at that point. For instance, forming a hemisphere results in a variation of thickness with the bottom of the hemisphere having the same thickness as the blank and the edge being the thinnest section, as shown in Figure 39.

Figure 40 shows a helium tank, 27-1/2 inches in diameter, that was produced by welding together two hydrospun hemispherical tank heads of 17-7 PH stainless steel. This application is typical of parts that have been produced by hydrospinning and welding.

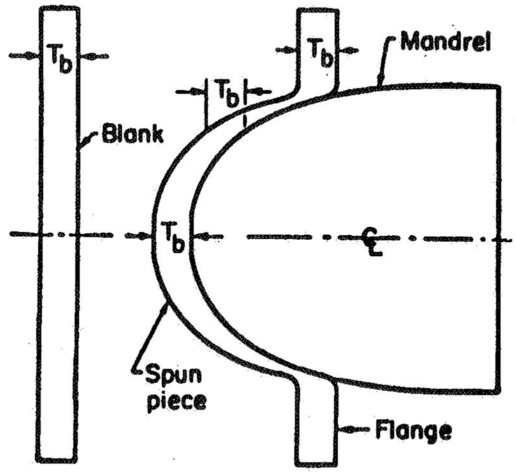


FIGURE 39. THICKNESS OF A MATERIAL IN A SHEAR-FORMED HEMISPHERE (REF. 64)

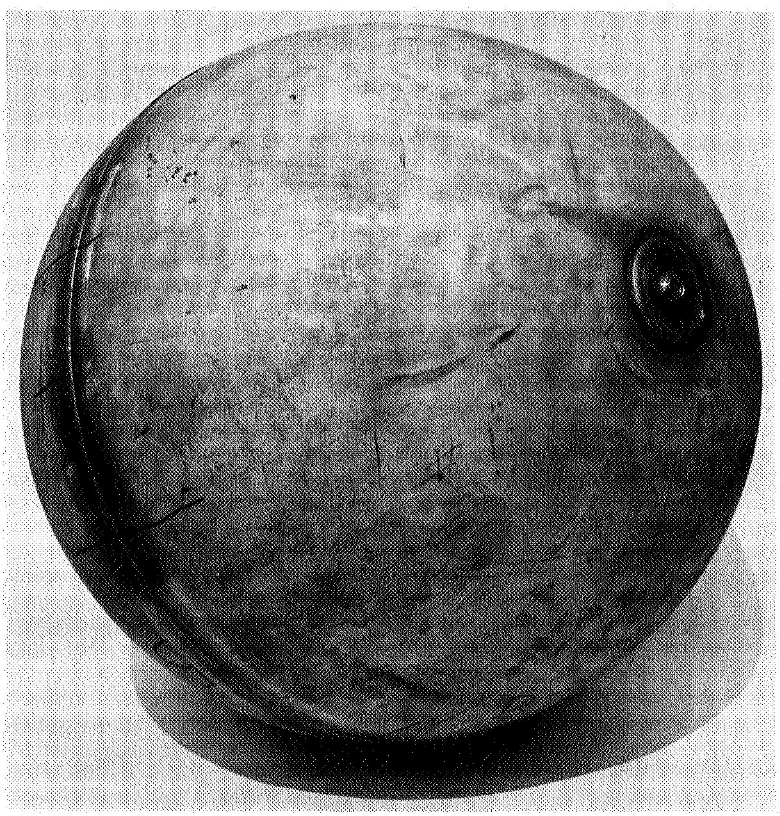


FIGURE 40. HELIUM TANK, 27-1/2 INCHES IN DIAMETER, PRODUCED BY WELDING TOGETHER TWO HYDROSPUN HEMISPHERICAL TANK HEADS OF 17-7 PH STAINLESS STEEL

Courtesy of The Boeing Airplane Company, Seattle, Washington.

Tube Shear Forming. Shear forming of tubes can be of two basic types: forward and backward, as shown in Figure 41. 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. 64).

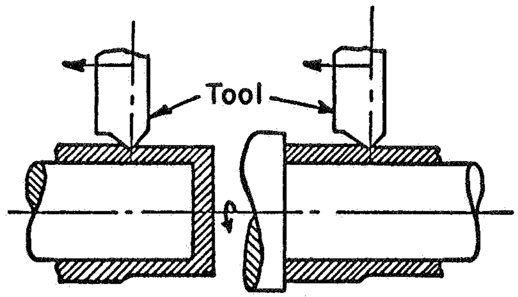


FIGURE 41. SCHEMATIC OF TUBE SHEAR FORMING (REF. 65)

Backward tube shear forming simplifies blank holding and permits higher production rates because 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 deformed material must travel the greatest distance it is most likely to be out of plane.

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 for shear forming cannot be applied. 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. 66). The experimental data shown in Figure 42 indicate that a maximum spinning reduction of about 80 per cent can be taken on materials with a tensile reduction-in-area value of 50 per cent. Beyond this level of tensile ductility there is no further increase in formability. Among materials with a reduction-in-area value less than 50 per cent, ductility determines formability.

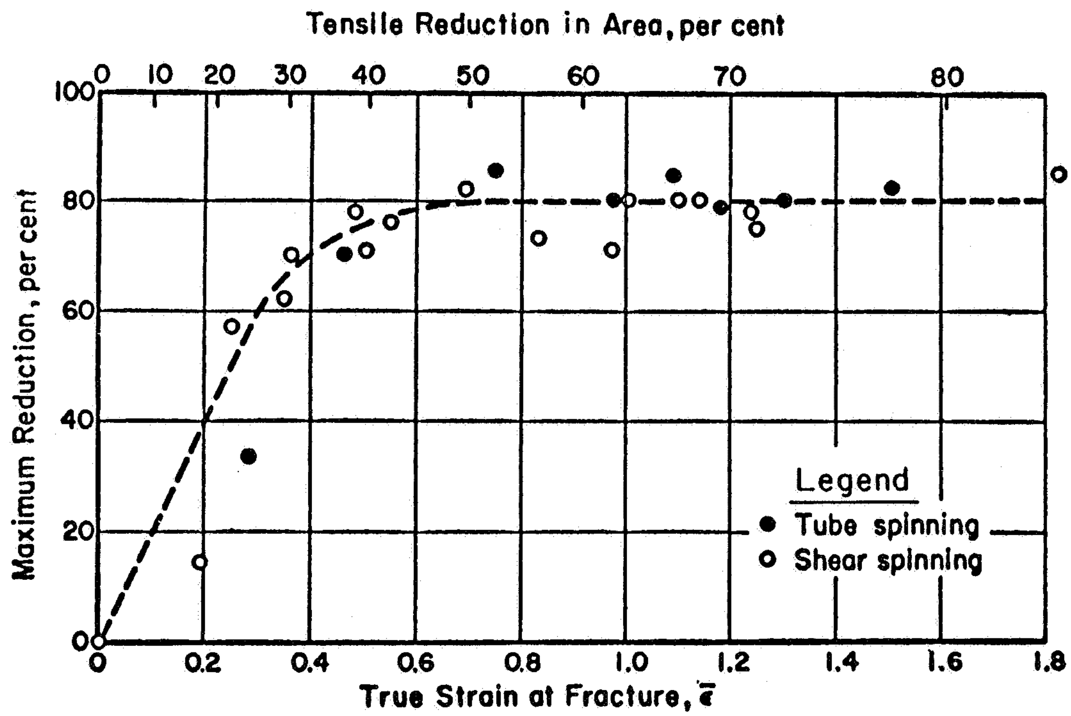


FIGURE 42. MAXIMUM SPINNING REDUCTION IN TUBE AND SHEAR SPINNING OF VARIOUS MATERIALS AS A FUNCTION OF TENSILE REDUCTION IN AREA (REF. 66)

Some of the process parameters affecting the allowed limits of reduction are the feed rate, corner radius of the tool, the depth setting of the tool, and the angle of the tool. In general, increasing the feed or corner radius will decrease the maximum permissible reduction. Within the range from 15 to 45 degrees, variations in the roller angle appear to have very little effect on the maximum reduction. Beyond those limits the effects are not known.

Equipment. Most engine-lathe manufacturers will make equipment for spinning. The manually operated machines have been replaced by 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.

One of the large shear-forming machines is shown in Figure 43. Some of the specifications are given in Table XXXIII for machines manufactured by Lodge & Shipley, Cincinnati Milling Machine Company, and Hufford Manufacturing Company. Additional sizes of machines may be available so that the manufacturers should be informed of specific requirements. A typical shop layout for shear forming is given in Figure 44. Integration of the shear-forming process with other manufacturing would probably dictate other layouts.

Tooling. Spinning. Mechanical or hydraulic spinning rollers of hardened tool steel (R_C 60-62) sometimes with a hard chromium plate are used for spinning precipitation-hardenable stainless steels. The surface of the rollers should be highly polished. 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 1/2 the smallest diameter of the part.

Mandrels or chucks for spinning can be made of tempered Masonite for production runs of 25 parts or less. These are generally used for intermediate operations where tolerances are liberal. For larger production quantities, the mandrels may be made of ductile cast iron or tool steel. A hard, smooth surface on the mandrel permits the removal of tool marks from previous forming stages and gives a closer tolerance on the finished part.

Shear Forming. Shear forming requires stronger tooling than spinning because greater forces are 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 45 and the more important surfaces 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 can be hard chromium plated for a good surface finish on the part.

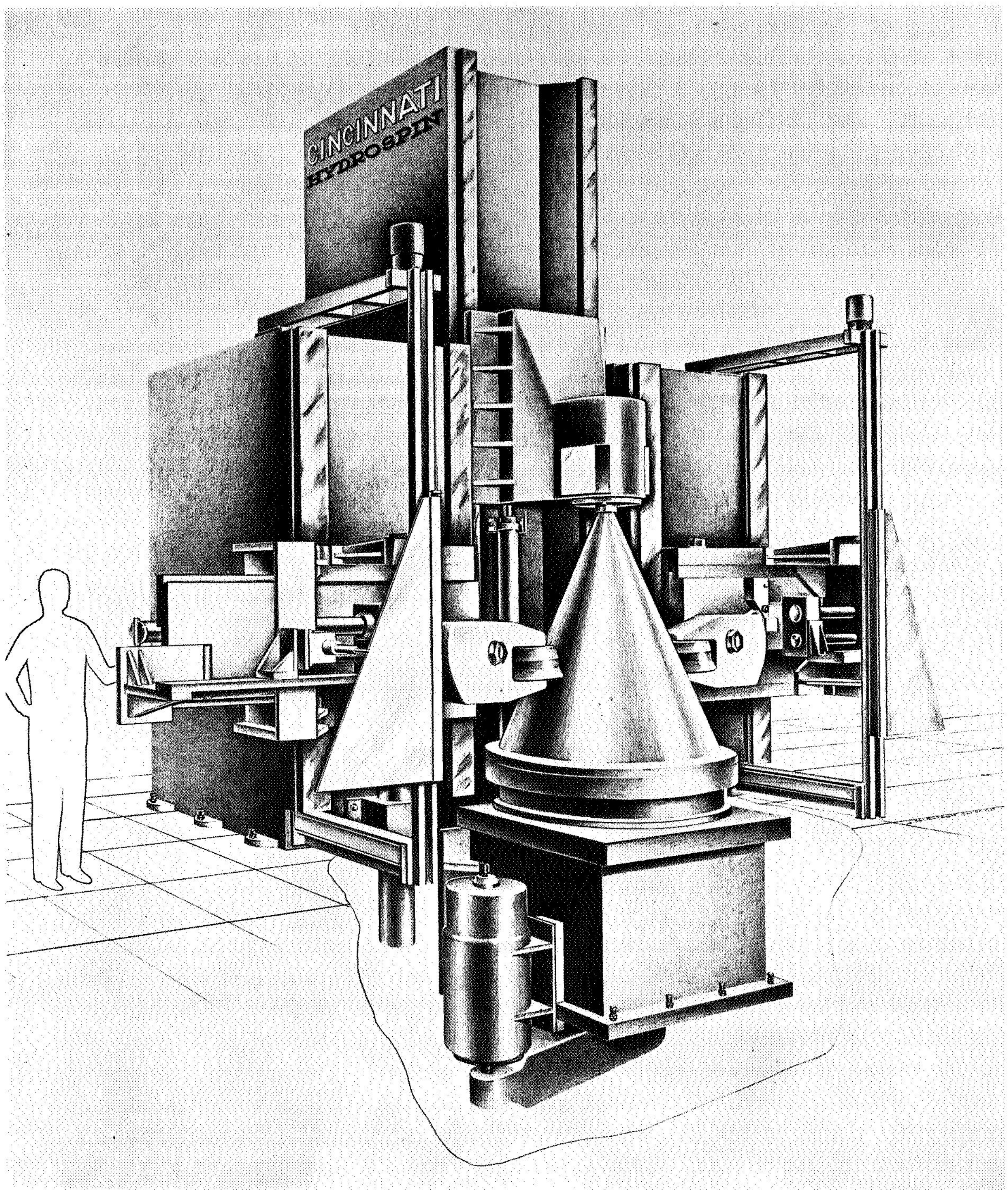


FIGURE 43. 70 x 72-INCH VERTICAL SHEAR-FORMING MACHINE

This machine can produce conical or curvilinear parts up to 70 inches in diameter and 72 inches long, tubular parts up to 144 inches long.

Courtesy of Cincinnati Milling Machine Company, Cincinnati, Ohio.

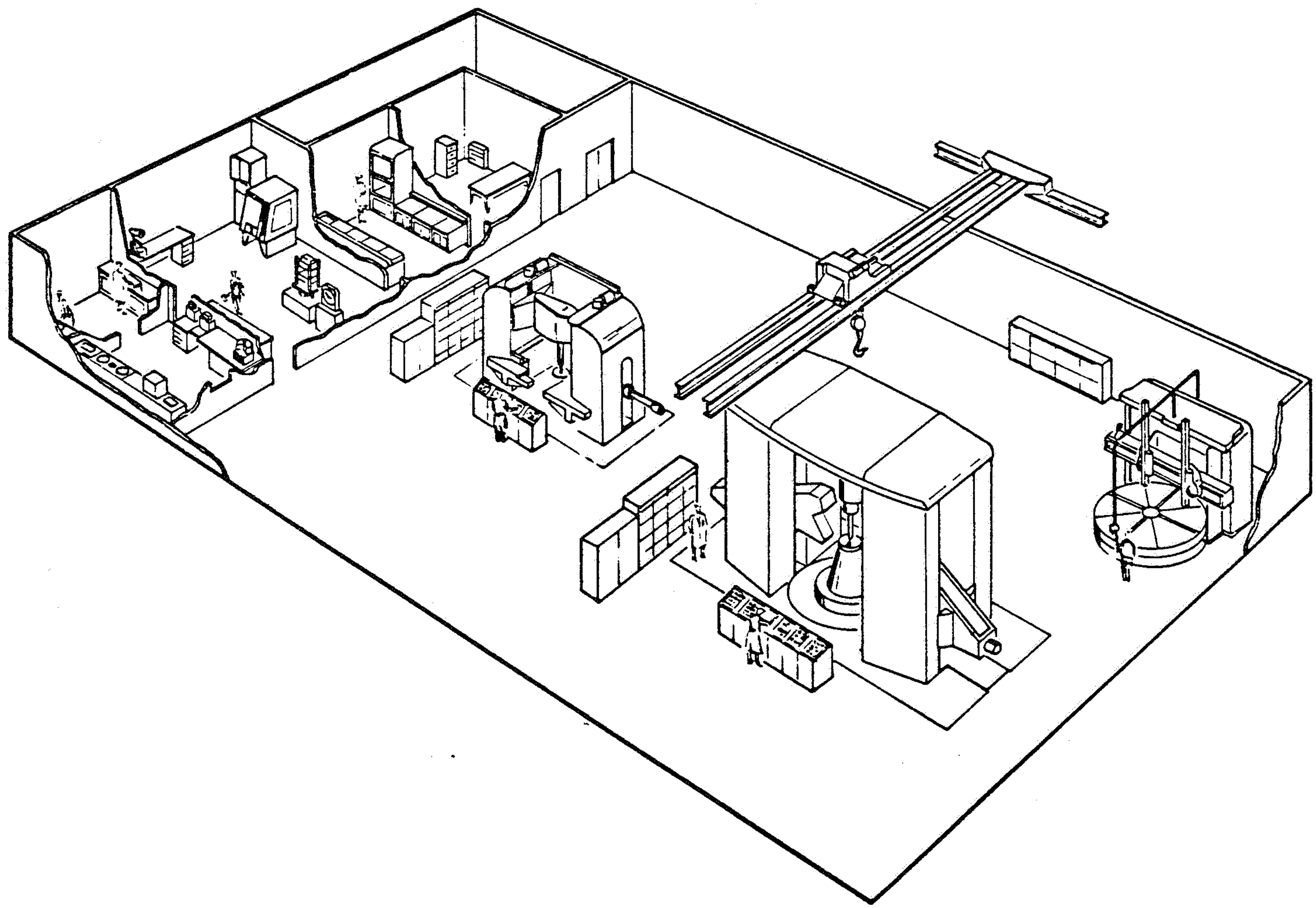


FIGURE 44. TYPICAL SHOP LAYOUT FOR SHEAR FORMING

Courtesy of Hufford Manufacturing Company, El Segundo, California.

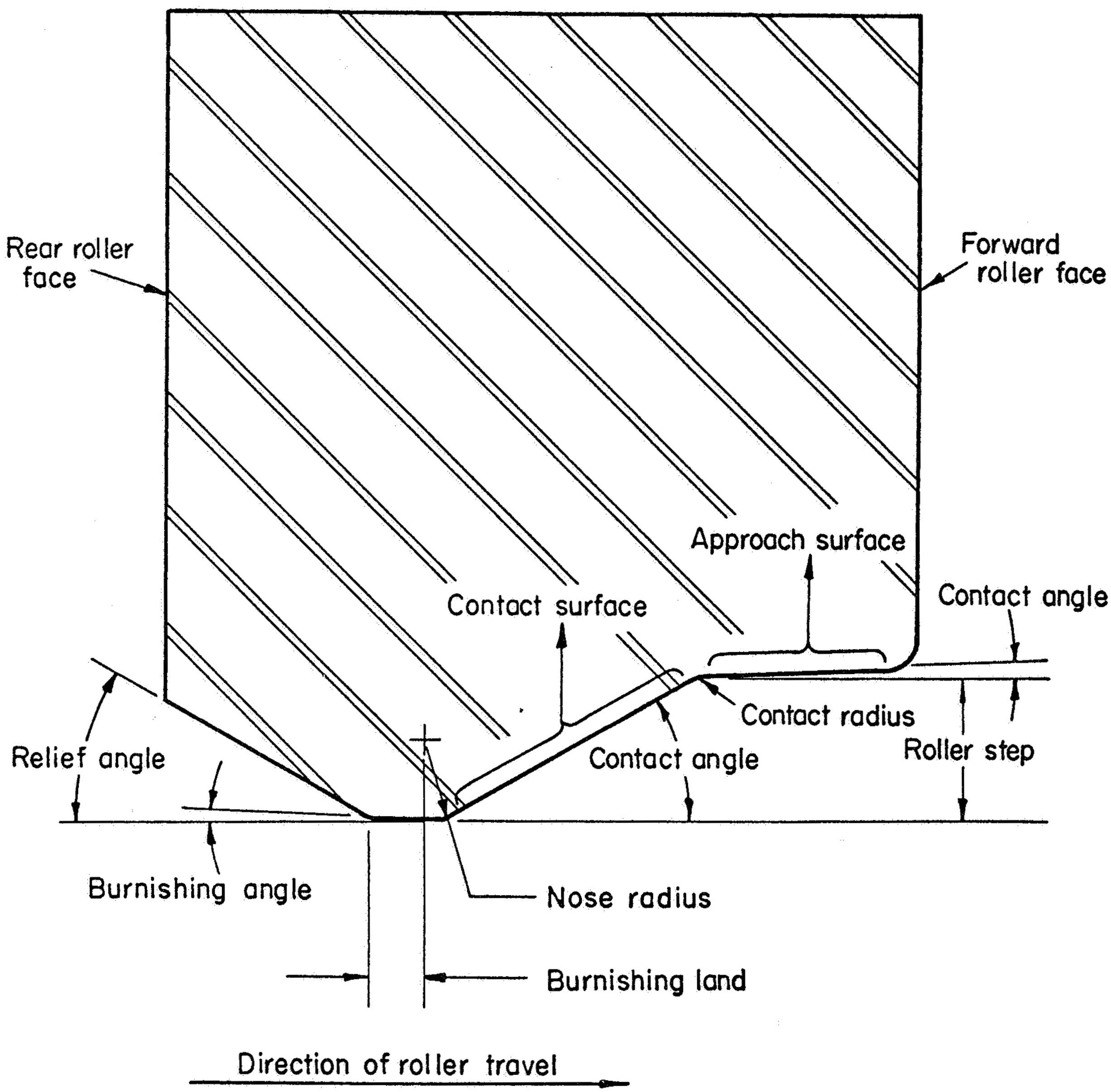


FIGURE 45. ROLLER CONFIGURATION FOR SHEAR FORMING (REF. 69)

TABLE XXXIII. TYPICAL AVAILABLE SPINNING AND SHEAR-FORMING-MACHINE SIZES (REFS. 62, 67, 68)

Manufacturer	Port Diameter, in.	Port Length, in.	Spindle, hp	Forces: Roller, lb	Forces: Carriage, lb	Forces: Tailstock, lb	Production Rate, piece/hr	Machine Weight, lb	Number of Rolls	Type
Lodge & Shipley	12	15	15	4,000	5,000	2,000	75-100	8,750	1	Horizontal
(Floturn)	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	42	50	20	50,000	50,000	35,000	--	53,970	1	Horizontal
Machine Company	42	50	20	50,000	50,000	35,000	--	78,970	2	Horizontal
(Hydrospin)	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 Manufacturing	60	60	200	225,000	225,000	200,000	--	--	2	Vertical
Company	60	120	200	225,000	225,000	200,000	--	425,000	2	Vertical
(Spin forge)										

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.

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 oxidation of materials and tooling. The rotating contacts that transmit 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. For 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 46. 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. An oxidizing flame is normally used. Propane-oxygen torches have been used in spinning PH 15-7 Mo and AM-355. Blanks for 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 for 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. Temperature increases of 150 F have been noted when shear forming AM-355 at room temperature (Ref. 70).

Blanks can also be heated by radiation from resistance units located around the part; this technique works well on tubing or preforms. For obvious reasons, this practice is difficult to control when processing flat blanks.

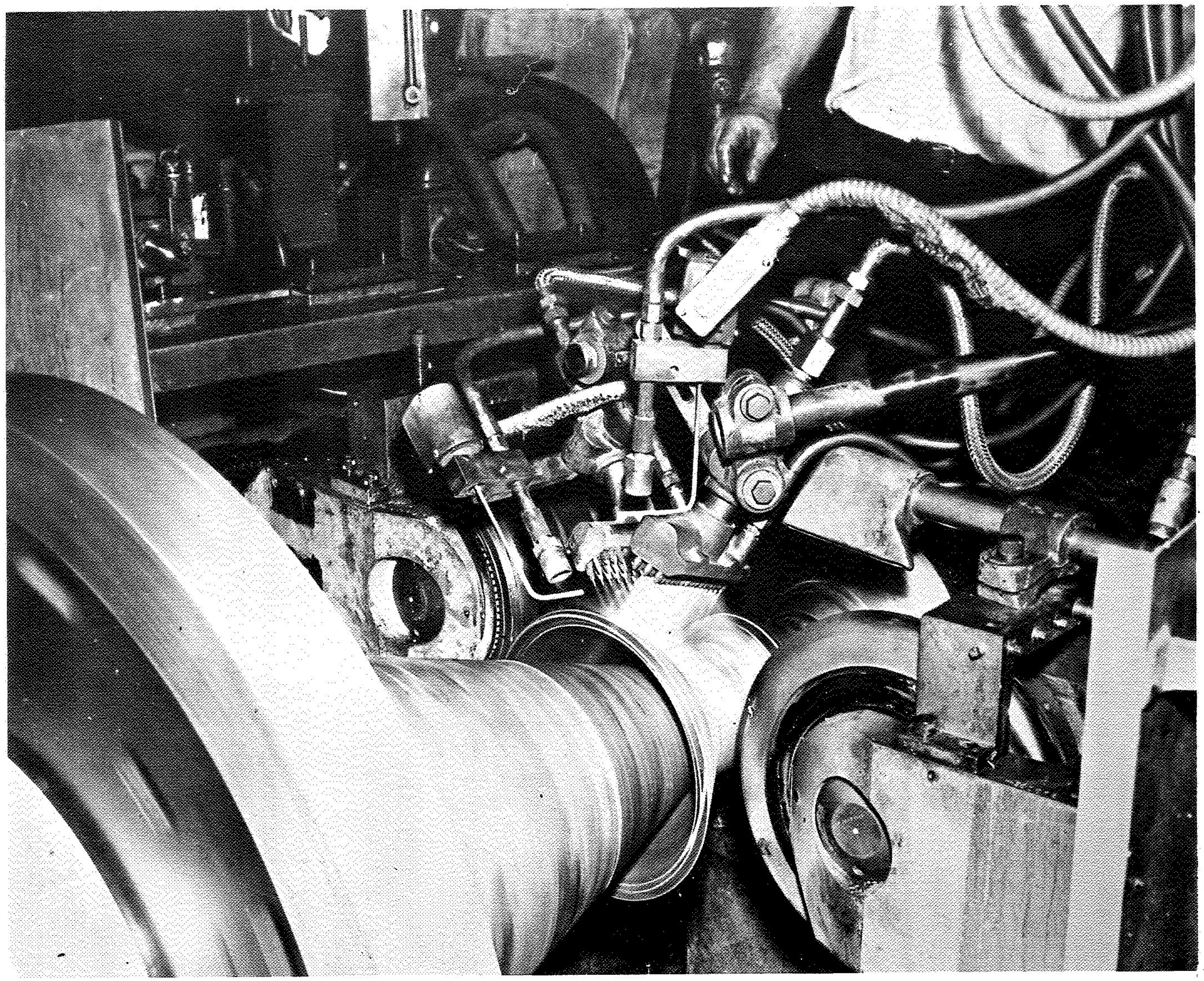


FIGURE 46. TORCH HEATING OF A BLANK DURING CONE SHEAR FORMING (REF. 69)

The rollers in shear forming are generally cooled to prevent distortion or creep under high loads. This is usually accomplished by spraying a water-miscible lubricant, such as ethylene glycol, on the roller surface (Ref. 71); internal-circulating cooling systems are not very practical.

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 a high-pressure colloidal zinc and molybdenum disulfide paste to prevent galling at roller pressures up to 400,000 psi on the precipitation-hardenable stainless steels (Ref. 71). For room-temperature spinning, yellow laundry soap, beeswax, tallow, or mixtures of the latter two may be used. Heavy-bodied oils are desirable for extremely severe work (Ref. 70) of spinning and shear forming.

Blank Preparation. 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. To this the allowance for trim stock is added. 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 Shearing Forming. Cone shear forming requires a blank with a diameter the same 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 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 considerations 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.

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 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 47

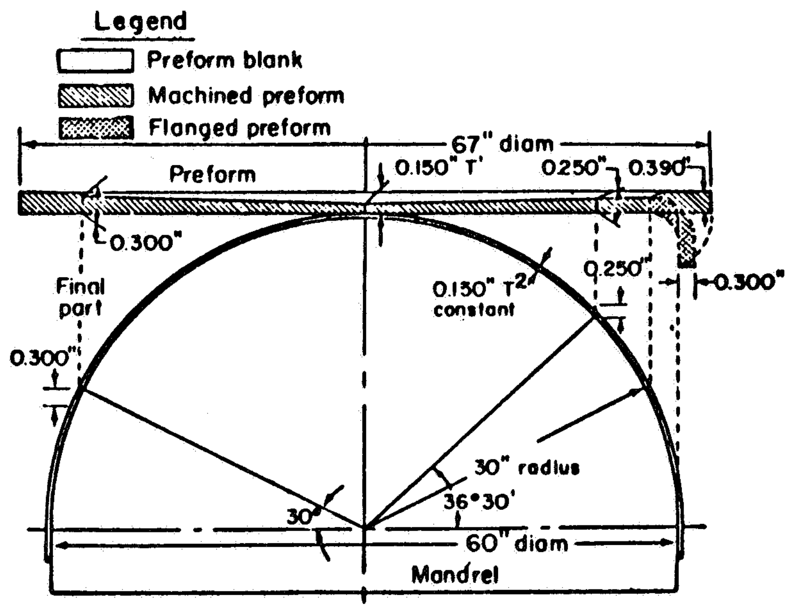


FIGURE 47. TYPICAL DEVELOPMENT OF A BLANK FOR CONSTANT SHEAR-FORMED THICKNESS (REF. 64)

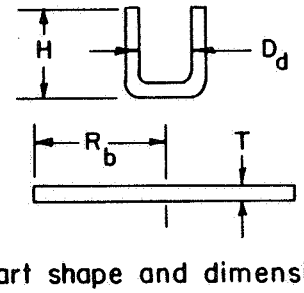
in which a maximum reduction of 50 per cent is expected to produce a constant wall thickness of 0.150 inch. Using the sine law to determine the vertical height of an element in the shell at increments of about 1/2 degree gives a continuous plot of the blank thickness. Since only a 50 per cent reduction 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. Preforming the edge from the 30-degree intersection to the lip of the hemisphere is therefore necessary, as shown in Figure 47. 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 a 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.

Spin-Forming Limits. The information available on spinning of precipitation-hardenable stainless steels is meager, but Wood and associates (Ref. 33) published some studies on the subject. The buckling limits are set by the ratios of the moduli to strengths of the workpiece. AM-350 has an optimum forming-temperature range between 500 and 1000 F, while PH 15-7 Mo and A-286 should be spun at 1000 F for best spinnability.

Figure 48 gives some formability limits for manual spinning several alloys at room and elevated temperatures. 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. For example, the limit for a 10-inch-diameter, 1/16-inch-thick blank of PH 15-7 Mo appears to be a flat cup 6.8 inches in diameter, 1.6 inches high. Spinning a 0.100-inch-thick blank of the same dimensions and material at 1200 F would give a part 4 inches in diameter and 3 inches high.

Spinning at elevated temperatures increases the amount of deformation that can be taken before buckling occurs. A higher deformation temperature postpones both plastic and elastic buckling to higher strains. Consequently, elevated forming temperatures permit spinning of cups with larger cup height/cup diameter ratios, and permits the use of thinner blanks. The optimum spinning temperature depends on the properties of the material at various temperatures.

Spinning of precipitation-hardenable stainless steels to deep cups at room temperature requires a number of stages and intermediate anneals. The forming operation is generally limited to a single pass. The material has then work hardened to a point where the ductility is too low and pressure requirements are too high. The material



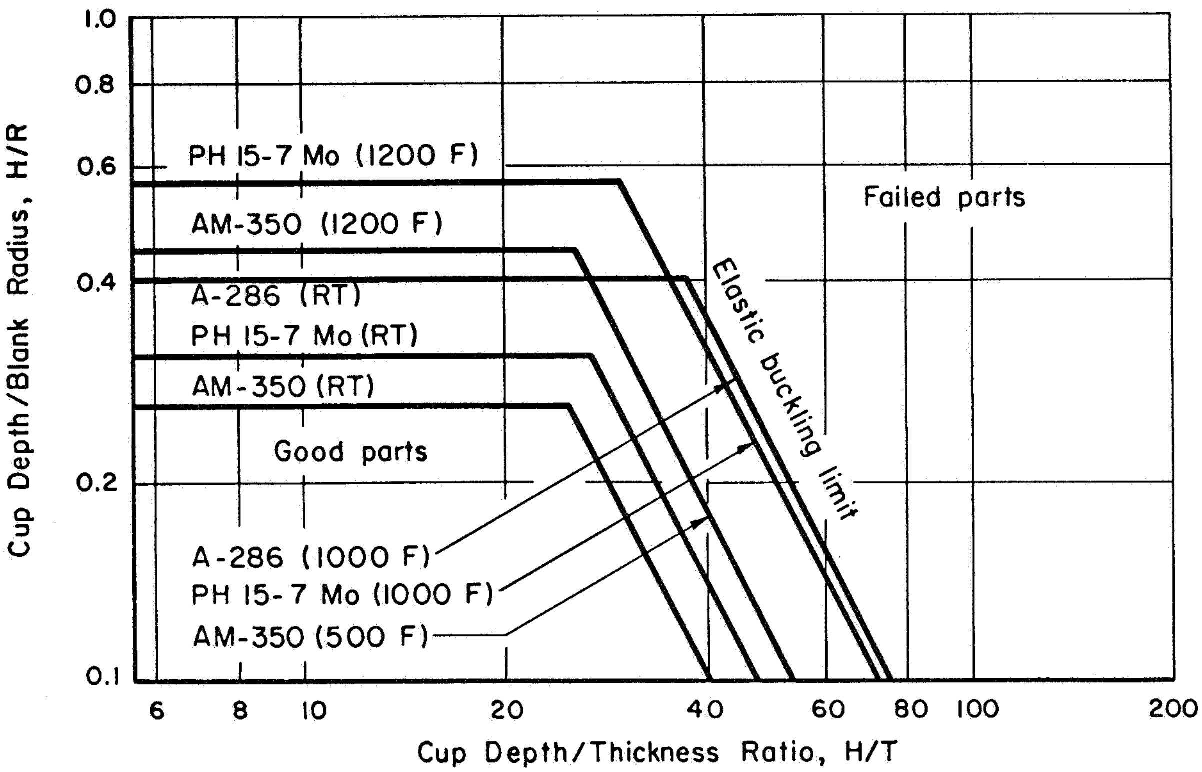


FIGURE 48. SPINNING-LIMIT CURVES FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

must then be annealed. Spinning at elevated temperatures permits more deformation and a larger number of passes depending on the material and forming temperature. An example was the spinning of a 65-inch-diameter, 25-inch-deep hemisphere made from PH 15-7 Mo and AM-350 (Ref. 72). The 83-inch-diameter starting blank was 0.290 inches thick and was heated to 1600 F for forming. The thickness was reduced 30 per cent during spinning and a configuration tolerance of ±0.020 inch was held.

The speed at which precipitation-hardenable stainless steels can be spun depends on the size of the blank; lower speeds are used on larger blanks. Speeds 1/3 to 1/2 the rate used to form carbon steel should give satisfactory results. Spinning lathes with speeds from 250 to 1000 rpm have been satisfactory for small parts. Parts of about 6 feet in diameter require much lower speeds from 30 to 60 rpm.

Examples of Spun Parts. A program conducted at Gruman (Ref. 73) showed the potential of spinning large-diameter parts from precipitation-hardenable stainless steels. PH 15-7 Mo blanks 72 inches in diameter and 0.100 inch thick were spun to a 68-inch-diameter dome at room temperature in two stages. The first forming operation was conducted over a Masonite mandrel with a 1-inch-thick steel backup. A 13-inch-diameter roller with a 0.600-inch-radius tool was fed along the blank at a feed rate from 2-1/2 to 3 inches per minute. The spinning lathe was operated at 35 to 40 rpm. A tailstock pressure of 850 psi was applied during the operation. This produced a flat-bottomed cup approximately 5 inches deep. In the second stage a cast iron mandrel was used with the same tooling. The machine rotated the blank between 50 and 65 rpm. A tailstock force of 800 psi and an axial-roller force of 550 psi was applied. A feed rate of 2-1/2 inches per minute was used for this operation. The first pass moved the material against the mandrel to a 12-inch diameter. Four additional passes were required to work the material out to a 36-inch diameter. The part was then annealed and the passes continued until the 68-inch dome was formed.

AM-350 was formed to the same configuration starting with a 0.030-inch blank. In the first stage the material was rotated at 40 to 50 rpm and a tool force of 275 psi was applied. A feed rate of 3-1/2 to 5 inches per minute was used. The rpm in the second-stage forming was increased to 50 to 65 rpm and the tool pressure to 550 psi. A 1-1/2-inch radius was used on the forming roller. With a feed rate of 3 to 6 inches per minute the blank was moved against the mandrel

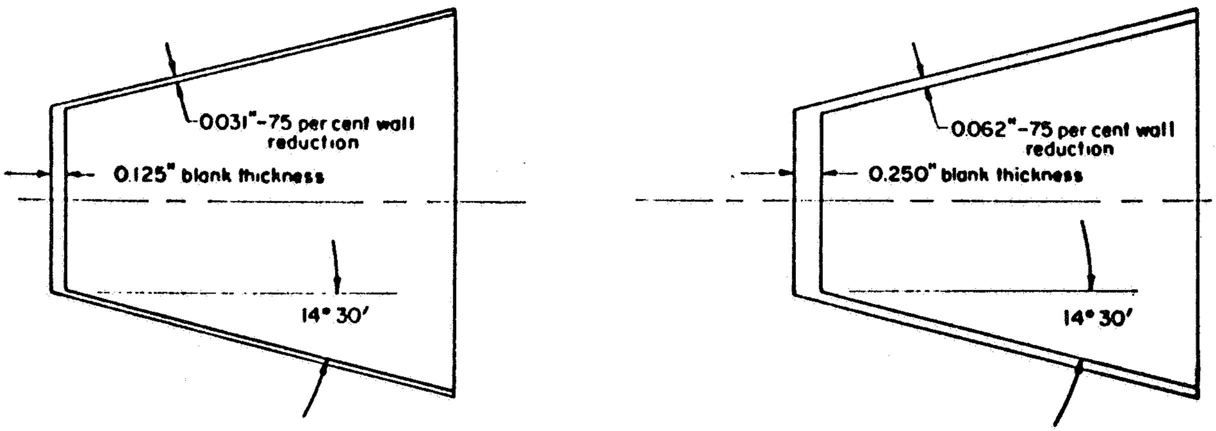


FIGURE 49. CONES SHEAR FORMED FROM AN 8 x 8-INCH-SQUARE STEEL BLANK, 0.050-INCH-THICK (REF. 75)

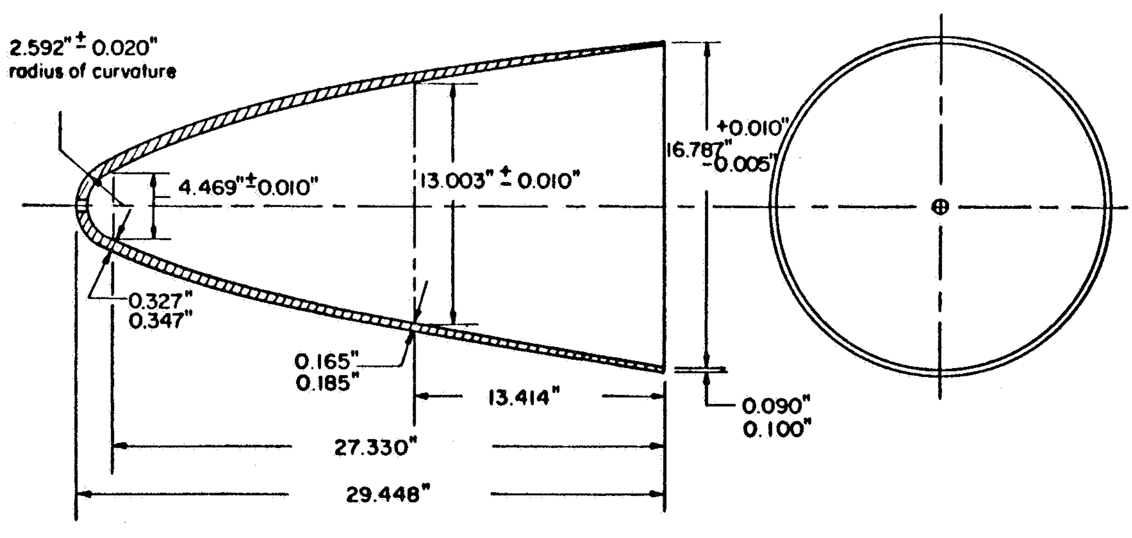


FIGURE 50. SHEAR-FORMED CONE WITH A TAPERED WALL MADE FROM A DISHED 7/8-INCH-THICK ALUMINUM BLANK (REF. 75)

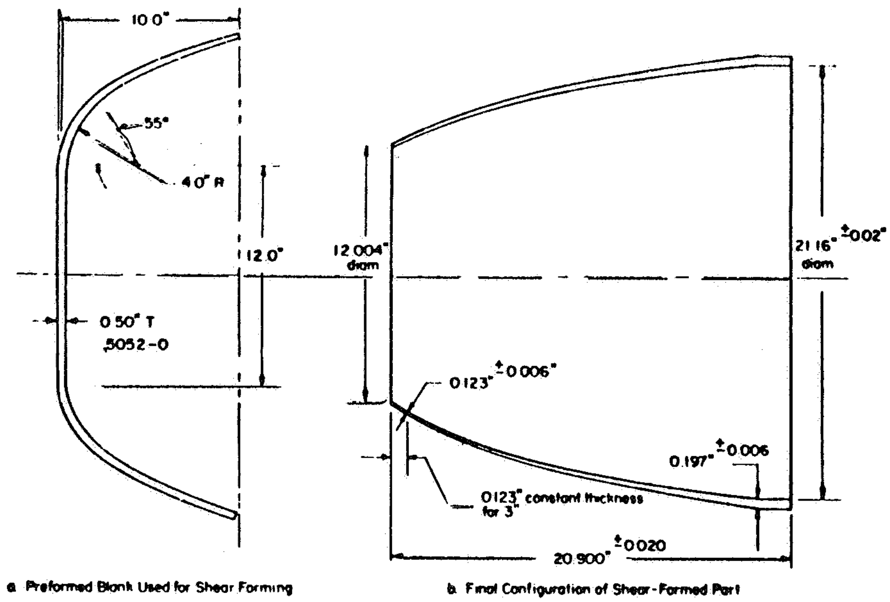


FIGURE 51. SHEAR-FORMED, VARIABLE-WALL CONE MADE FROM A 45-INCH-DIAMETER, 0.50-INCH-THICK ALUMINUM BLANK, PREFORMED TO DISH SHAPE ON AN HYDRAULIC PRESS (REF. 75)

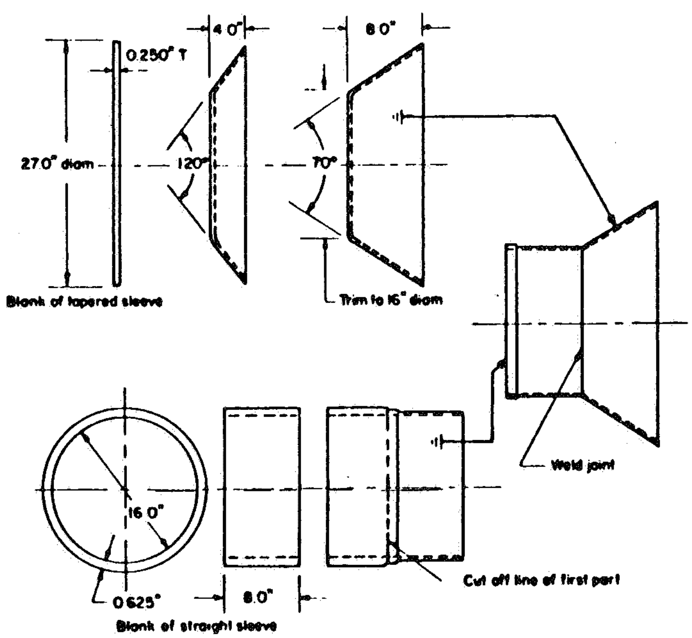


FIGURE 52. SHEAR FORMING OF A CONE AND TUBE MADE OF STEEL FOR A FINAL SHEAR-FORMING OPERATION SHOWN IN FIGURE (REF. 75)

to produce a 10-inch-diameter cup on the first pass. The second pass increased the contact diameter to 23 inches. Five more passes brought the contact diameter to 43 inches. The part was then annealed and the passes continued until the part was completed.

Shear-Forming Limits. Shear forming is generally used to reduce machining time on parts with shapes that cannot be made by conventional forming methods. An example of this was in the shear forming of an A-286 jet-engine shaft that saved approximately $700 in costs over the previous method of machining a forging (Ref. 74). The parts shown in Figures 49 through 53 are representative of parts that can be made of precipitation-hardenable stainless steels by shear forming. The part may be a simple cone with straight sides as shown in Figure 49 or one with a complex curvature and a variable wall thickness as shown in Figure 50. Depending on the shape and the material, parts are made from flat blanks or from preforms. An example of a shear-forming procedure using a preformed part is shown in Figure 51. In this case the preform was made on a hydraulic press. Spinning or a previous shear-forming operation could also have been used.

The wide variety of operations that can be used to make a part is illustrated in Figures 52 and 53. In these samples, a disk and a

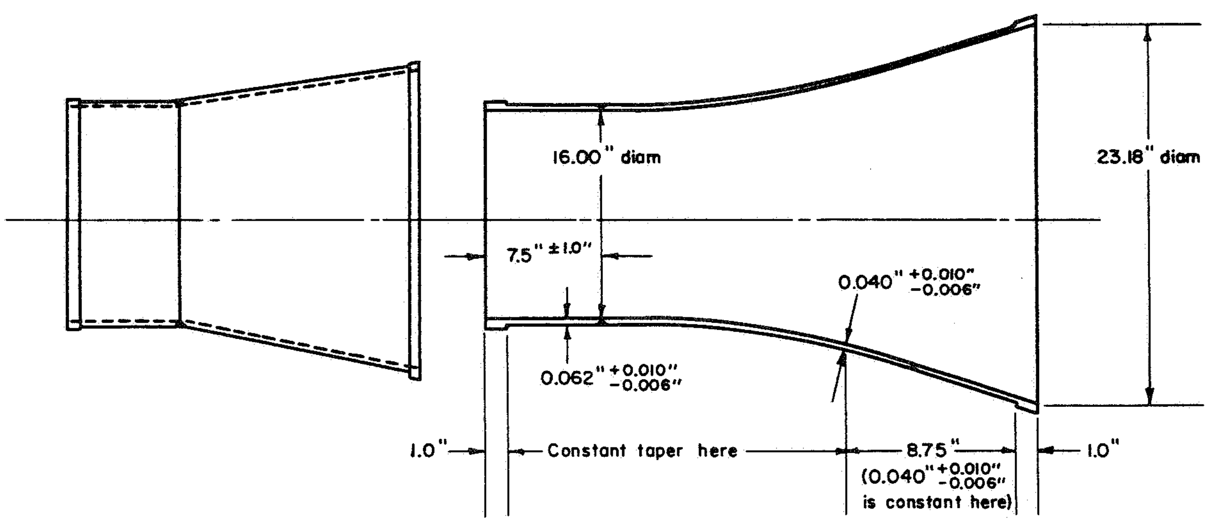


FIGURE 53. SHEAR-FORMED PART MADE FROM TWO SHEAR-FORMED PIECES AND WELDED TOGETHER (REF. 75)

TABLE XXXIV. SHEAR-FORMING DATA FOR PRECIPITATION-HARDENABLE STAINLESS STEELS

Material and Condition	Preform	Speed, rpm	Rate, in./min	Roller, in.	Lubrication	Reduction in Area, per cent	Pressure, tons	Cone: Included Angle	Cone: Smallest, in.	Cone: Largest, in.
17-7 PH (Ref. 60) mill annealed	12-in. diam, 0.125 in. thick	180-300	2.5	8.7 diam 0.1 radius	SAE No. 46 turbine oil	52	6	60°	3	11
				First Pass						
17-4 PH (Ref. 60) annealed forging	16.58-in. diam OD cylinder, 12.25 in. long, 0.200 in. wall	300	1	12 diam 1/2 radius	Molykote on mandrel BB high-pressure oil on roller	--	--	--	--	--
				Second Pass						
				Annealed						
		250	2.5	12 diam 3/16 radius	--	50	--	--	--	--
17-7 PH (Ref. 62) annealed	15-1/4-in. diam. 0.150 in. thick	75-425	3/4-3	1/4 radius	--	50	--	30	--	15-1/4
PH 15-7 Mo (Ref. 62) annealed	12-1/4-in. diam., 0.150-in. thick	75-425	3/4-3	Ditto	--	70		17°-30'	--	12-1/4
AM-355 (Ref. 62) annealed	12-1/4-in. diam, 0.130 in. thick	75-425	3/4-3	"	--	60	--	23°35'	--	12-1/4
A-286 (Ref. 5) annealed forging	Cone 24 in. long	--	--	--	--	58	--	40°	--	--

cylindrical tube were used to form a circular blank and a cylindrical-formed part. They were then trimmed and welded together to make a preform for the final shear-forming operation. The shear-formed part resulting from these operations is shown in Figure 50.

Only limited work has been carried out on shear forming precipitation-hardenable stainless steels, so very little specific information has been reported on the process. Some of the available data are given in Table XXXIV for 17-4 PH, 17-7 PH, PH 15-7 Mo, AM-355, and A-286. In general the materials appear to be well suited to shear forming.

Properties After Shear Forming. Like other cold-working processes, increasing the amount of deformation in shear forming usually increases the strength and reduces the ductility of the workpiece in a regular manner. An exception to this was noted by Jacobs (Ref. 76) who found that a reduction of 50 per cent impaired the strength of both 17-7 PH and PH 15-7 Mo steels. The strange behavior of these materials after that particular reduction was also noted when the shear-formed parts were heat treated to the TH 1050 condition. Jacobs found that a heat treatment that completely reaustenitized all of the martensite formed during cold work developed normal properties. AM-355 showed an increase in mechanical properties with increasing cold work both when shear formed and after heat treatment. Table XXXV gives data obtained on the properties of AM-355, 17-7 PH and PH 15-7 Mo after various amounts of cold work and after an aging treatment or the full heat treatment. These data indicate that reductions as low as 20 per cent more than doubled the yield strengths, and increased the ultimate strengths by 1/4. Reductions of 60 per cent or more on PH 15-7 Mo lowered the elongation values to less than 1 per cent. This undesirable effect of cold work can be removed or alleviated by heat treatment. After solution treatment and aging, the deformed AM-355 had good ductility and higher strengths than samples that had not been shear formed. 17-7 PH and PH 15-7 Mo had poorer properties than undeformed heat-treated materials. Aging after shear forming developed reasonably good properties in all the materials tested.

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

TABLE XXXV. RESULTS OF TENSILE TESTS ON SHEAR-FORMED MATERIALS (REF. 76)

Material	Condition	Per Cent Reduction	Ultimate Strength, 1000 psi	Yield Strength, 1000 psi	Per Cent Elongation in 2-Inch Gage Length	Hardness[(a)]
17-7 PH	As received shear formed	0	125	60	33	R_B 91
		20	155	132	17	35
	Ditto	30	168	155	13	38
	"	40	182	178	5	40
	"	50	170	158	14	38
	Shear formed and aged at 1050 F for 1-1/2 hr	20	152	116	16	33
		30	168	130	14	37
		40	190	175	11	40
		50	167	125	15	37
	Shear formed and given TH 1050 heat treatment	0	170	140	12	38
		20	170	140	12	40
		30	168	130	11	37
		40	150	100	11	33
		50	158	114	10	35
PH 15-7 Mo	As received shear formed	0	140	55	28	R_B 91
		20	184	130	12	38
		30	184	155	10	41
		45	210	200	4	44
		50	200	140	12	41
		60	230	220	1	46
		70	245	240	1	47
	Shear formed and aged at 1050 F for 1-1/2 hr	20	190	145	14	38
		30	196	170	13	43
		40	228	215	4	47
		50	195	160	15	41
		60	244	238	1	48
		70	265	253	1	50
PH 15-7 Mo	Shear formed and given TH 1050 heat treatment	0	208	198	6	44
		20	195	167	8	43
		30	194	168	10	43
		40	190	168	10	43
		50	191	161	11	43
		60	168	110	9	37
		70	170	118	12	35
	As received shear formed	0	137	50	40	R_B 94
		20	210	125	22	42
		30	225	140	20	46
		40	238	155	18	47
		50	245	145	17	47
		60	260	223	13	52

TABLE XXXV. (Continued)

Material	Condition	Per Cent Reduction	Ultimate Strength, 1000 psi	Yield Strength, 1000 psi	Per Cent Elongation in 2-Inch Gage Length	Hardness[a]
	Shear formed and aged at 850 F for 3 hr	20	205	165	29	42
		30	218	180	21	47
		40	235	185	20	48
		50	242	182	17	48
		60	270	257	6	53
	Shear formed and -100 + 850 F heat treatment	0	200	140	20	46
		20	235	185	14	48
		30	232	193	14	48
		40	230	198	9	49
		50	232	202	11	48
		60	247	210	8	50

(a) All hardness is Rockwell C except where otherwise indicated.

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.

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 54, 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. 55). 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.

The platen sizes of commercially available drop hammers vary from 21 by 18 inches to 120 by 96 inches. 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. 77).

Tooling. The basic tool materials for drop-hammer forming are Kirksite and lead. Lead is preferred for the punches (see Figure 54) since it will deform during service and conform to the female die. The wide use of Kirksite as a die material stems from the ease of casting it close to the final desired configuration. 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 generally the additional cost is not warranted. Ductile iron and steel dies are used where longer tool life is desired, and for some elevated-temperature forming operations.

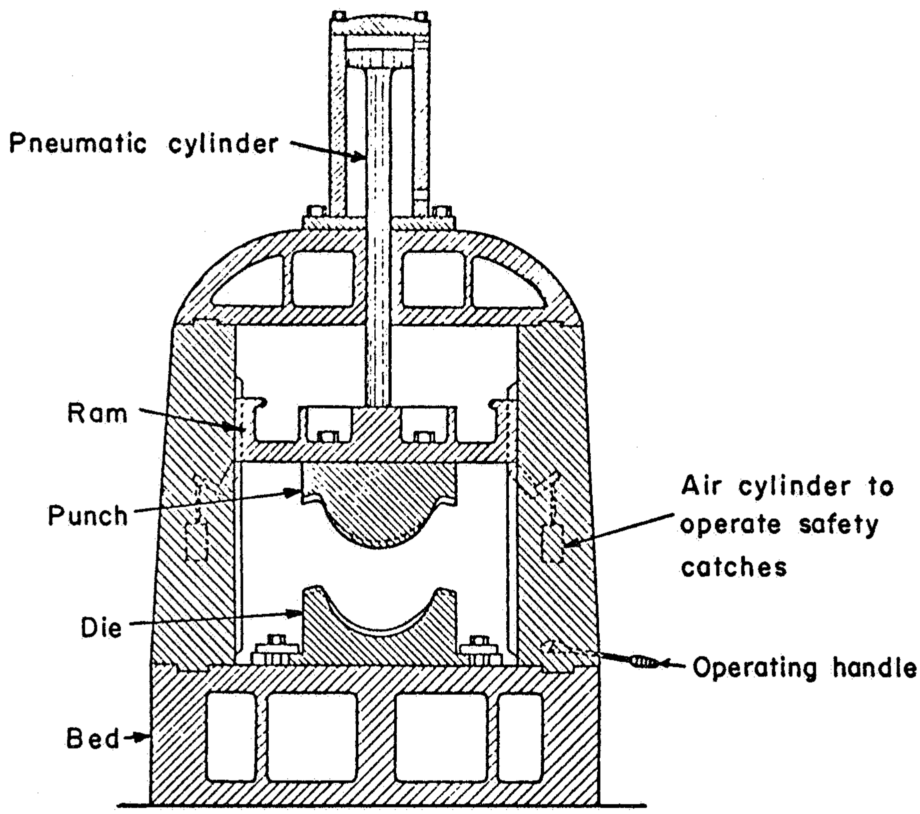


FIGURE 54. PNEUMATIC HAMMER (REF. 55)

Several typical drop-hammer dies are shown in Figure 55 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 56 indicates the positioning of pads for a particular part. The maximum thickness of rubber is placed 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.

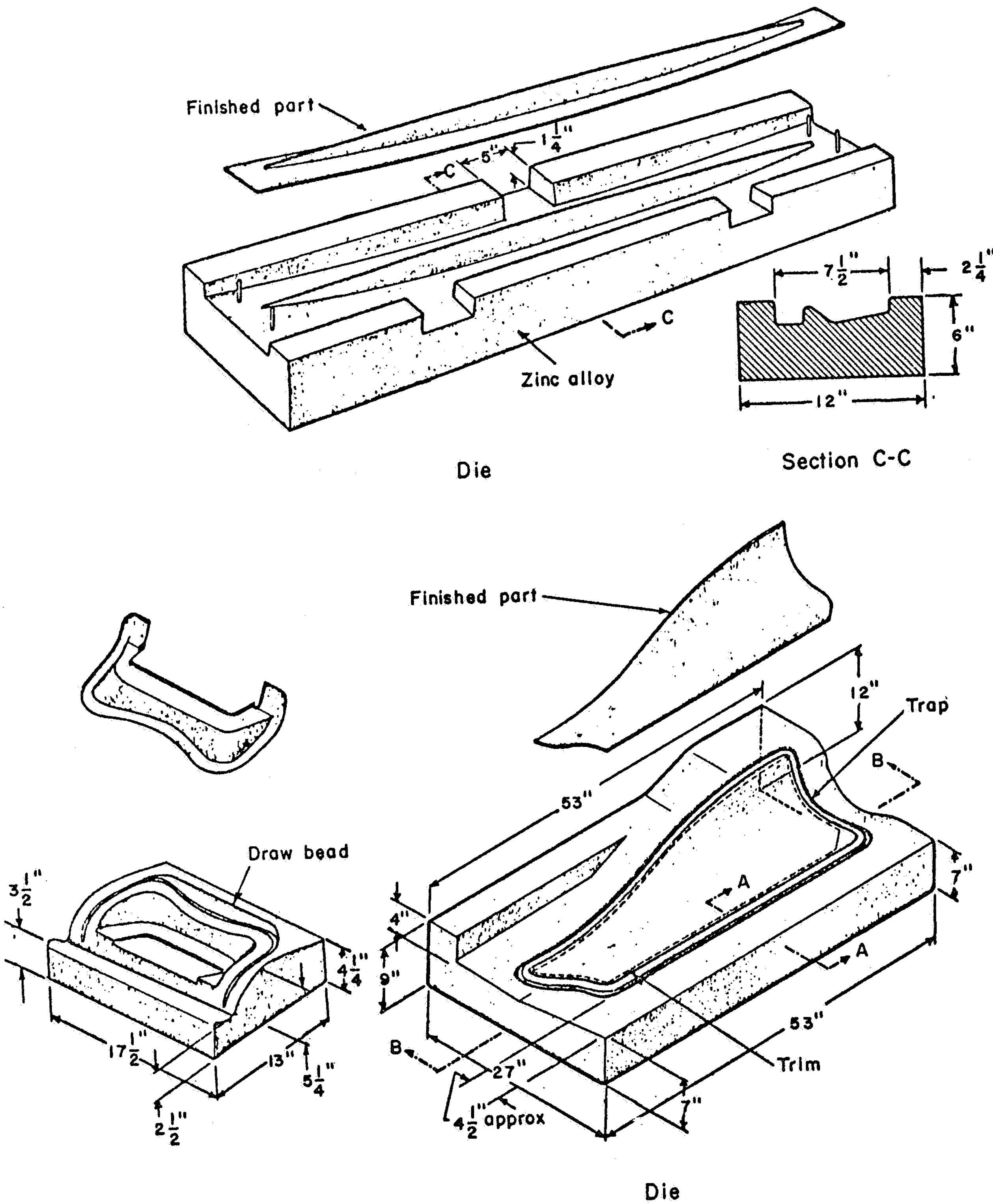


FIGURE 55. TYPICAL DROP-HAMMER DIES AND FORMED PARTS (REF. 55)

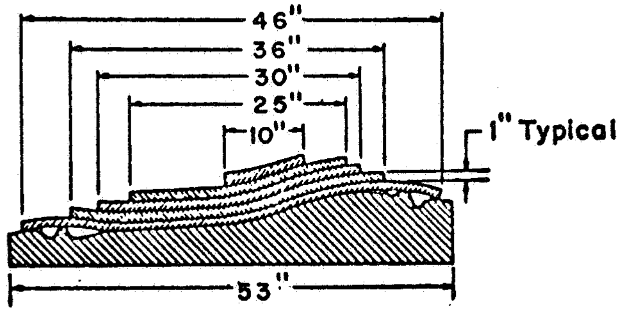


FIGURE 56. POSITIONING OF RUBBER BLANKETS (REF. 55)

The blank is placed between the die and the first pad.

Smoothly contoured parts can be made in Kirksite dies. 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 uniformly make contact. 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 thickness allowance for the sheet thickness to be formed.

After a set of tooling has been constructed, the tools are proved out by forming either aluminum or austenitic 300 series stainless steel parts. Stainless steel is the best trial material because it has springback characteristics similar to the precipitation-hardenable stainless steels.

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 55) 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.

When 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 oversize in the first-stage tools and by coining the final shape in a second set of tools.

Techniques of Drop-Hammer Forming. The procedures for forming precipitation-hardenable stainless steels at room temperature in drop hammers resemble those used for the austenitic 300 series stainless steels. 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 57. 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 gradual 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.

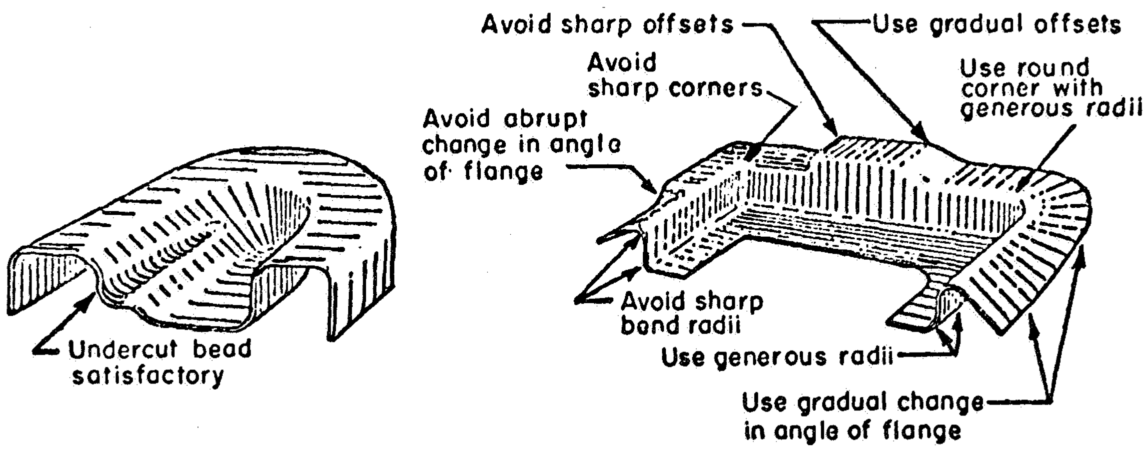
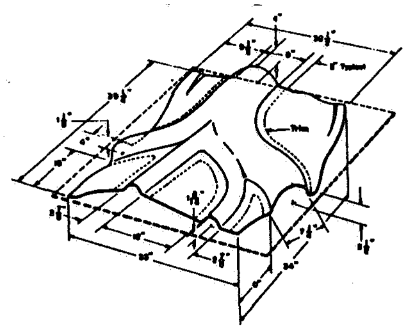


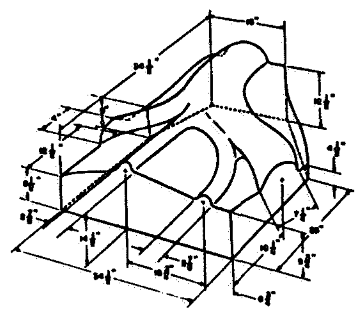
FIGURE 57. TYPICAL DROP-HAMMER-FORMED PARTS

Courtesy of The Boeing Airplane Company.
Seattle, Washington.

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 1/2 of the depth of the draw. A complex semitubular part and die for drop-hammer forming is shown in Figure 58. 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 made from Type 301 stainless steel.



a. Formed Part Before Trimming



b. Punch

FIGURE 58. DROP-HAMMER FORMING OF SEMITUBULAR PART MADE FROM 301 STAINLESS STEEL (REF. 55)

Lubricants used in drop-hammer forming of precipitation-hardenable stainless steels should be of the high-pressure type. Extreme pressure oils and pigmented drawing compounds are preferred. For elevated-temperature forming, the Turco Precoat II applied to the die has been used successfully in preventing galling when drop-hammer forming 17-7 PH at 580 to 700 F (Ref. 78). The lubricants are generally swabbed onto the blank surface prior to forming. The lubricants should be removed from the part surface 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 the geometrical considerations and the properties of the work piece material. According to Wood (Ref. 33) 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 59.

The upper and lower 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 inch. 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 workpiece 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. 33) is:

$$\frac{R}{L} = \frac{50\,(\epsilon_{0.5})^2}{(R/T)} \qquad (20)$$

where

R = bead radius

L = center to center spacing of beads

$\epsilon_{0.5}$ = 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 PH 15-7 Mo, AM-350, and A-286 at room temperature and elevated temperature are shown in Figure 59. Although the limits apply to beaded panels they can be used with caution as guides to forming other types of parts with drop hammers.

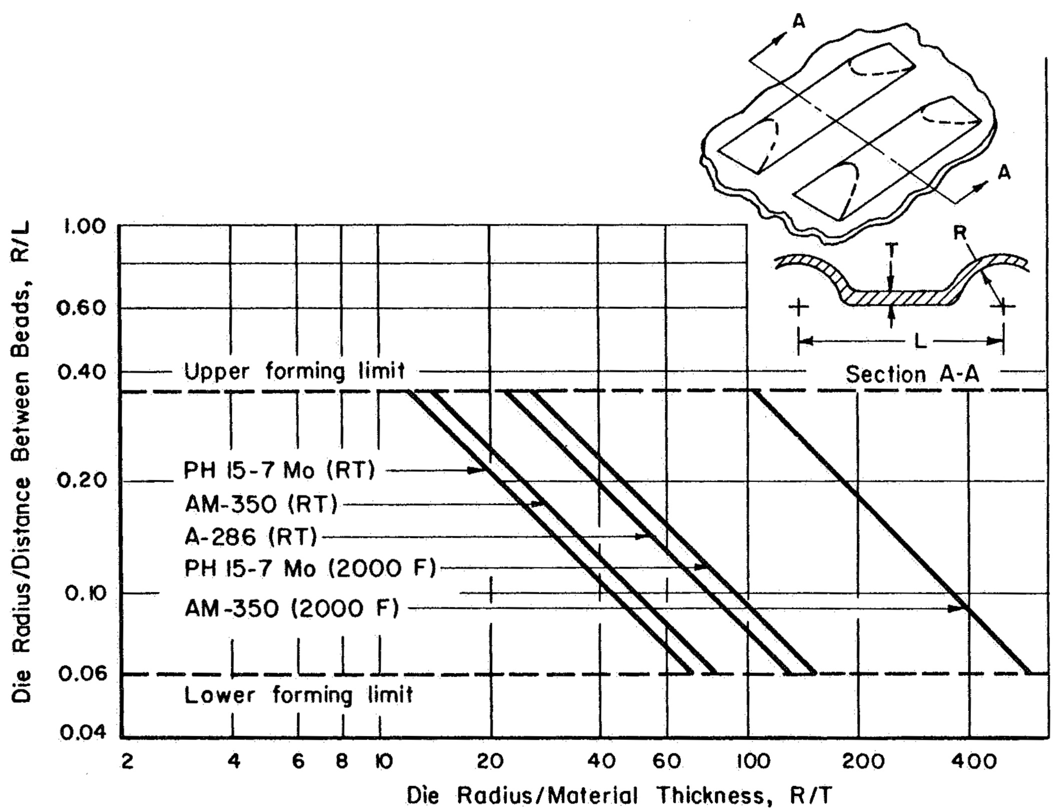


FIGURE 59. DROP-HAMMER-FORMING-LIMIT CURVES FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

The minimum thickness for hammer-formed parts of precipitation-hardenable stainless steels is about 0.025 inch. A reduction in uniform elongation with material thicknesses below this results in reduced formability. Heavier stock should be used for more complex shapes.

It is difficult to predict proper springback allowances for complex parts. Forming the material in the solution-treated or annealed condition at room temperature minimizes springback so that dies made to net dimensions will generally produce parts to forming tolerances of ±1/16 inch. Elevated-temperature forming will also minimize springback. Boarts found that for complex parts, 17-7 PH should be formed in the annealed condition on a starter die (Ref. 78). He heat treated the parts at 1400 F for 90 minutes and rehit them on the finish dies at a temperature between 550 and 700 F. Completing the forming process and cooling the part to 60 F must be accomplished within 1 hour from the time the parts are removed from the 1400 F furnace. The parts should then be given the final heat treatment.

Drop-hammer forming of PH 15-7 Mo and AM-350 should be conducted at a moderate temperature of 200 F to prevent transformation of the material during forming (Ref. 79). The parts are then hot sized to remove springback and given the final heat treatment.

For best results the parts should be degreased, passivated, and pretreated at each stage of forming prior to any thermal treatment. Lack of proper handling and cleanliness can result in contaminated material and the generation of scrap.

These processing principles are illustrated in the 17-7 PH stainless steel parts shown in Figure 60. These components, ranging from 0.050 to 0.063 inch thick, were drop-hammer formed and then cryoformed according to the following cycle:

(1) Hammer formed in the mill annealed condition

(2) Cleaned

(3) Condition annealed at 1450 F for 90 minutes

(4) Cryoformed to size.

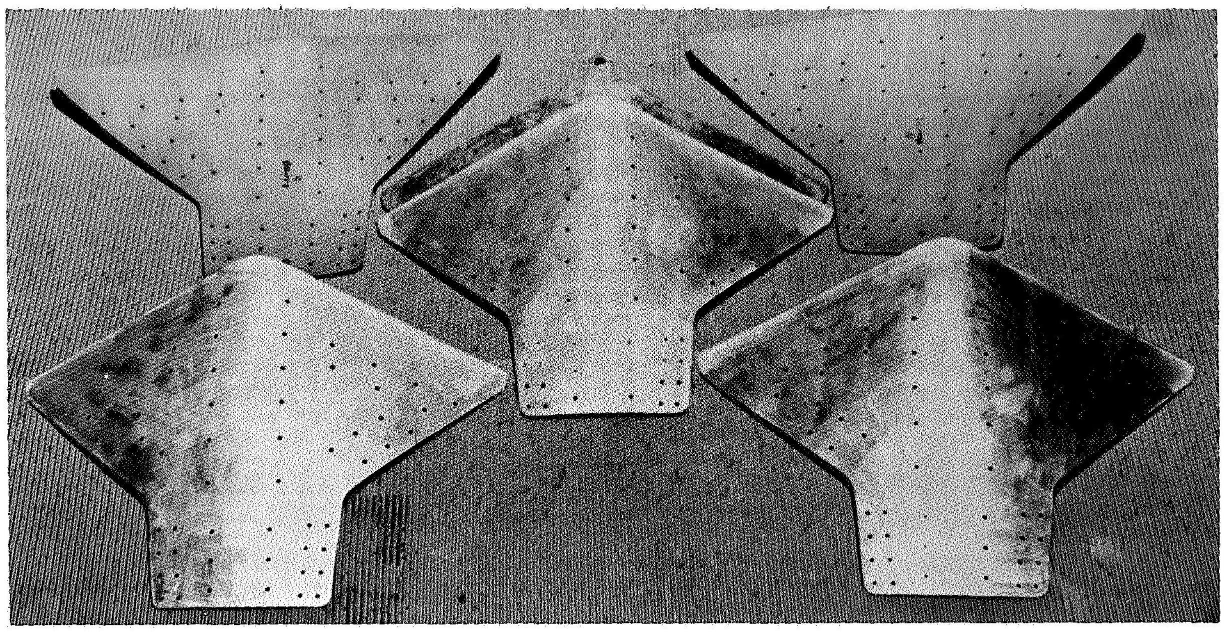
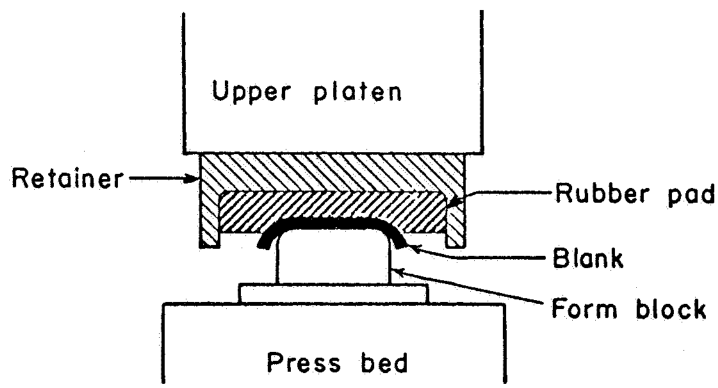


FIGURE 60. HAMMER-FORMED, 0.050- AND 0.063-INCH-THICK 17-7 PH STAINLESS STEEL PARTS

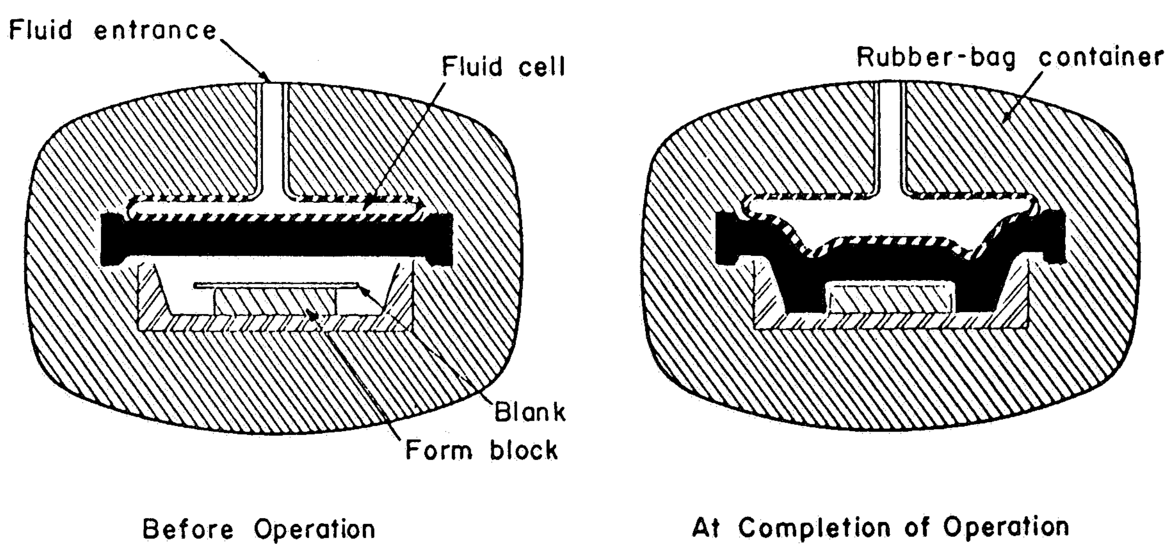
Parts were cryoformed following cleaning and condition annealing at 1450 F for 1-1/2 hours. Courtesy of The Boeing Airplane Company, Seattle, Washington.

TRAPPED-RUBBER FORMING

Introduction. In trapped-rubber forming, a rubber pad is used as part of the tooling, usually as the female die for a punch or group of punches. The rubber pad is confined or trapped in a retainer as indicated in Figure 61a. 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 other advantages, trapped-rubber forming requires only the punch, which is the simpler half of conventional tooling. The process is best suited to making small quantities of parts with shallow recesses. The original or Guerin approach to trapped-rubber forming and a modification by Wheelon are shown in Figures 61a and 61b. In the latter process inflating a rubber bag with a pressurized fluid causes the rubber pad to deform the blank and form the part. Either process can be used to form several parts simultaneously depending on their size and the area of the press available for mounting punches.



a. Guerin Process



b. Wheelon Process

FIGURE 61. METHODS USED FOR TRAPPED-RUBBER FORMING (REFS. 55, 81)

The maximum pressure ordinarily developed in trapped-rubber forming is about 10,000 psi. Impact presses are able to produce still higher pressures. Some work has been conducted at pressures as high as 18,750 psi (Ref. 80). Parts formed by this process generally require some additional work to correct for springback. The operation is usually conducted at room temperature.

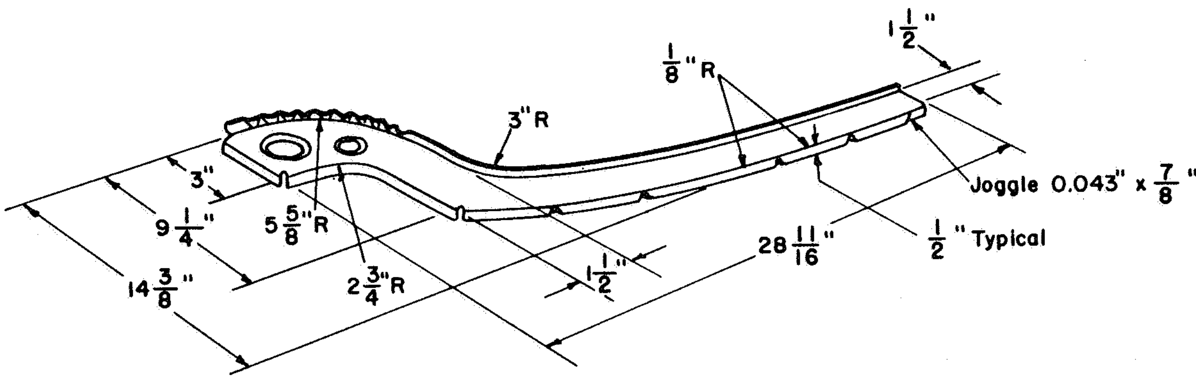
The trapped-rubber process has been used extensively in the aircraft industry for forming parts with straight and curved flanges. The parts may be formed in one operation or in stages requiring several form blocks depending on the shape of the part. Some typical trapped-rubber-formed stainless steel aircraft parts are shown in Figure 62. The material thickness and condition are indicated on the drawings.

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 63, 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 strength of the container surrounding the rubber pad.

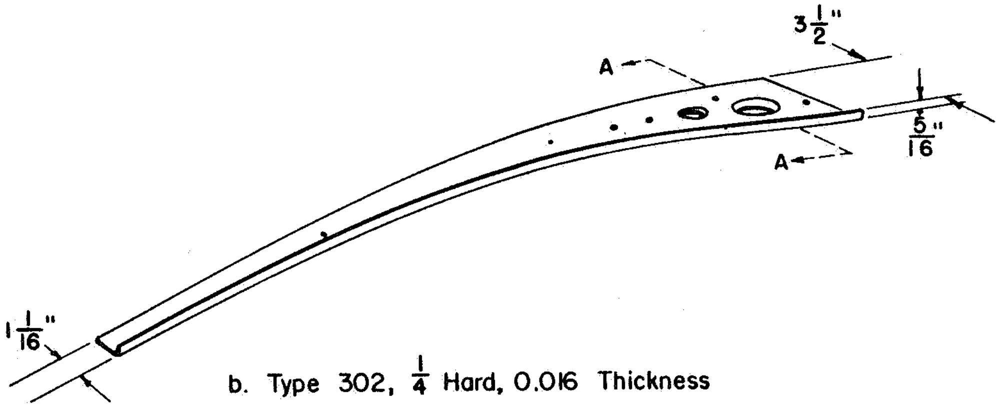
New developments in trapped-rubber forming are centered around methods of increasing the pressure that can be applied to the rubber. Heavier containers are being built, and new synthetic-rubber

TABLE XXXVI. SIZES OF TYPICAL TRAPPED-RUBBER PRESSES

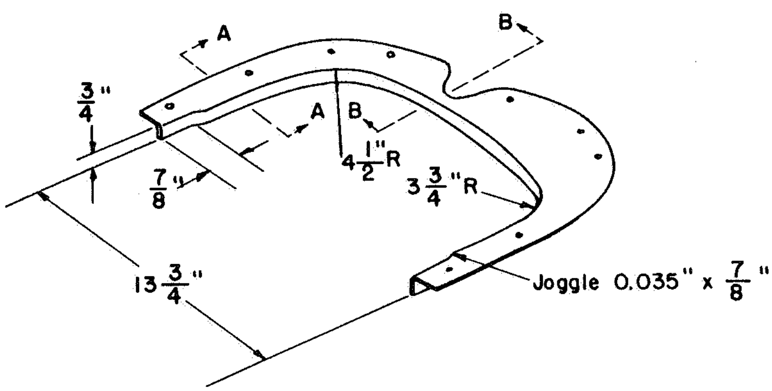
Manufacturer	Work Area, in.^{2}	Press Stroke, inches	Forming Pressure, 1000 psi	Strokes/Hr
Cincinnati Milling Machine Co.	50	5	5	1200
	113	7	10	1200
	177	7-9	Up to 15	1200
	314	10	Up to 15	1200
	490	12	10	1200
	531	12	Up to 15	90
	804	12	10	90
The Hydraulic Press Manufacturing Company	Up to 2200	15	Up to 7	20



a. Type 302, 1/4 Hard, 0.016 Thickness



b. Type 302, 1/4 Hard, 0.016 Thickness



c. Type 302, Annealed, 0.030 Thickness

FIGURE 62. TYPICAL TRAPPED-RUBBER-FORMED STAINLESS STEEL PARTS (REF. 55)

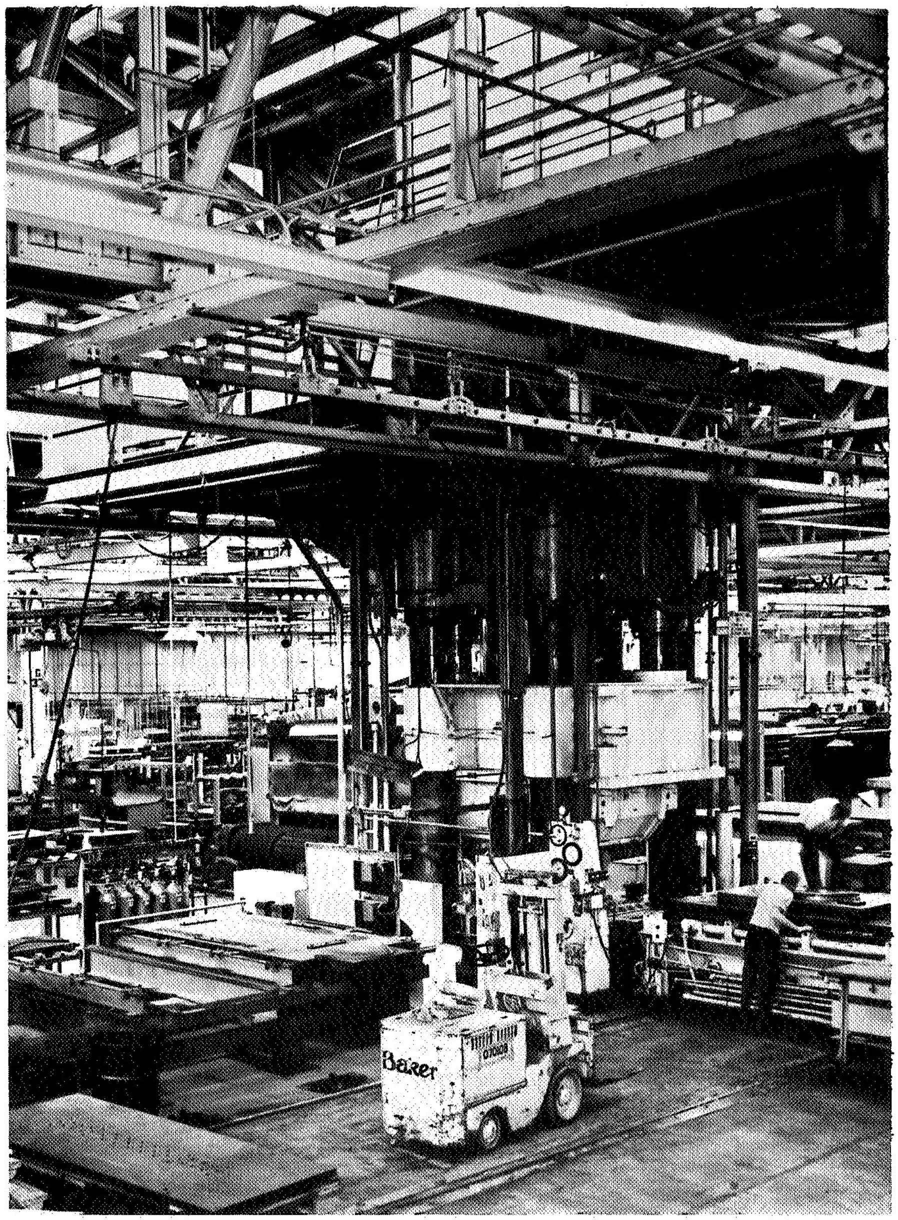


FIGURE 63. 7000-TON TRAPPED-RUBBER PRESS

Courtesy of North American Aviation, Inc., Columbus, Ohio.

compositions, which will withstand the higher pressures, are being developed. A representative list of available press equipment and sizes are given in Table XXXVI.

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 inexpensive and fairly easy to machine. When a 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 more difficult to machine, cast iron and ductile iron have been used. Kirksite has been used, but may give a very short life in working precipitation-hardenable stainless steels.

Since there is very little rubbing action on the die during forming, very little wear occurs 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 may 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 precipitation-hardenable stainless steels. 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 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 removed by benching or hot-sizing operations. Benching is generally very limited since the materials tend to harden considerably during forming. 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 strips of lead over the flange area. Additional pads of rubber may also be placed over those areas where more pressure is required.

Increasing the rubber pressure usually has little effect on forming limits, but Wiegand and Lee found some benefits in the plastic-buckling region for medium- and heavy-sheet materials (Ref. 80). No evidence of increased formability was found from higher pressure when stretch flanges were formed. On the other hand, there was some benefit from increased pressure when forming shrink flanges on medium- and heavy-sheet materials. A check between parts formed by high-pressure and high-velocity trapped-rubber forming indicated no significant difference in formability between the two processes.

A higher rubber pressure is expected to decrease springback, but the effect is more noticeable for thin, soft materials than it is for the precipitation-hardenable stainless steels.

Techniques for Trapped-Rubber Forming. The multidirectional pressure in trapped-rubber forming, as compared with uniaxial loading 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 decreases 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 developed 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 require an increase in pressure to complete the forming.

The use of an external flange restrains trapped-rubber parts 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.

Hot forming of precipitation-hardenable stainless steels by the trapped-rubber process can be accomplished provided the rubber is shielded from the high temperatures. Boarts has described a production technique for trapped-rubber forming of 17-7 PH at 1000 F (Ref. 82). He used a 1/4-inch-thick 6061 aluminum overlay that was cut to a configuration 1 inch wider than the blank. The overlay and blank were heated together and then transferred to the rubber press for forming. A heat-resistant rubber pad was placed between the part and the trapped-rubber head to prevent deterioration of the trapped-rubber head.

Lubricants are seldom used in trapped-rubber forming since there is very little siding-type friction involved in the process. If a lubricant is used, it should be a type that can be easily removed before a subsequent elevated-temperature treatment.

Blank Preparation. Blank-preparation procedures for trapped-rubber forming are the same as those for other forming processes. Usually, however, tooling holes must be provided to maintain 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.

Forming Limits. The trapped-rubber process is commonly used for producing contoured flanged sections and stiffened panels from precipitation-hardenable stainless steels. 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 formed to final size after solution annealing.

Ductility and stiffness are the principal properties influencing the performance of a material in trapped-rubber forming. Wood and associates (Ref. 44) 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 annealed precipitation-hardenable stainless steel parts, should be 5 inches or larger for sheet thicknesses 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 pressure minimizes buckling or wrinkling. That expedient is not helpful in stretch flanging. The minimum permissible bend radii in rubber-pad forming of various precipitation-hardenable stainless steels 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 pressure of 5000 psi or more, the ratio of stretch flange length to sheet thickness should fall in the range from 25 to 30. A ratio of 20 would apply for shrink flanges. Flange angles can usually be formed to tolerances of about 5 degrees.

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 conventient to consider, separately, the different criteria limiting formability.

Figures 64 and 65 show the calculated limits for stretch and shrink flanges that can be produced from AM-350, A-286, and PH 15-7 Mo by the trapped-rubber process at room and elevated temperatures. They are based on a theoretical analysis of the mechanics of the operation and knowledge of the tensile properties (Ref. 34). Experiments at room temperature by the same investigators indicate the formability limits are realistic. Tests by other investigators have indicated that the calculated limits are too high for shrink flange forming as indicated in Figure 66. The stretch- and minimum flange-forming limits, however, were found to be about the same as the calculated ones.

The calculated stretch-forming limits for A-286, PH 15-7 Mo, and AM-350 in descending order of formability are very close together so that for all practical purposes they can be considered identical. The slight increase in formability obtained at temperatures of 500 F and above would not appear to warrant the use of elevated temperatures in forming these materials by the trapped-rubber process. A forming temperature of 300 F for AM-350 may prevent transformation

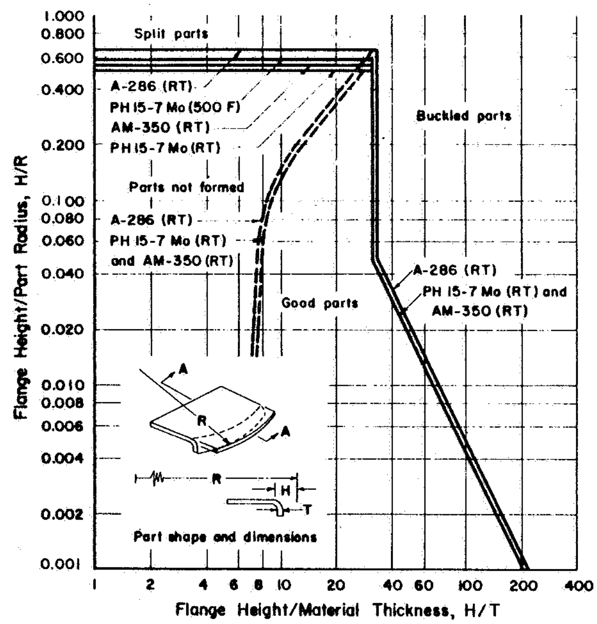


FIGURE 64. CALCULATED FORMABILITY LIMITS FOR SELECTED PRECIPITATON-HARDENABLE STAINLESS STEELS IN RUBBER-STRETCH-FLANGE FORMING (REF. 34)

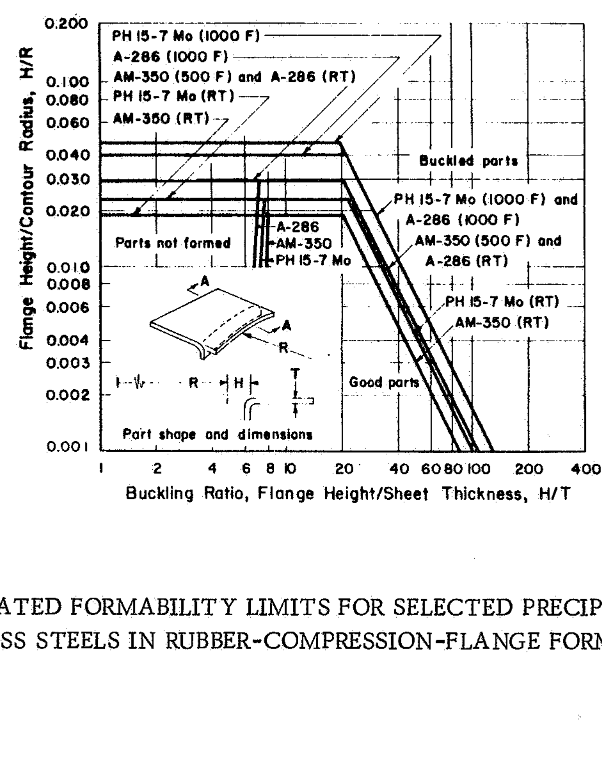


FIGURE 65. CALCULATED FORMABILITY LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS IN RUBBER-COMPRESSION-FLANGE FORMING (REF. 34)

during the forming operation. Since the springback of the precipitation-hardenable stainless steels formed at room temperature is relatively large, the materials are generally given a hot-sizing treatment to obtain the final configuration. A small additional amount of deformation can be accomplished during sizing. By this expedient, the same configuration tolerance is obtained by room-temperature forming and hot sizing as with elevated-temperature forming.

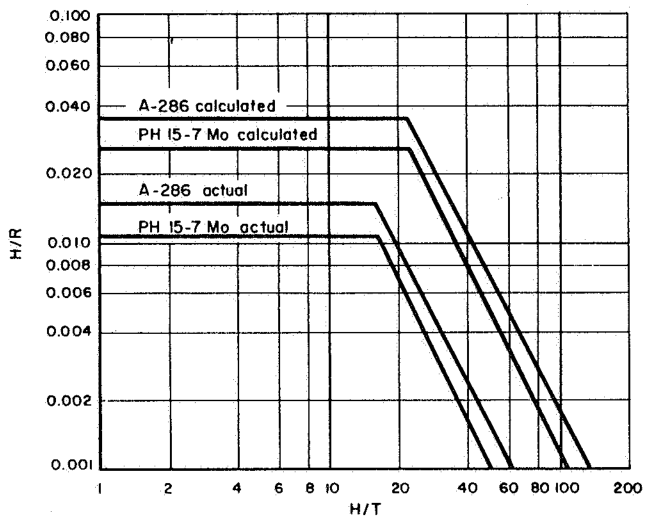


FIGURE 66. COMPARISON OF CALCULATED AND ACTUAL FORMABILITY LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS IN RUBBER-COMPRESSION-FLANGE FORMING (REF. 70)

From the standpoint of buckling in compression flange forming, the A-286 alloy has the best formability. For equal flange heights and sheet thicknesses, it can be formed to a smaller contour radius.

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 precipitation-hardenable stainless steel sheet is the same as that for the brake bending. How closely the minimum bend radius of either a bead or the die bend radius of the forming block can be approached depends on the forming pressure. The minimum radii that can be formed in 0.020, 0.063, and 0.125-inch-thick material for 17-7 PH and A-286 at various pressures are shown in Figure 67. The graph indicates that increasing the pressure in the range up to 25,000 psi permits forming to smaller radii. Increasing the pressure in the

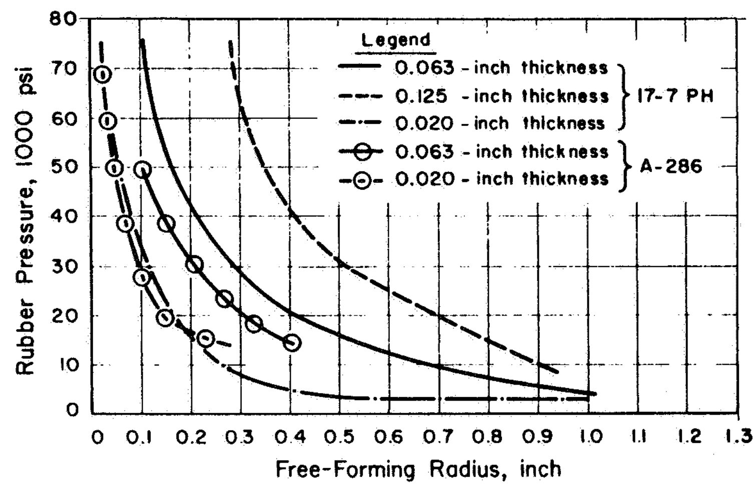


FIGURE 67. FREE-FORMING RADIUS AT VARIOUS PRESSURES, FOR 17-7 PH AND A-286 (REF. 34)

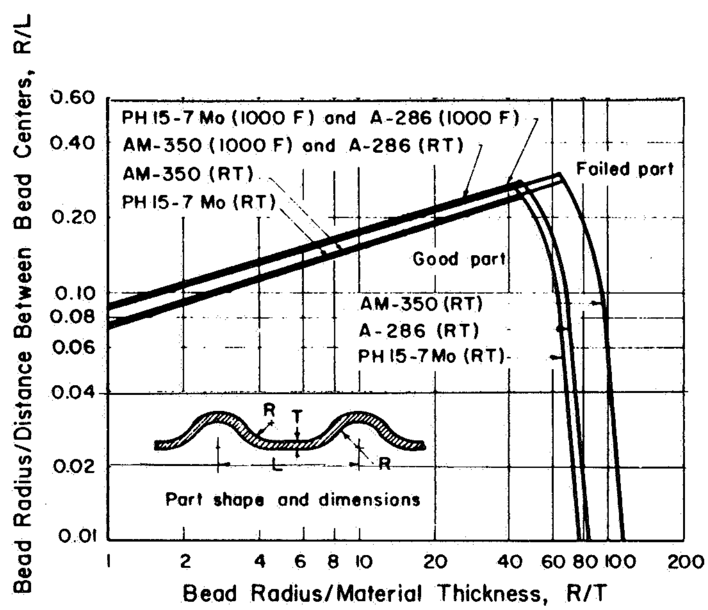


FIGURE 68. CALCULATED FORMABILITY LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS IN TRAPPED-RUBBER-BEAD FORMING (REF. 34)

higher range has much less effect on the minimum radius that can be produced by rubber-forming processes. The practical limit for both materials appears to be a bead radius of about 6 T.

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

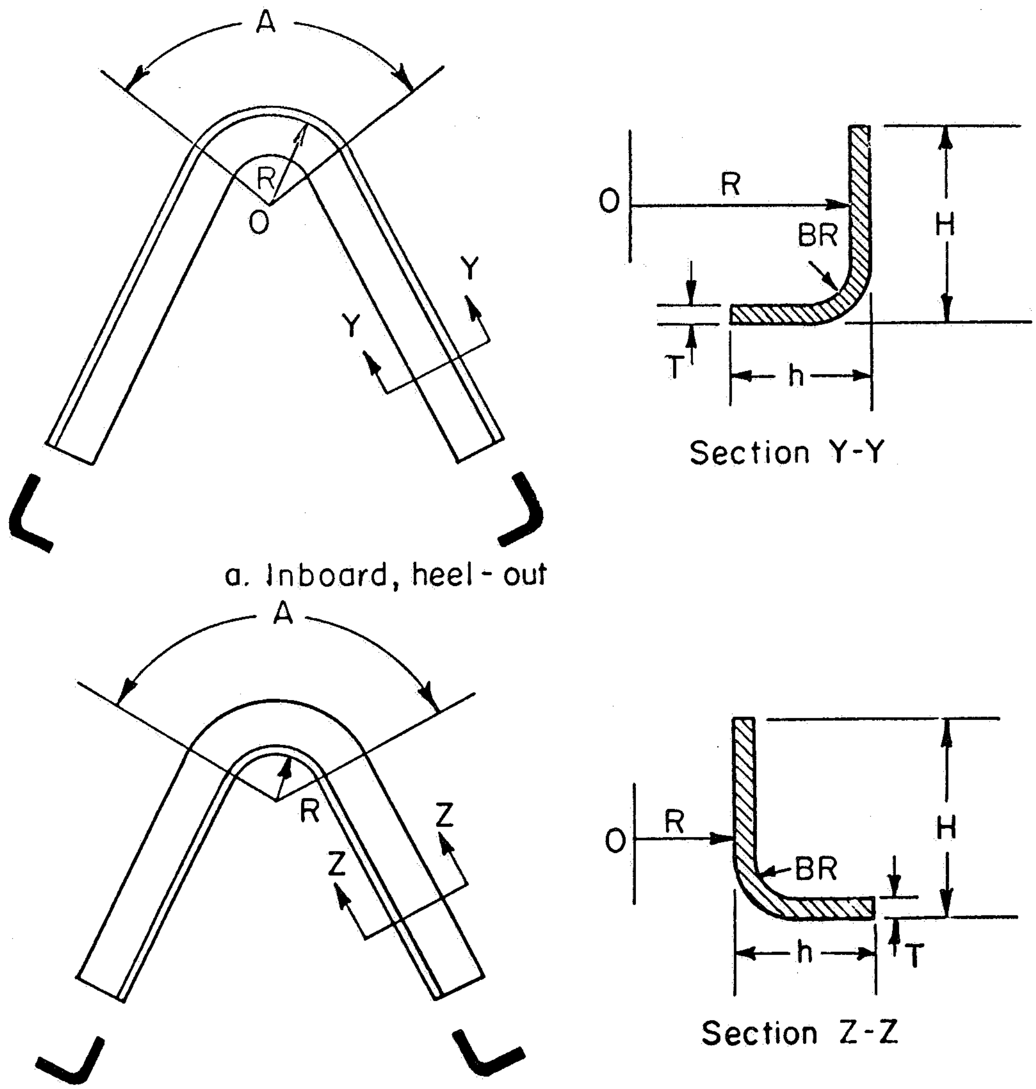
Figure 68 gives the calculated forming limits for beaded panels made by the trapped-rubber process. The experiments used to verify these limits were made with a relatively low forming pressure, 3000 psi. Increasing the forming pressure increases the limiting R/T ratios. The A-286 alloy has slightly better formability than the other materials. This means that beads can be formed with closer spacing, or to smaller radii in sheets of a particular thickness. The use of elevated temperatures in the forming of these alloys does not appear practical because of the slight increase in forming limits indicated.

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 69 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 70.

Stretch forming is also used for producing double contours in sheet. Ordinarily, the sheet is stretched and bent around a male die 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 71.



a. Inboard, heel - out

b. Outboard, heel - in

FIGURE 69. PARAMETERS OF HEEL-IN AND HEEL-OUT LINEAR STRETCH-FORMED ANGLES

Courtesy of North American Aviation, Inc., Inglewood, California.

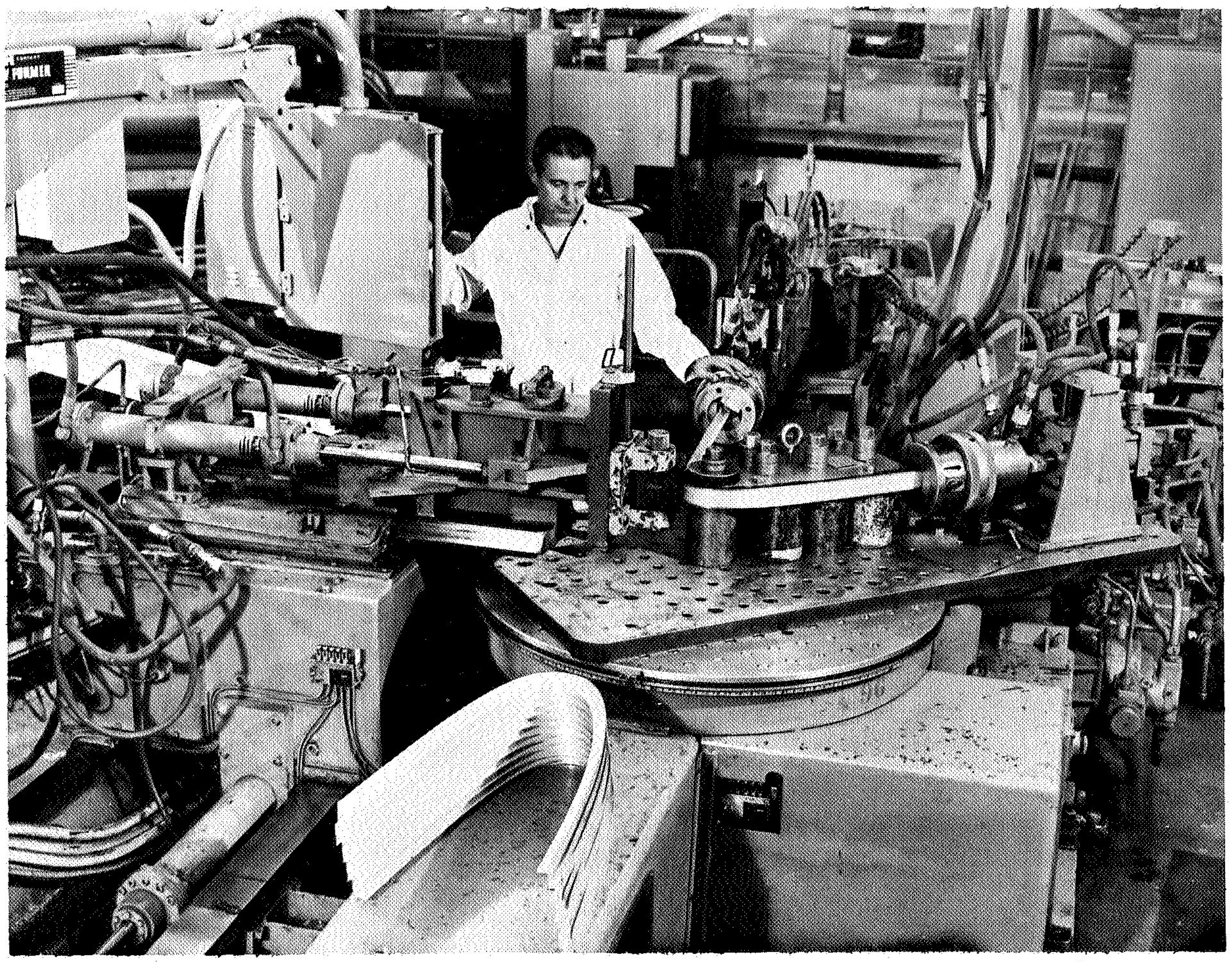


FIGURE 70. STRETCH-FORMING MACHINE FOR EXTRUDED OR FORMED SECTIONS

In-board or heel-out tee sections are being formed.

Courtesy of Cyril Bath Company, Cleveland, Ohio.

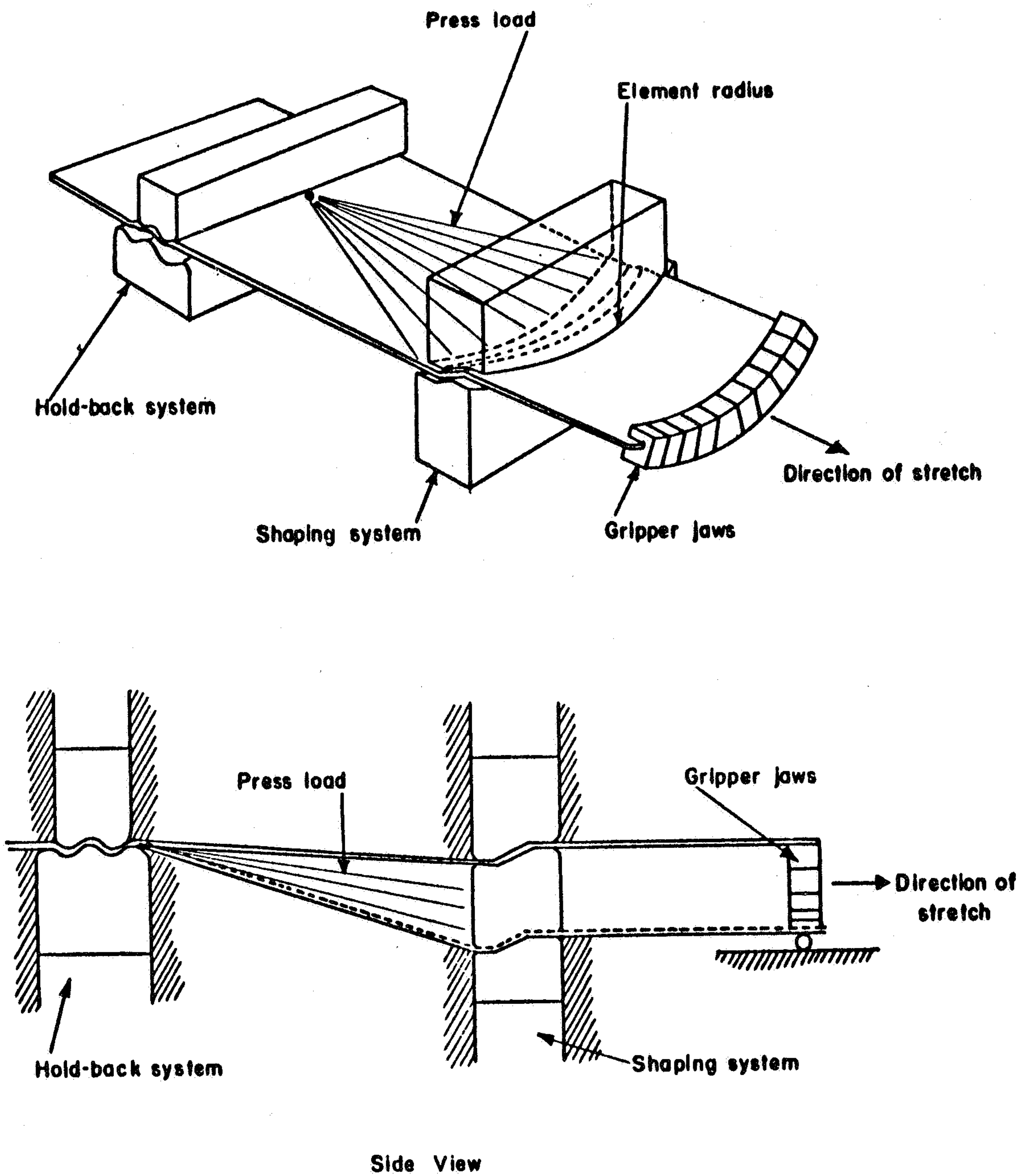


FIGURE 71. ANDROFORM MODIFICATION OF THE STRETCH-FORMING PROCESS (REF. 44)

Stretch-Forming Equipment. 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 larger capacity machines are used either for sheet and plate or heavy sections. The specifications of some commercially available equipment for stretch forming are given in Table XXXVII. Equipment that could be used to stretch form annealed precipitation-hardenable stainless steel plate 14 x 20 feet and 1/2 inch thick with a capacity of 6000 tons has been proposed (Ref. 81).

The press in Figure 72 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-action, deep-drawing press.

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. For the 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 73. Die inserts and shims are used for adjustment to various thicknesses and angle-leg lengths, as shown in Figure 74. Adjustable tooling reduces the number of different-size tooling sets that are stocked.

For room-temperature operations on sheet, the tooling can be made from zinc-base alloys (Kirksite) or from concrete faced with steel. The high yield strengths of the precipitation-hardenable stainless steels coupled with their rapid work hardening normally would cause rapid wear of plastic-faced tooling. Consequently, plastic tooling is not recommended for this application. The life of zinc-base-alloy tooling can be extended by first stretch forming a thin sheet of commercial stainless steel over the tool and using it as a protective cover. This also prevents pickup of zinc by the formed parts, which might cause contamination and a reduction in properties after heat treatment.

Since the properties of the precipitation-hardenable stainless steels change with the severity of deformation, it is advantageous to obtain a fairly consistent amount of stretch throughout the part. This is accomplished by permitting the material to move uniformly over the tooling during stretching. Lubrication and tool smoothness

TABLE XXXVII. CAPABILITIES OF TYPICAL STRETCH-FORMING MACHINES

Tonnage[a]	Rate of Forming, deg/min	Material Size, inches	Type
		Cyril Bath (Ref. 82)	
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. 83)	
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
120-5000 stretch	--	48-240 width	Sheet stretch draw[b]
300-1000	--	96-360 length	Sheet stretch draw[b]

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

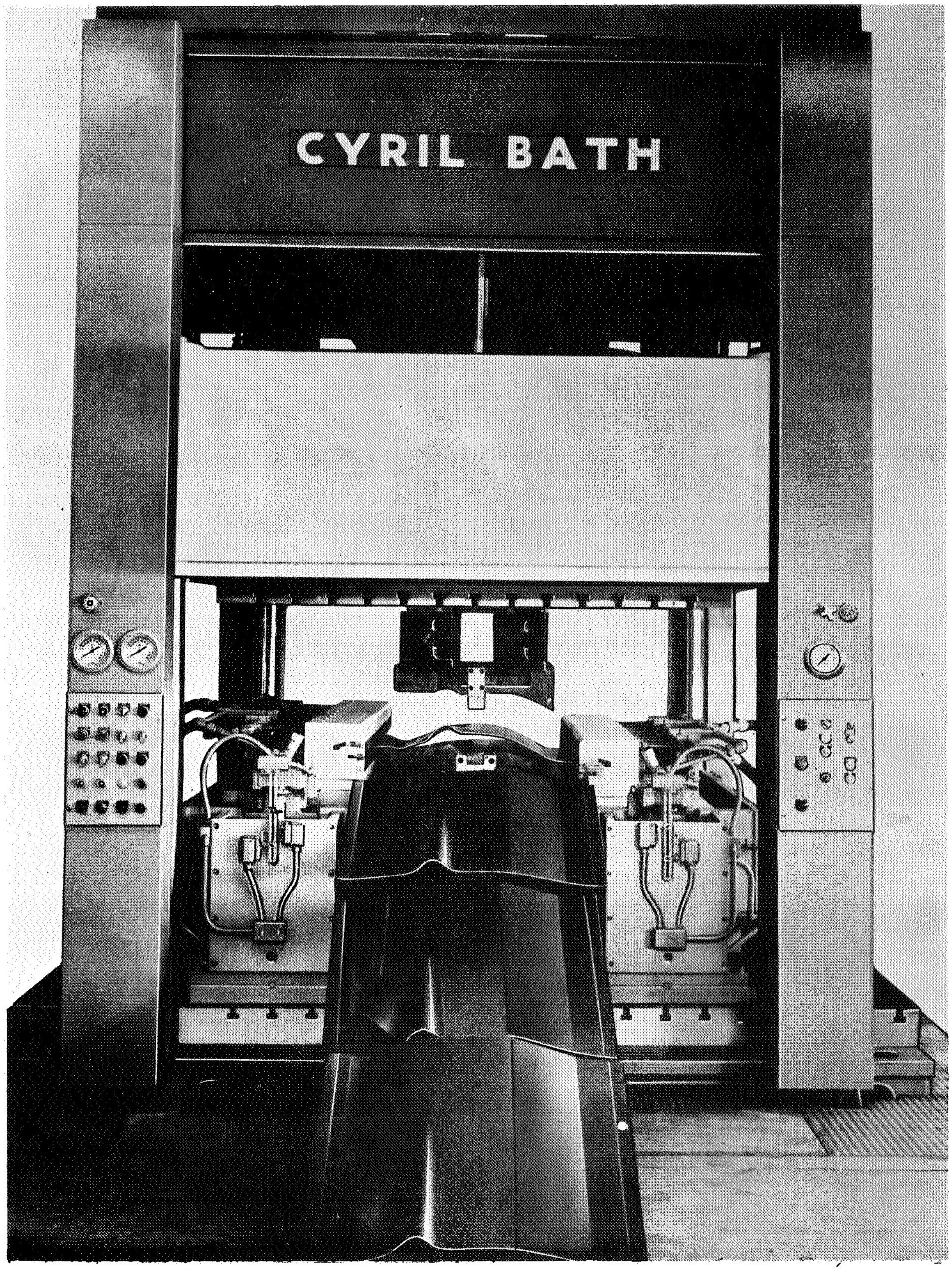


FIGURE 72. STRETCH-DRAW-PROCESS MACHINE FOR SHEET
250-ton pressing, 85-ton stretching.
Courtesy of Cyril Bath Company, Cleveland, Ohio.

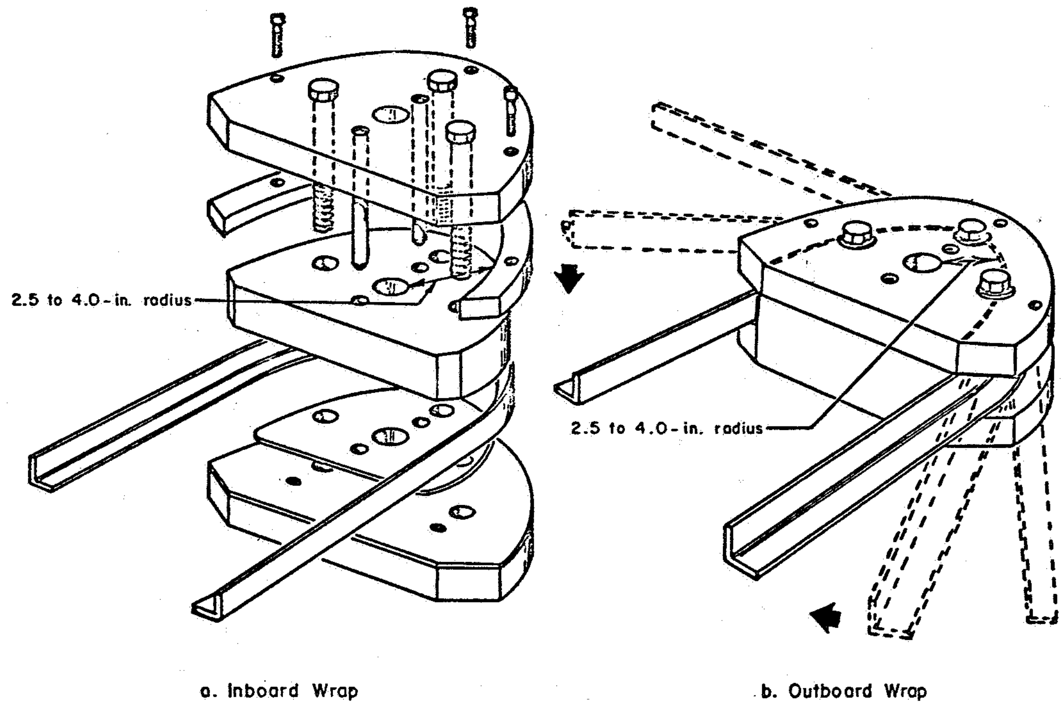


FIGURE 73. STRETCH-MACHINE (ANGLE SECTIONS) TOOLS

Courtesy of North American Aviation, Inc., Inglewood, California.

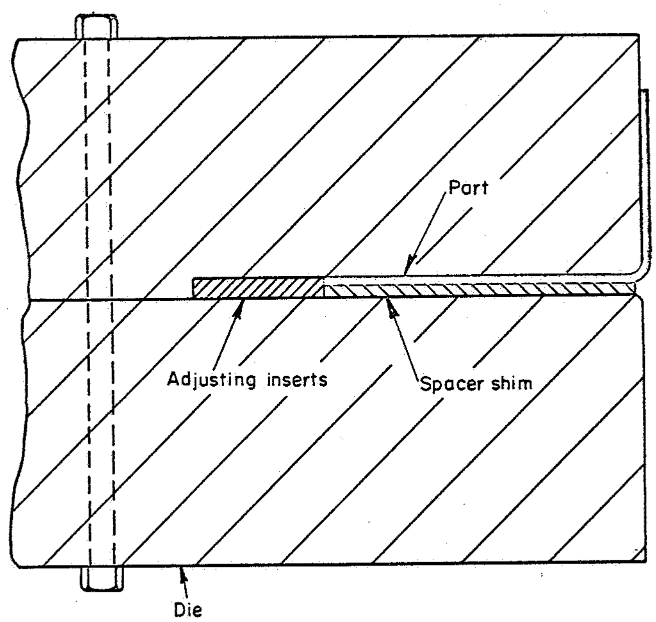


FIGURE 74. SECTIONAL VIEW OF LINEAR STRETCH TOOLING FOR HEEL-OUT ANGLES (REF. 35)

have been found to have a significant effect on the uniformity of stretching. Wallace reported on the use of ice as a tool covering and lubricant (Ref. 84). He found that greases applied to the tooling tended to squeeze out from the areas of higher normal pressure, causing a local breakdown of lubrication. The use of a rubber overlay was also considered, but the problems associated with relative motion between the part, the rubber pad, and the tool were believed too difficult to overcome. This approach would only be advantageous if the coefficient of friction between the part and the rubber were less than that between the part and the tool. The use of porous tooling that would permit fluids to be injected between the part and the tool was evaluated and rejected in favor of ice.

Since the solid-to-liquid phase change of ice can be induced by an increase of pressure or absorption of the heat generated during metal forming, ice was selected as a possible candidate for a stretch-forming lubricant. When the ice has a coating of water over its surface at points of maximum pressure the friction that occurs is due only to the viscosity of the water. In the tests conducted by Wallace, a layer of ice was built up on the surface of the tool by spraying or brushing water on the refrigerated tool. It was found that a rough surface on the tool was desirable for a mechanical bond between the ice and the tool. The ice produced a smooth surface on the tool. Since the pressure between the part and die is generally quite low, the maximum depression of the melting point of ice was calculated to be 0.5 F. It was found that for stretch forming at room temperature with an ice film of 1 to 2 mm in thickness on the tool it was necessary to maintain an ice-film temperature below 25 F. External heat is then applied to the part during forming. Heating the surface of the blank with an infrared lamp at an intensity of about 15 watts/in.^{2} for 30 seconds was found to give the best forming results. It was found that the ice film should not be less than 1-1/2 mm to prevent film breakdown. If the film is too thick there is a tendency to develop an uneven surface that may be reproduced on the part. An optimum film thickness of 2 mm was found.

Some difficulty might be expected in using ice dies for the stretch forming of precipitation-hardenable stainless steels, which tend to transform to martensite during forming at room temperature. Materials such as AM-350 and AM-355 would be expected to have poorer formability during stretching on ice dies.

A study conducted by Cornell and associates on nonmetallic dies for stretch forming indicated that they are suitable at room or elevated temperatures (Ref. 85). The low-temperature-curing castable ceramic tooling was used in stretch forming PH 15-7 Mo. Two materials that were found suitable for stretch-form tooling were 33 HD made by the Norton Co., and Special Hi-Alumina Castable made by General Refractory Co. In preparing tooling from these materials, it is best to construct the molds from dense plaster and then seal them. Peanut oil was found to be a suitable parting agent. The tooling design should permit monolithic construction with a minimum thickness of 3 inches and as large a radius as the part configuration permits. During the pouring of the ceramic, vibration is desirable. The ceramic should be dried slowly by covering the mold with wet burlap while drying at an oven temperature of 250 F. The base of the mold must be rigid and flat. A plastic back of 70 to 80 Durometer hardness will aid in seating the mold.

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. Some types of grips permit the sheet to be wrapped around a rod for increased holding efficiency.

Techniques of Stretch Forming. In stretch forming, skilled operators and careful attention to details are essential for success. Trouble may result from exceeding the uniform elongation of the material. Since most precipitation-hardenable stainless steels have good uniform elongation and a wide spread between yield and ultimate strength, they stretch form with a minimum of difficulty.

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 as 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 may be as high as 10 degrees 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 springback can be expected from room-temperature stretch forming of precipitation-hardenable stainless steels, the machine is adjusted for overforming to compensate for this. In forming sections, a springback from 5 to 10 per cent of the bend angle can be expected for annealed material. Work-hardened material might have a springback as high as 30 per cent.

To obtain maximum formability in stretch forming, the material should be stretched in the rolling direction. For preformed angles, channels, or hat sections, this requires that the prior operation be performed across the rolling direction of the material. The direction of initial shape forming is important when cold-worked material is being stretch formed at room temperature.

When severe deformation is required, multistage forming with intermediate anneals may be used. Stretch forming of precipitation-hardenable stainless steels is normally carried out at room temperature. The curves for the stretch-formability index of AM-350, A-286, and PH 15-7 Mo in Figure 75 indicate an optimum formability for PH 15-7 Mo and AM-350 at 500 F, while A-286 is best formed at room temperature.

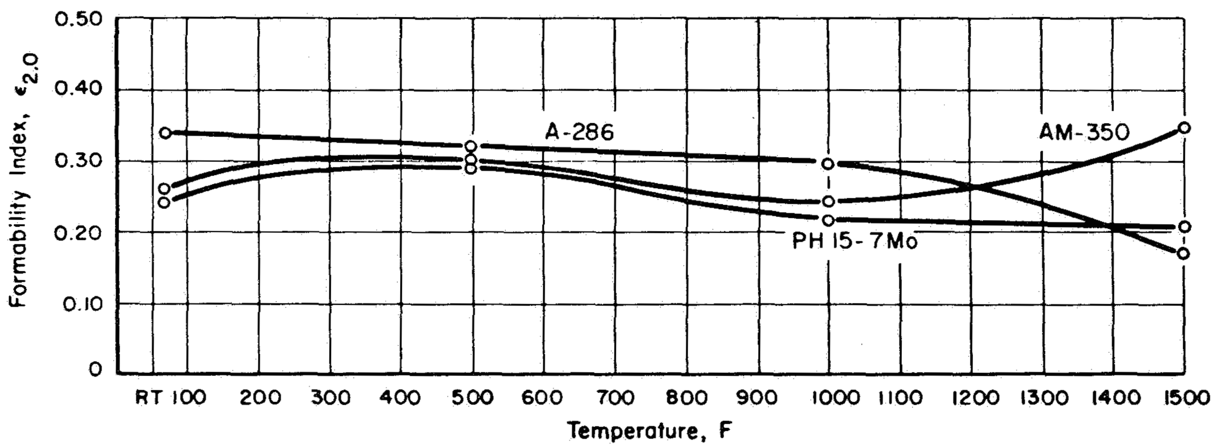


FIGURE 75. OPTIMUM FORMING TEMPERATURE CURVES, LINEAR STRETCH AND SHEET STRETCH (REF. 34)

Lubricants have very little effect on stretch-forming limits because of the relatively small movement of the material over the die. When used they are generally applied only to localized areas. They should be of the type that can be easily removed. Light-bodied machine oils, soap solutions, and greases should be effective.

Blank Preparation. For room-temperature stretch forming, the blanks should have clean, smooth surfaces. Blanks with as-sheared edges are used, provided burrs are removed to prevent tooling damage. Sections to be linear stretch formed should be cleaned after brake forming and annealed for maximum formability. 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 on to the sheet for gripping. A reduction in strength due to the welding may limit the amount of stretching possible by this method.

Stretch-Forming Limits. Success or failure in stretch forming to a particular shape depends on the mechanical properties of the material and on the geometry of the part. Failures occur from buckling or from splitting, as illustrated in Figure 76. The geometrical factors controlling the 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. 34) 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. 34, 35, 44) predicted splitting and buckling limits in PH 15-7 Mo, AM-350, and A-286 alloys in stretch forming. 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 77 shows the forming limits for heel-in or outboard stretch forming of PH 15-7 Mo, AM-350, and A-286. The A-286 alloy can be stretched more, without splitting, than PH 15-7 Mo or AM-350 at room temperature. This is indicated by the relative H/R ratios, which reflect ductility and ability to stretch. The same relative formability is shown when buckling rather than splitting is more likely to control failure.

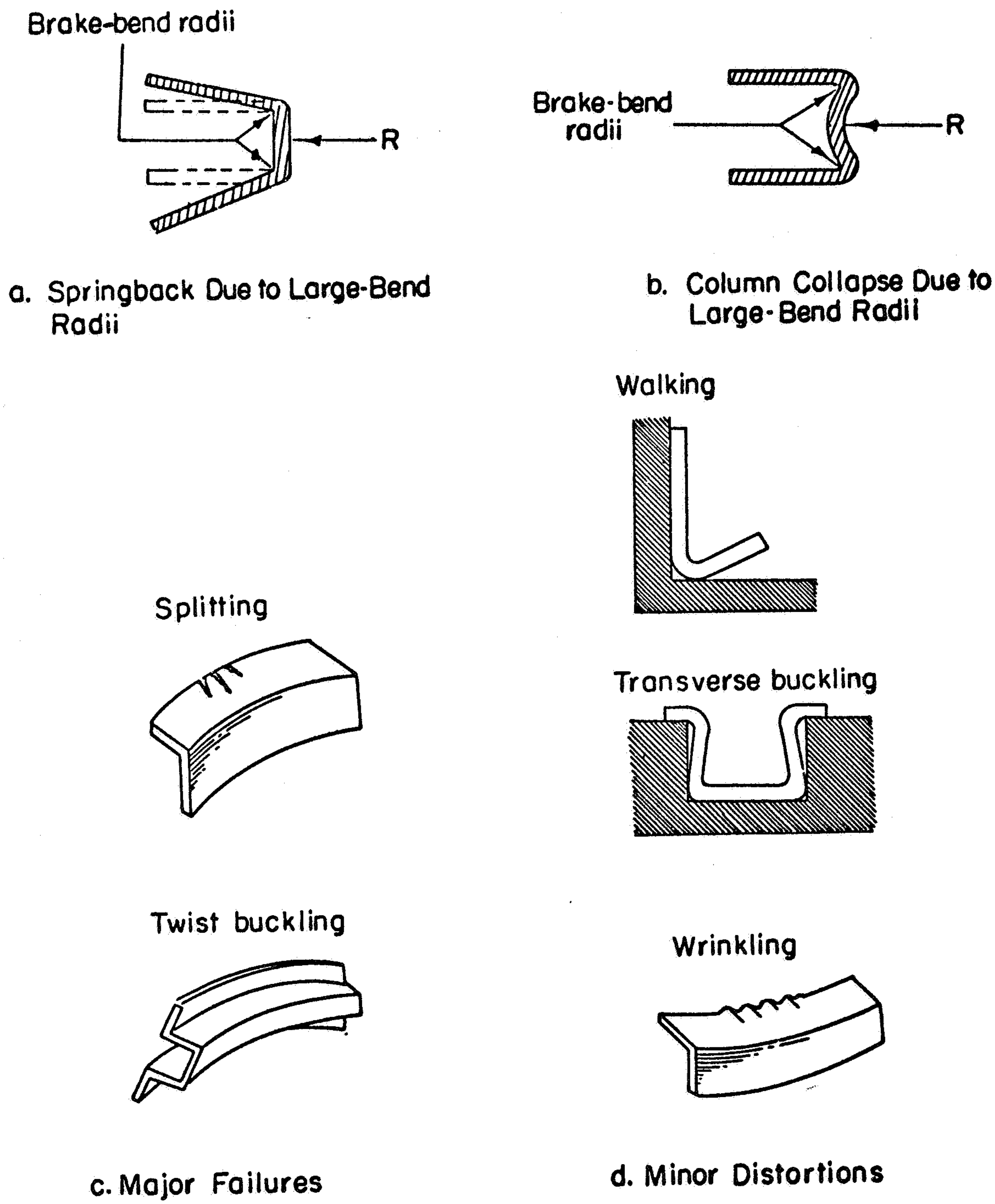


FIGURE 76. TYPES OF FAILURES FOR LINEAR STRETCH FORMING (REF. 34)

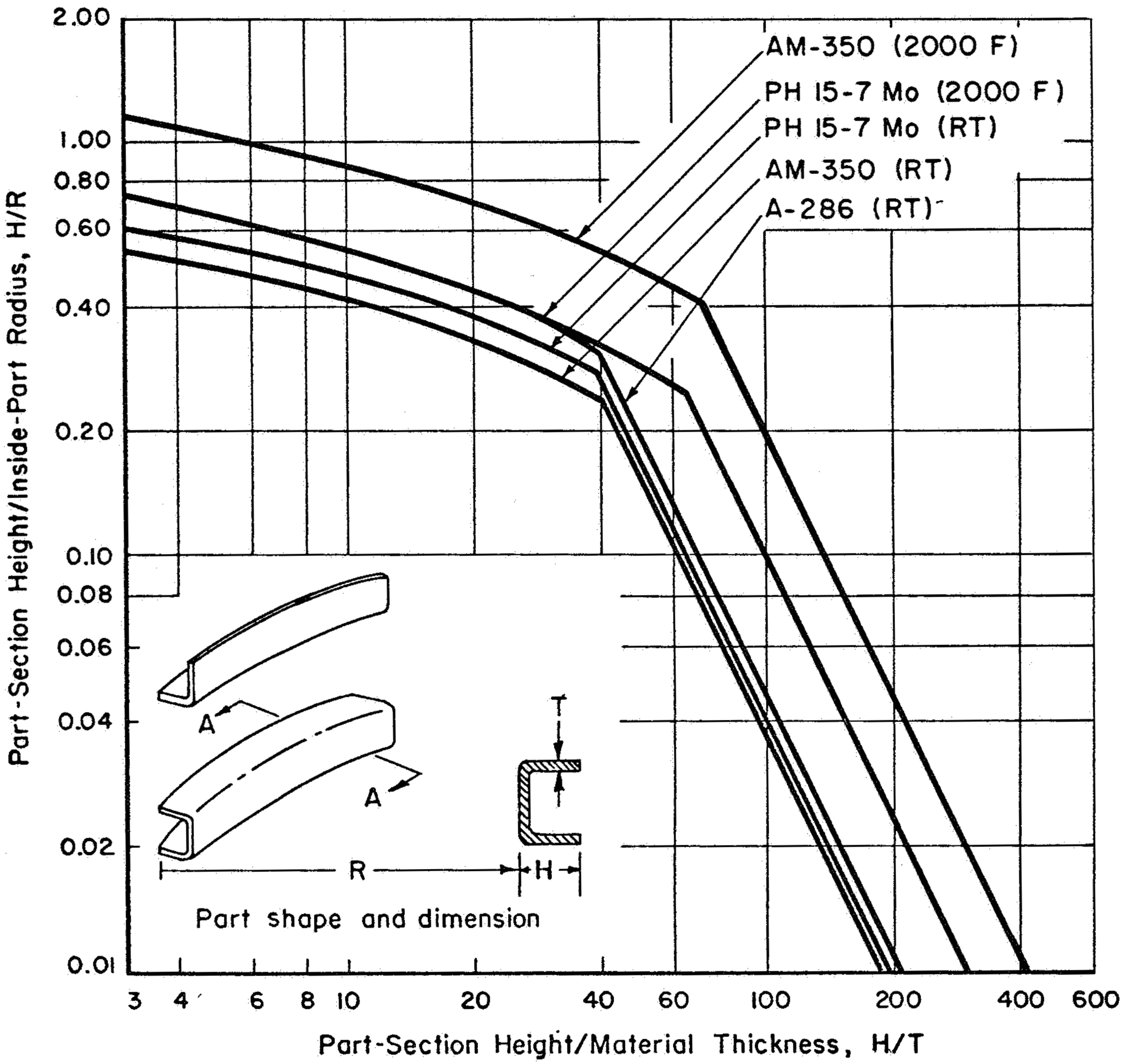


FIGURE 77. LIMIT CURVES FOR LINEAR STRETCH HEEL-IN ANGLE AND CHANNEL SECTIONS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

Figure 78 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 because it affects the severity of deformation. The relative order of formability between the materials is not changed because it depends on their mechanical properties.

The formability limits of hat sections, in the heel-in position, are shown in Figure 79. The buckling limits are a little higher than for angles and channels because the flange on the hat 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 80:

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

The tensile load should be applied in the direction necessary to stretch the sheet over the smaller radius because this requires more elongation. 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 80 also shows the stretch-forming limits for PH 15-7 Mo, AM-350, and A-286. The limits, expressed in ratios of die radii to chord lengths, are based on elongation values in room-temperature and elevated-temperature tensile tests. Although the differences are small, the A-286 alloy is expected to show better forming properties.

In androforming sheets between matched dies, shaping-system elements (Figure 81) permit the forming of smaller contour radii. Unlike simple stretch forming, however, 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 81 include an allowance for sheet thickness. The limiting ratios for several precipitation-hardenable stainless steels are given in Figures 81 through 84 for two different size-forming elements.

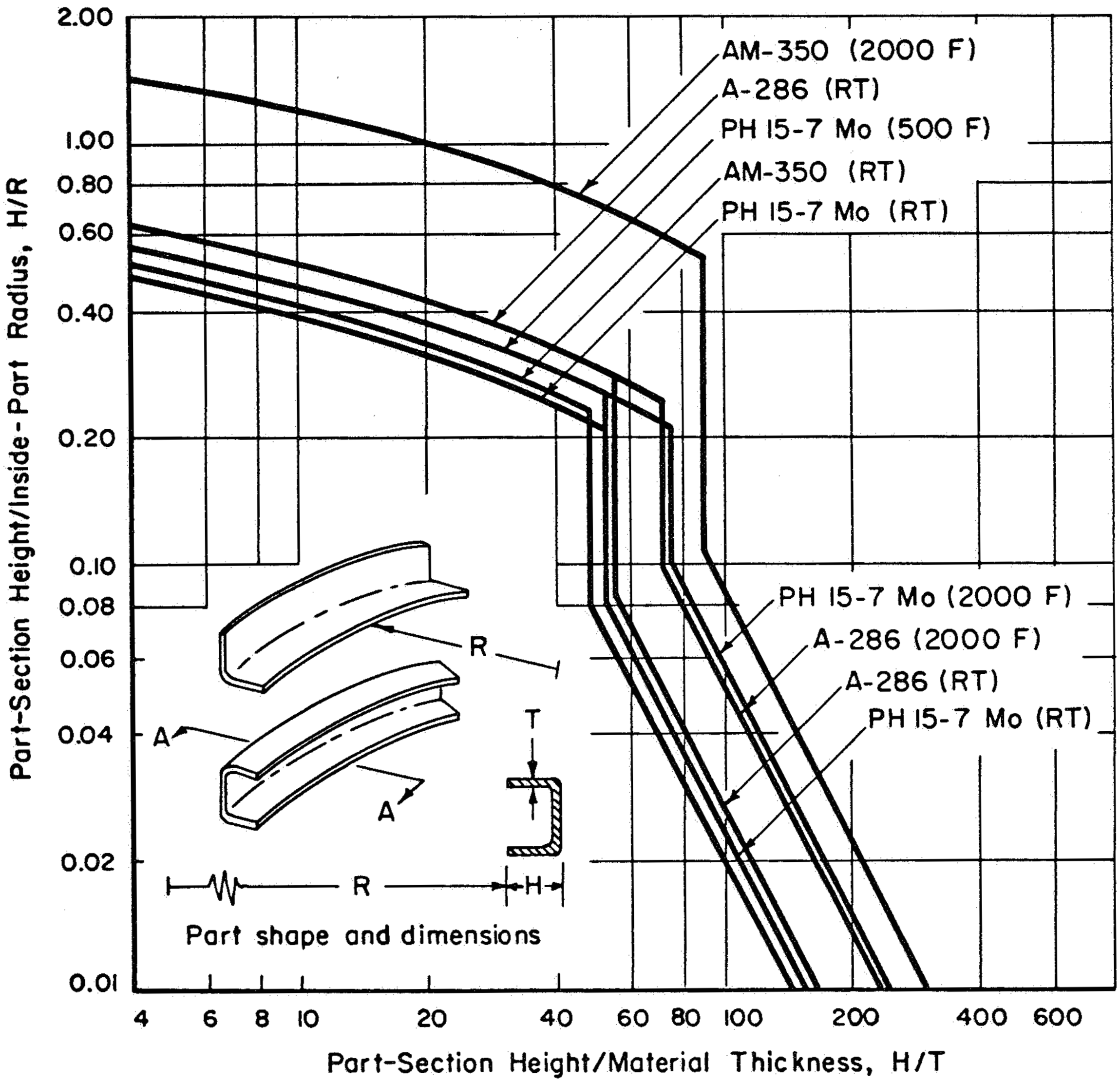


FIGURE 78. LIMIT CURVES FOR LINEAR STRETCH HEEL-OUT ANGLES AND CHANNELS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

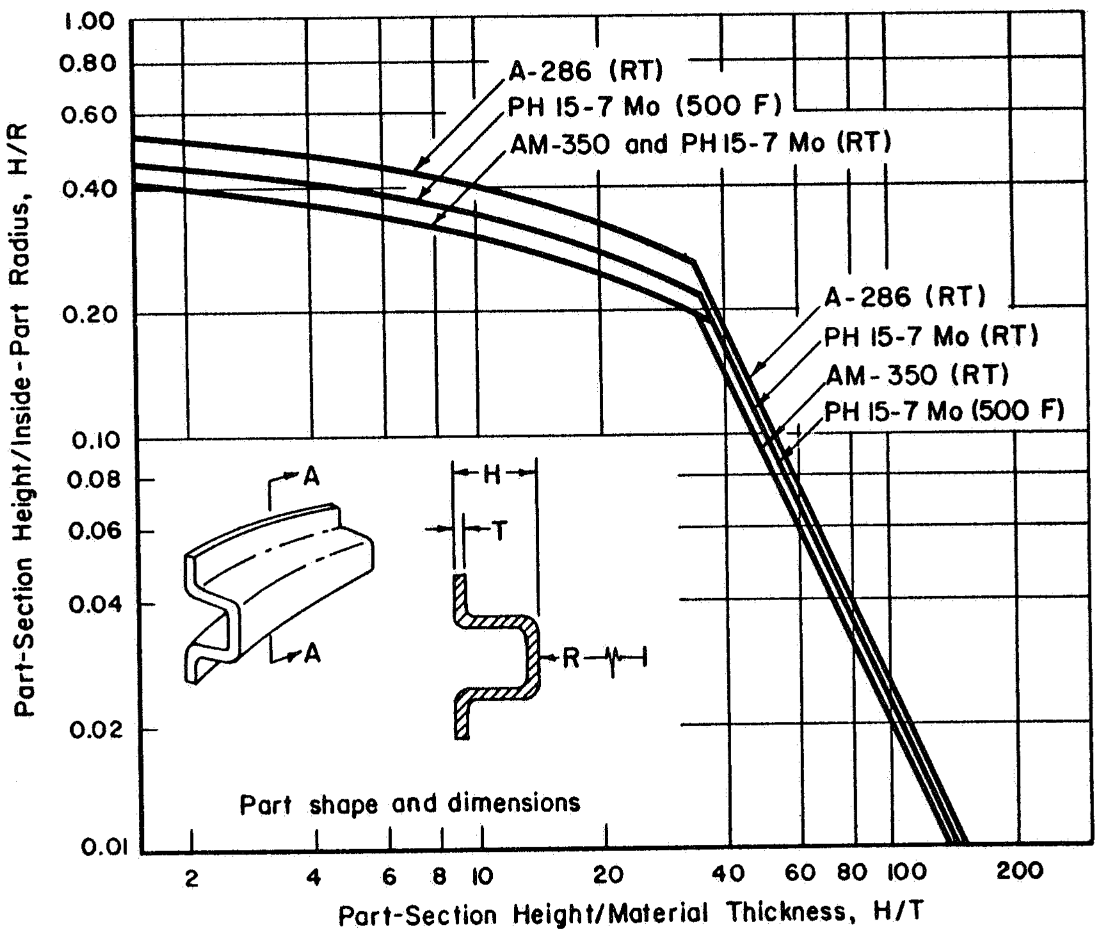


FIGURE 79. LIMIT CURVES FOR LINEAR STRETCH HEEL-IN HAT SECTIONS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

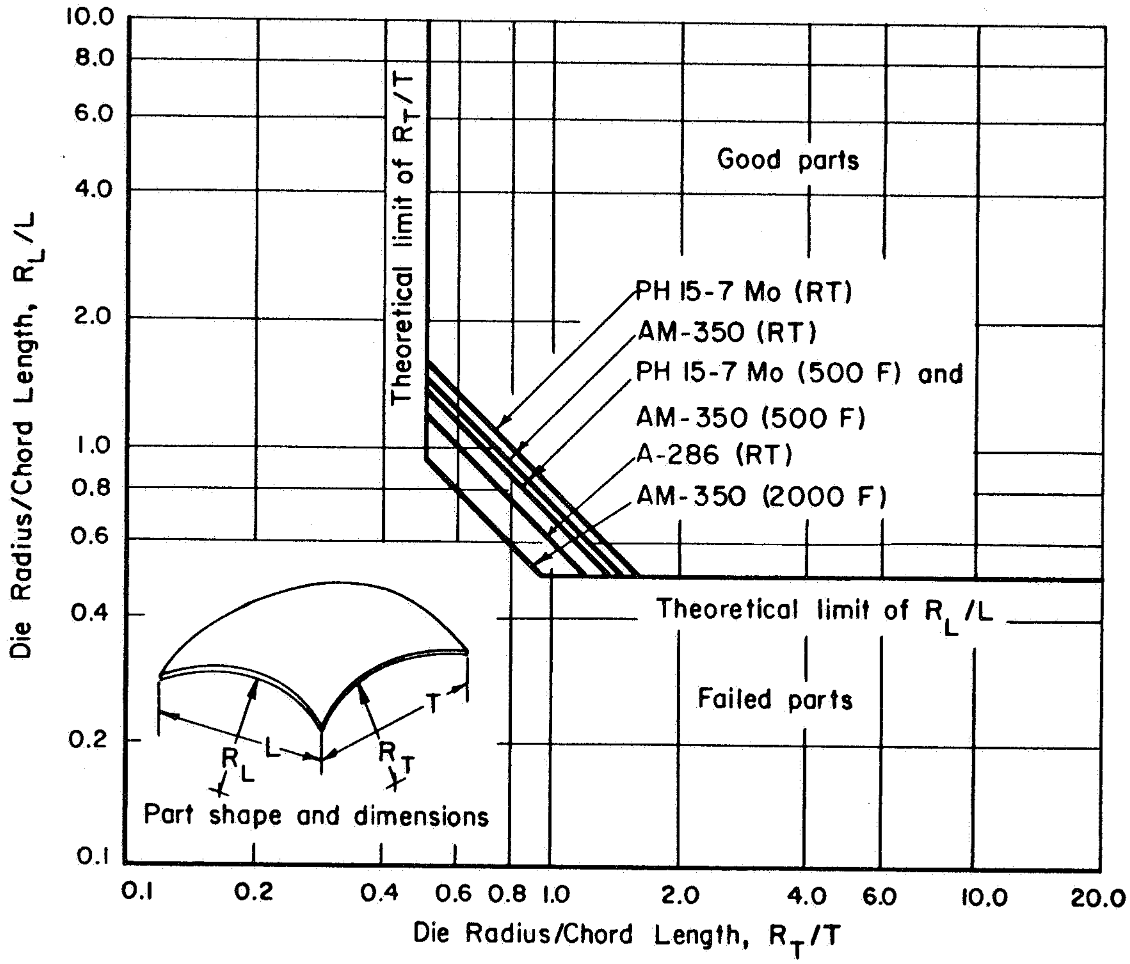


FIGURE 80. LIMIT CURVES FOR SHEET STRETCH FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 34)

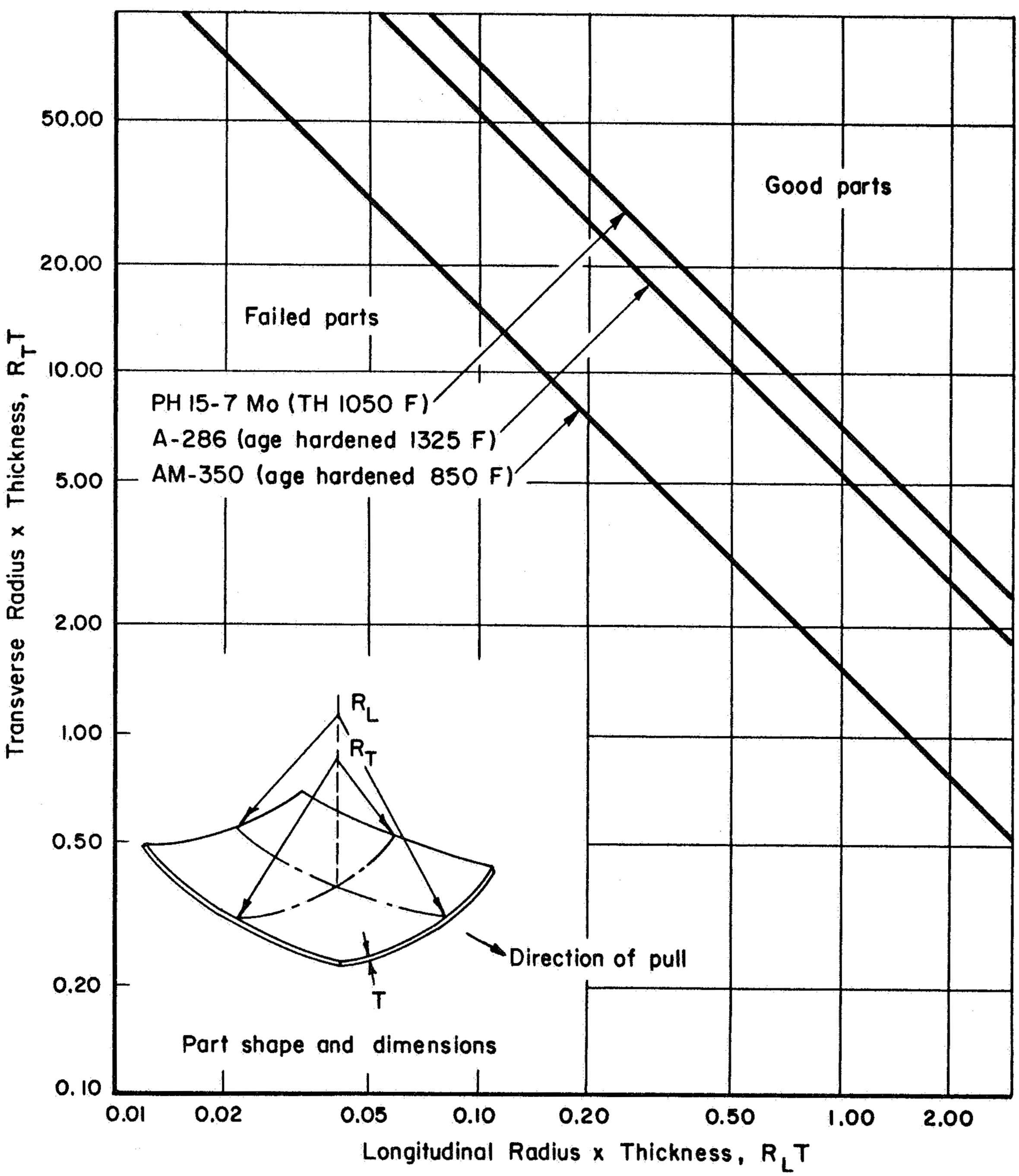


FIGURE 81. COMPOSITE GRAPH FOR ANDROFORM BUCKLING LIMITS FOR 20-INCH FORMING ELEMENT (REF. 34)

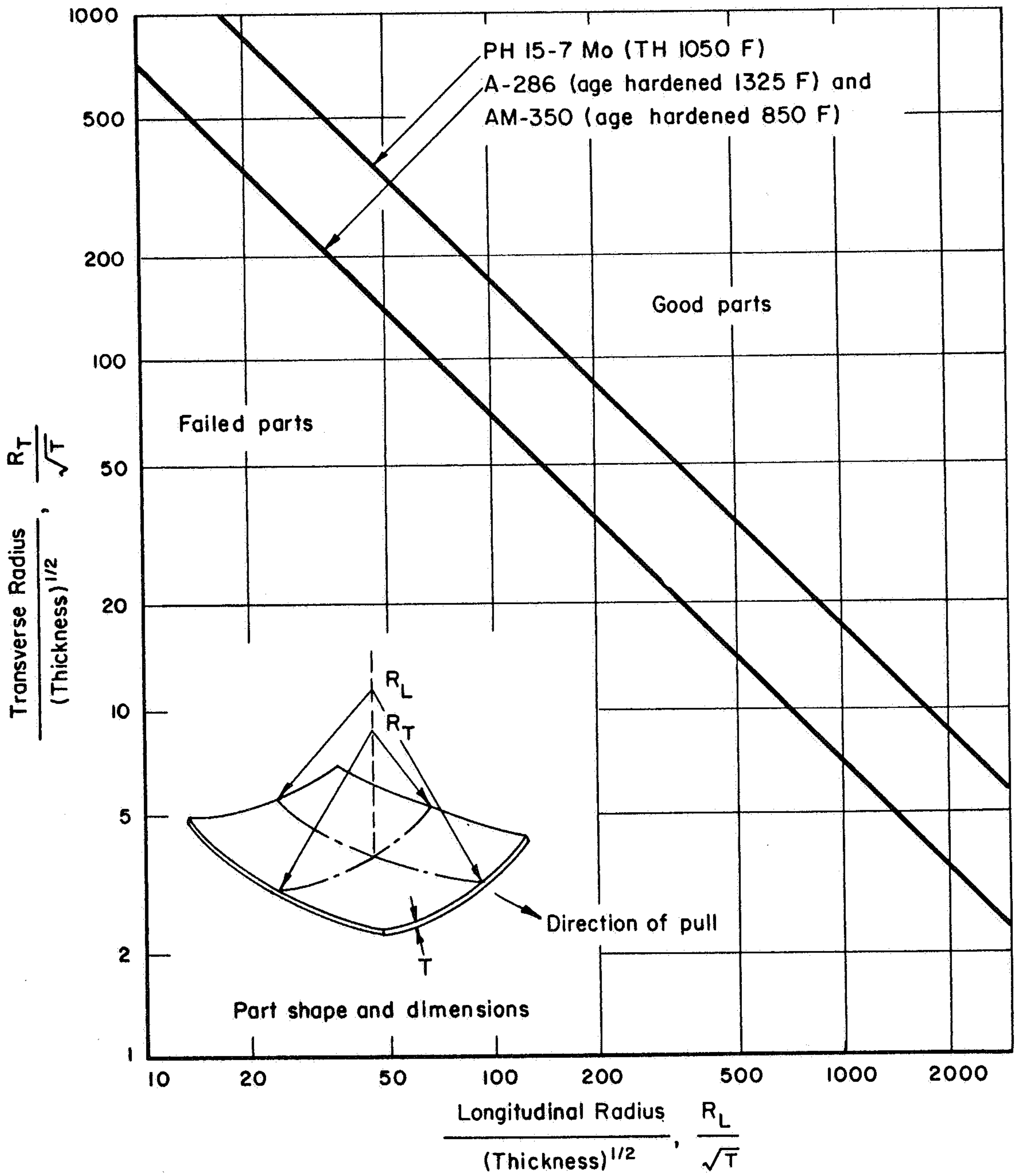


FIGURE 82. COMPOSITE GRAPH FOR ANDROFORM SPLITTING LIMITS FOR 20-INCH FORMING ELEMENT (REF. 34)

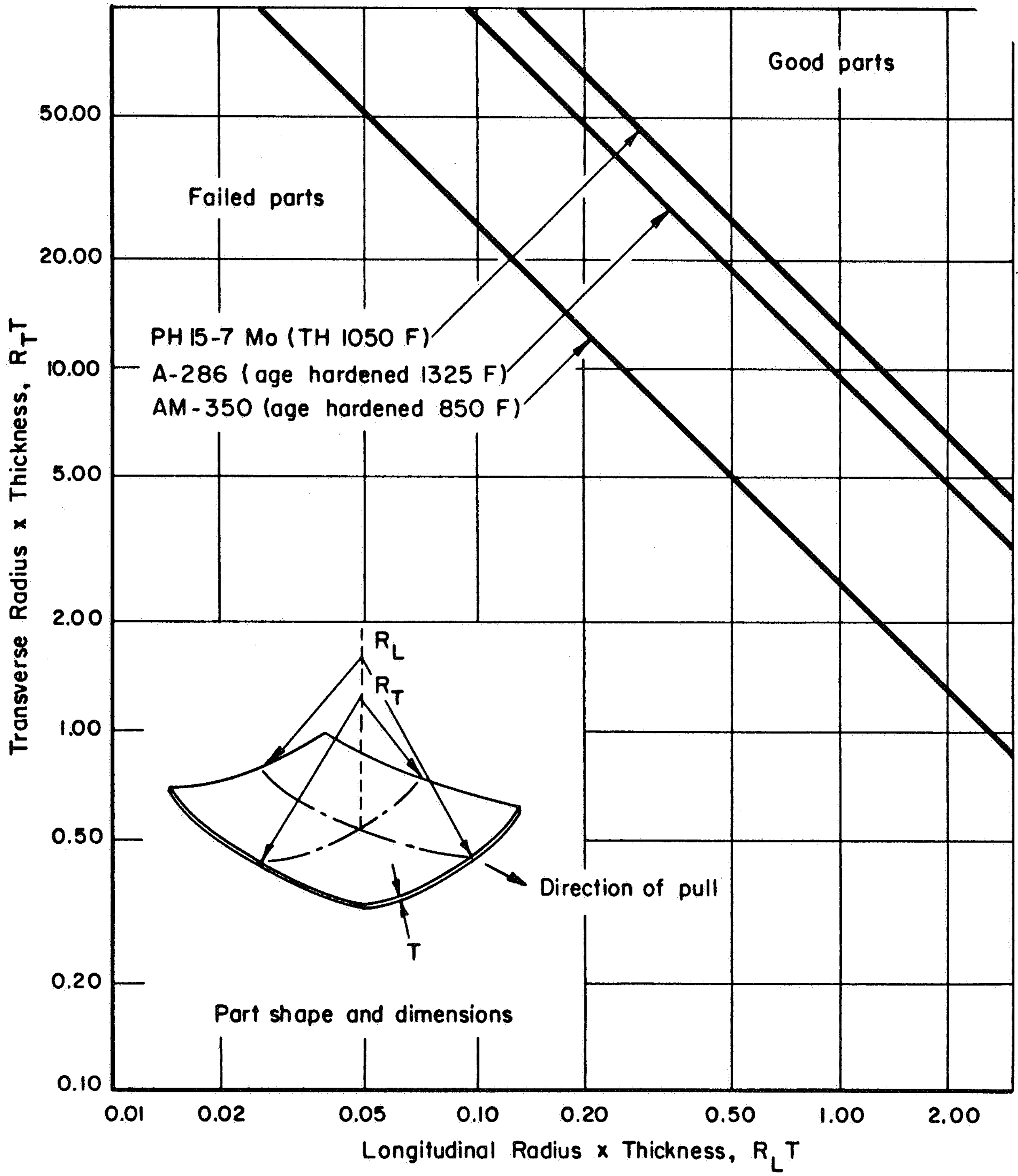


FIGURE 83. COMPOSITE GRAPH FOR ANDROFORM BUCKLING LIMITS FOR 50-INCH FORMING ELEMENT (REF. 34)

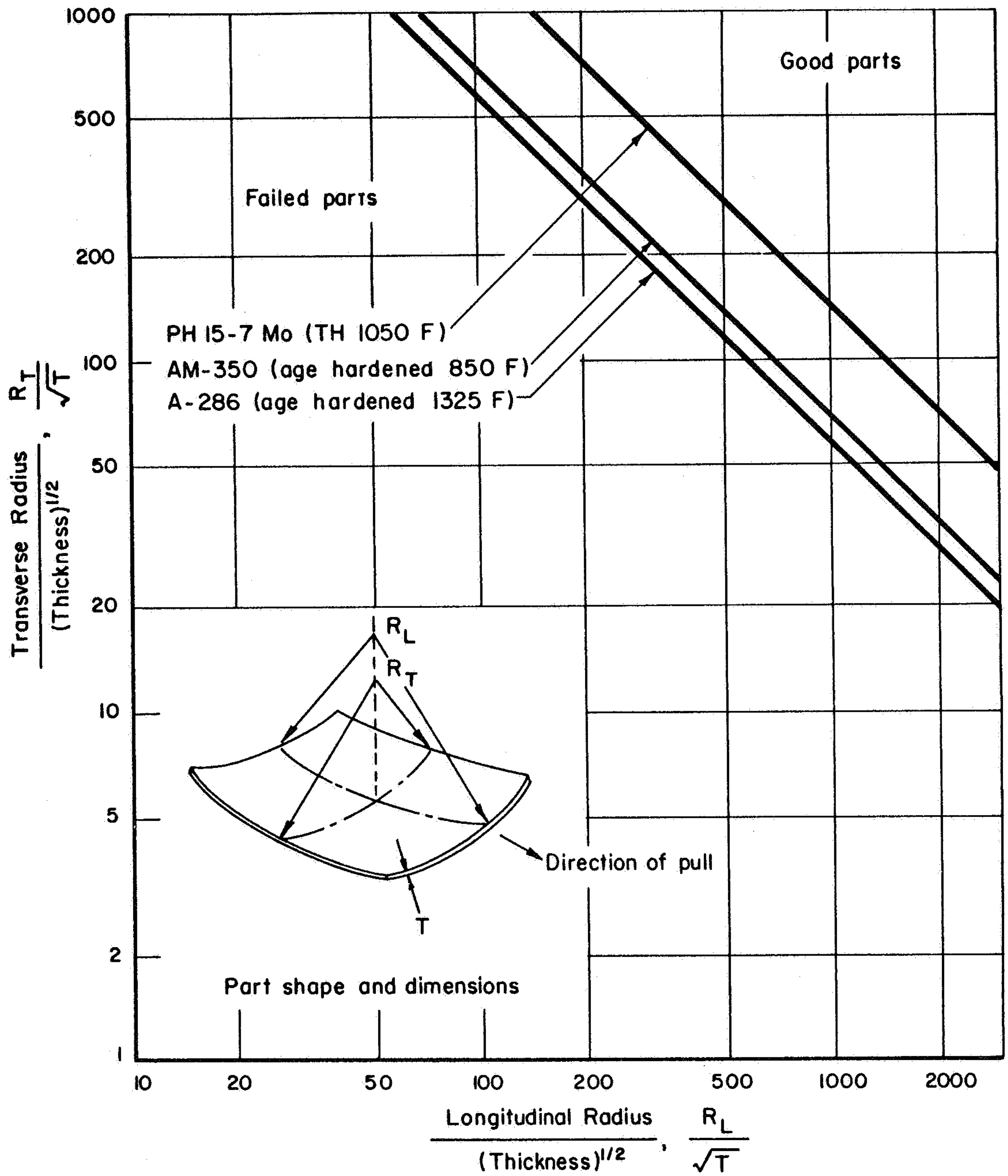


FIGURE 84. COMPOSITE GRAPH FOR ANDROFORM SPLITTING LIMITS FOR 50-INCH FORMING ELEMENT (REF. 34)

Changing from a 50-inch to a 20-inch forming element lowers the limiting parametric ratios. The room-temperature limit curves in Figures 82 and 83 indicate that AM-350 or A-286 in the age-hardened condition are less likely to buckle or split in androforming than the PH 15-7 Mo alloy in the age-hardened condition.

Properties of Stretch-Formed Parts. Stretch forming develops uniform and consistent properties in parts formed and heat treated from 17-7 PH steel. A method of stretching and transforming the material simultaneously was developed by North American Aviation, Inc. (Ref. 86), and resulted in the manufacture of parts with a reduction of warpage and rework requirements. Stretching the steel with a stress of 113,500 ± 570 psi at a temperature of 30 ± 8 F, followed by aging, resulted in a tensile minimum of 185,000 psi, tensile yield (0.2% offset), minimum of 155,000 psi, and an elongation of 5 per cent in a 2-inch gage length. The stretch aged material was found to have superior ductility at the same strength level over the 1400 F treated material.

To better control the stretching process and to insure more uniform properties, an eddy-current gage was developed to indicate the as-aged condition of the sheet (Ref. 87). With this gage the operator can produce sheet with uniform properties of 180,000 to 220,000 psi ultimate tensile strength with 5 per cent elongation. The material then can be blanked or formed and, subsequently, aged at 850 F for 1 hour.

Lanz and associates (Ref. 88) examined the effect of androforming on the properties of 17-7 PH. The material was stretch formed in the annealed condition; three thicknesses of 0.010, 0.080, and 0.125 inch were evaluated. The tensile yield increased considerably; the ultimate tensile increased slightly; the elongation decreased slightly; and compressive yield strength increased. An increase in compressive yield with increasing thickness was noted. After the material was stretch formed and placed in the TH 1050 condition a drop of 3 per cent in elongation was noted. This was attributed to the forming operation. Some of the elongation loss could be restored by stress relieving the material.

TUBE FORMING

Introduction. One of the principal uses of tubing made from the precipitation-hardenable stainless steels is hot-air ducting in jet-type aircraft anti-icing systems. Figure 85 shows a complex bend made in 2-inch-diameter AM-350 stainless steel tubing. Forming operations are also necessary for producing reduced sections, bulges, bends, etc. The problems in tube forming generally become more difficult as the diameter of the tube is increased and the wall thickness is decreased. Some of the current methods for forming tubing from the precipitation-hardenable stainless steels are described in this section.

FIGURE 85. BEND IN 2-INCH-DIAMETER TUBING OF AM-350 STAINLESS STEEL USED TO CARRY HOT AIR FROM ENGINE TO WING SURFACES TO PREVENT ICING ON LOCKHEED ELECTRA AIRPLANE

Courtesy of Allegheny Ludlum Steel Corporation, Pittsburgh, Pennsylvania.

Tube Bending. 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. These are depicted schematically in Figure 86. Ram or press bending is accomplished by placing the tube between two supports and pressing the ram and tube between the supports, thus forcing the tube to bend around the ram. Roll bending is accomplished by passing the tube through a

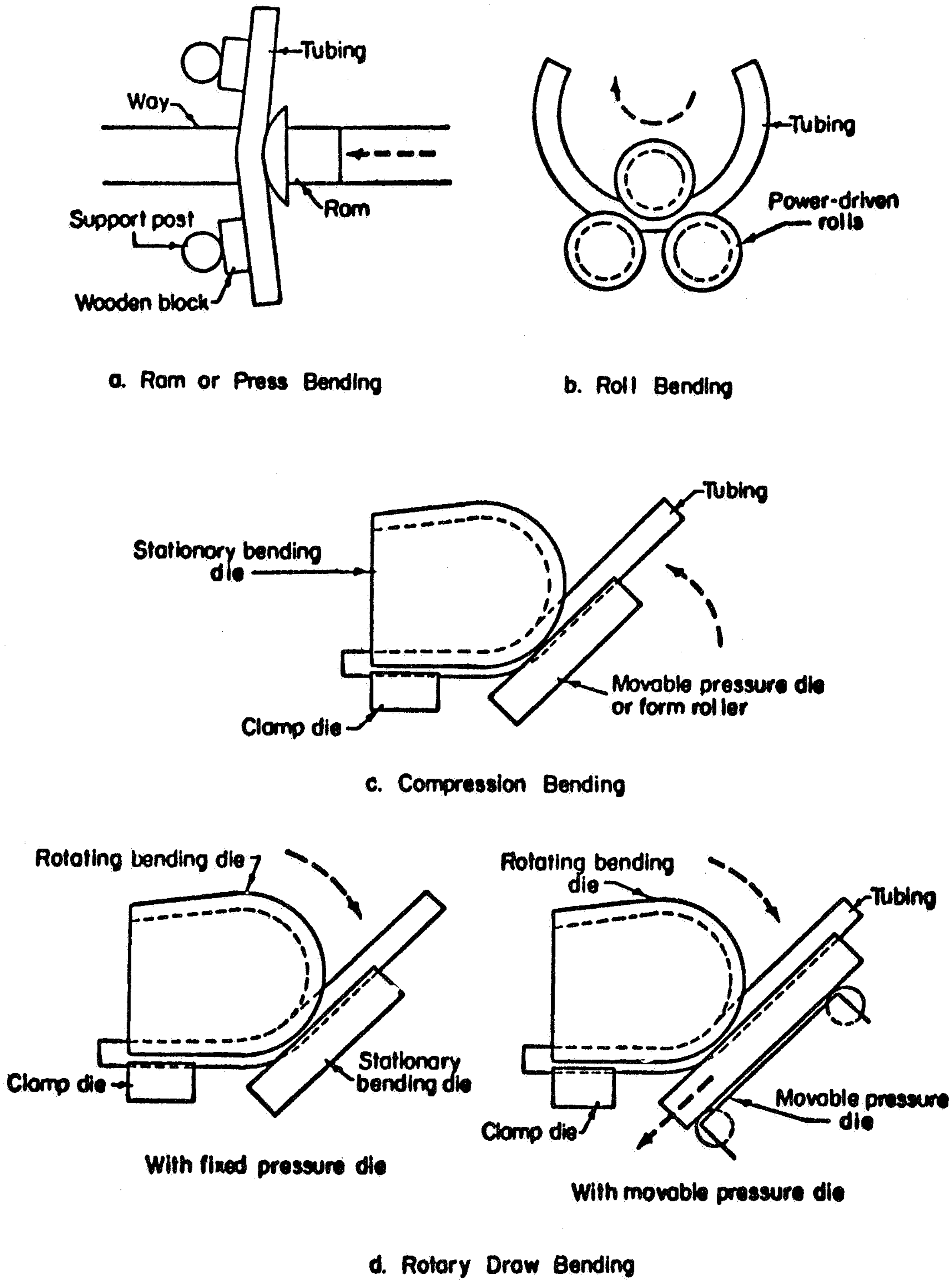


FIGURE 86. METHODS OF TUBE BENDING (REF. 57)

suitable series of grooved, power-driven rolls. 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. The first three methods are used for heavy-wall tubing or tubes filled with a matrix material but are likely to cause thin-wall tubing to wrinkle, fracture, or even collapse. They are generally limited to forming generous bend radii usually more than five times the tubing diameter. The fourth method, draw bending, is used to bend thin-walled tubing and to obtain bend radii as small as 1.5 D. The tube is confined during bending, and is supported internally by a flexible mandrel.

Each method of bending has special limitations that often control the success or failure of the operation. Generally speaking the processes can be used for the operations shown in Table XXXVIII. Figure 87 shows the various stainless steel tube sizes that can be bent by the different tube-bending processes.

TABLE XXXVIII. LIMITS OF VARIOUS TUBE-BENDING PROCESSES (REF. 57)

Bending Process	Types of Bends Usually Accomplished	Maximum Angle of Bend, degrees
Ram or press	Single bends Tube straightening	<120
Roll	Circular Spirals Helical coils	360
Compression	Single bends	<180
Rotary draw	Single Multiple Compound	180

An interesting and new experimental technique for bending tubing was developed at Battelle Memorial Institute. The process consists of filling the tube with a low-melting-point alloy and applying an axial load to the tube forcing it around a bend of the desired contour in a closed die. AM-350 tubing in the CRT condition was bent 90 degrees with a bend radius of 1 D measured to the centerline of the tube. The tube had 1/2-inch diameter with a 0.010-inch-thick wall. After forming, the wall thickness at the outer fibers was found to have decreased

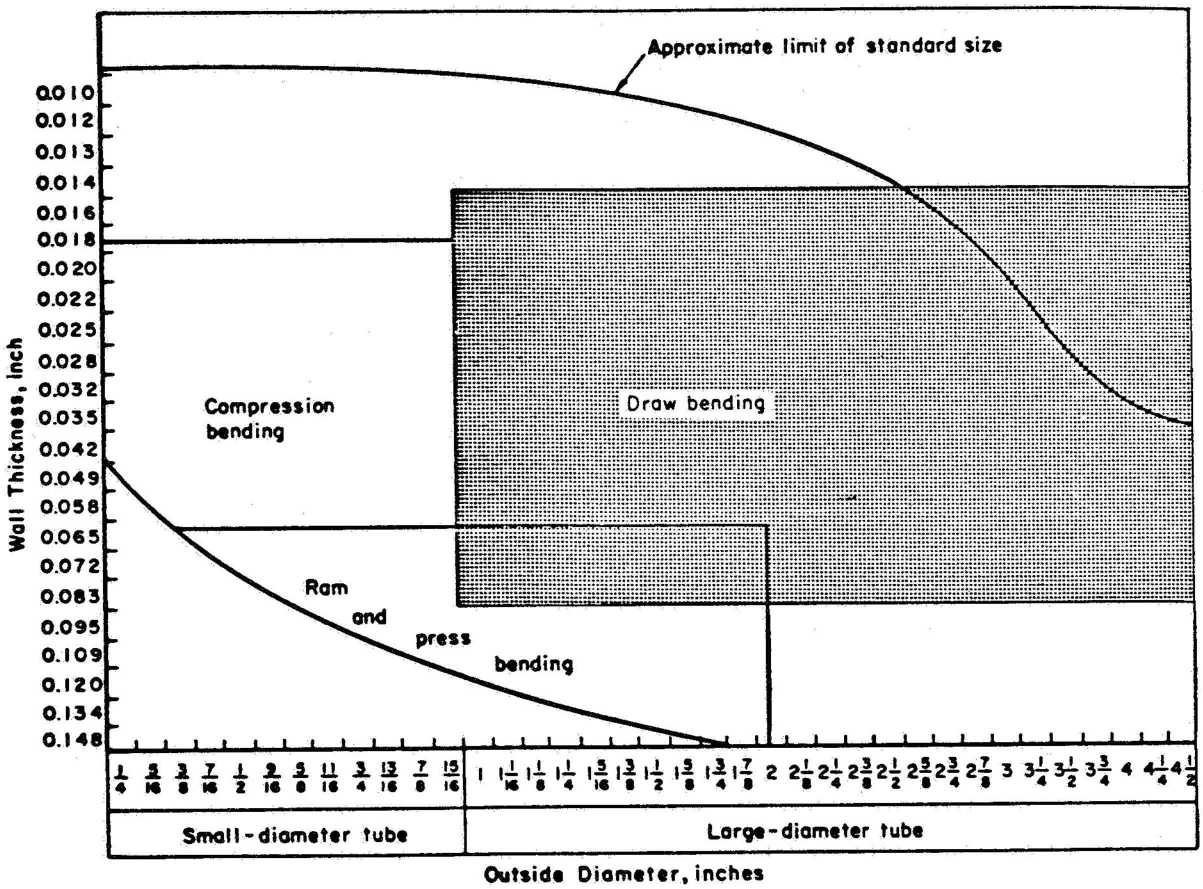


FIGURE 87. AREAS OF SUITABILITIES FOR VARIOUS BENDING PROCESSES BASED ON STANDARD TUBING SIZES OF STAINLESS STEEL (REF. 57)

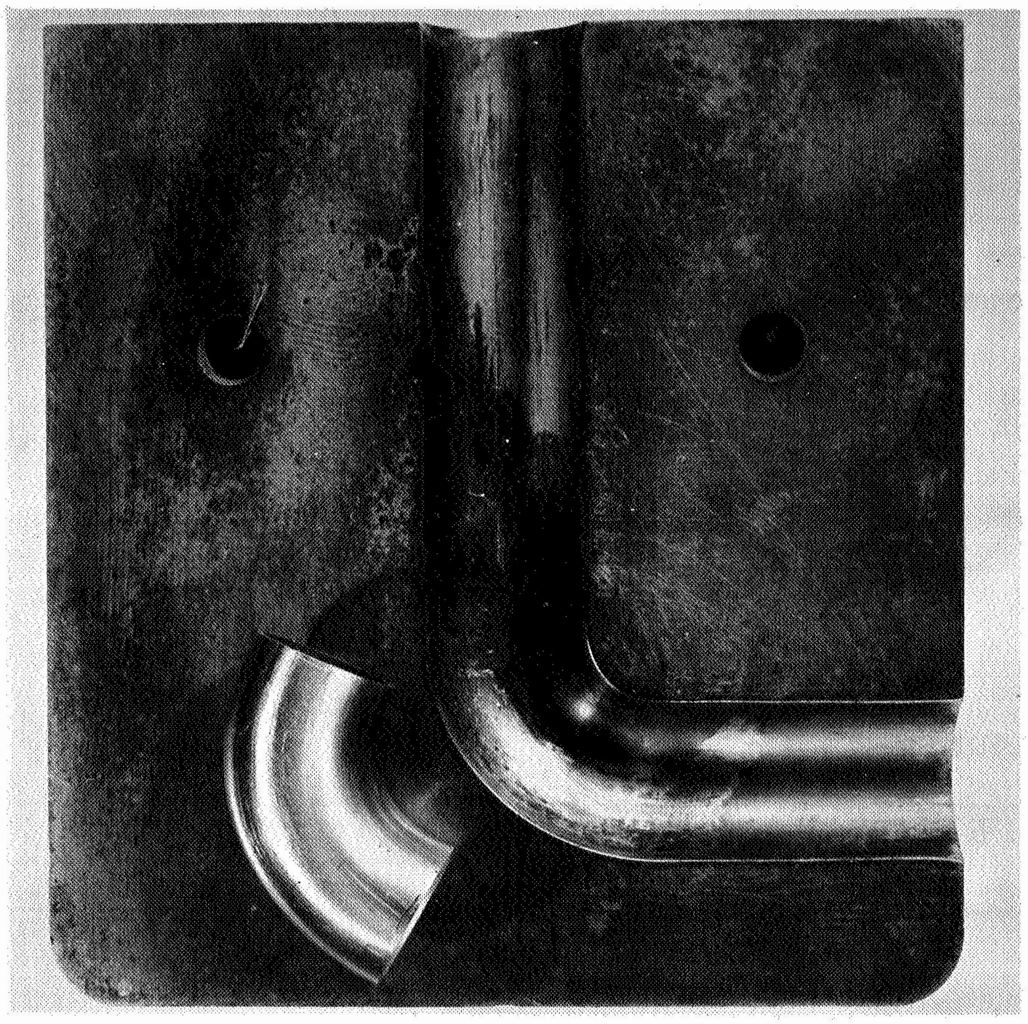


FIGURE 88. ELBOW OF AM-350 STAINLESS STEEL FORMED BY FORCING STRAIGHT 1/2-INCH-DIAMETER TUBING AROUND A BEND IN A CLOSED DIE

Courtesy of Battelle Memorial Institute, Columbus, Ohio.

only 5 per cent while the inner wall had increased in thickness by approximately 50 per cent. Figure 88 shows one of the AM-350 tubes that was formed by this method along with half of the forming die.

Equipment. The precipitation-hardenable stainless steel tubes are bent in commercially available equipment. The diameter of the tube dictates the equipment size, and one equipment manufacturer* supplies aircraft tube-bending equipment in the following sizes:

Bender Model No.	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. Equipment for bending thin-wall tubing must be in good condition; spindles should have no more than 0.0005-inch total runout (Ref. 89). A full complement of machine controls is essential.

Tooling. SAE 4340 steel heat treated to Rockwell C 45-48 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). For bending thin-wall tubing, the bend die, wiper die, pressure die, mandrel, and clamp die must all be made to close tolerances (Ref. 89).

Figure 89 shows five basic types of mandrels that are used in bending tubing (Ref. 90). Mandrels are made of tool steel,

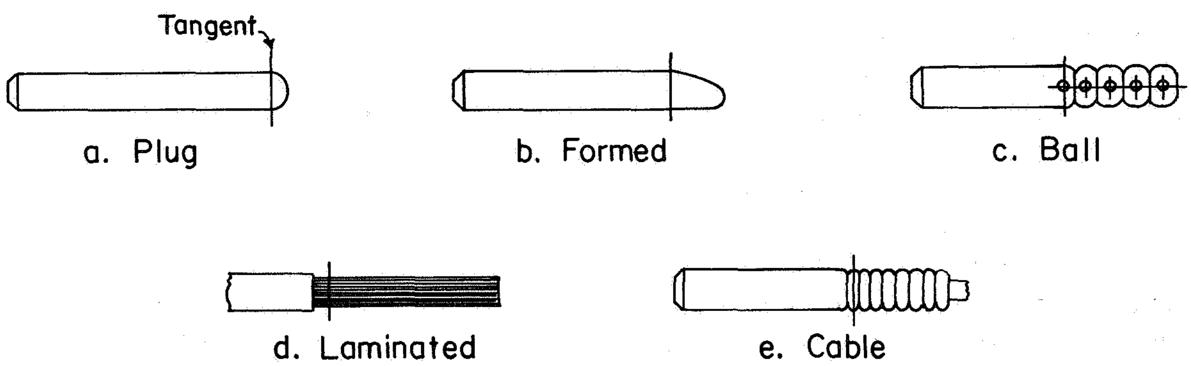


FIGURE 89. FIVE BASIC TYPES OF MANDRELS USED FOR TUBE BENDING (REF. 90)

*Pines Engineering Company, Inc., Aurora, Illinois.

case-hardened steel, chromium-plated tool steels, and bronze. AMPCO bronze mandrels are preferred for bending stainless steel tubes because they are resistant to galling and scoring with or without lubrication.

Tube Preparation for Bending. Tubes straight within 0.030 inch per foot give good 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 may cause problems if the tube warps during the annealing operation.

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. Generally the tubes are cut to length with a trim allowance after forming.

Lubricants. Many conventional lubricants do not provide the continuous film needed to separate the tools from the workpieces under high bending loads. Ineffective lubrication causes galling. Drawing grease and oil has been found to be suitable for bending stainless steel tubes. Prior to bending, large amounts of lubricant are applied to the mandrel and the inside diameter of the tube. This sometimes is applied by spraying the heated lubricant (250 F), especially on the inside of the tube. Lubrication of the wiper die is essential but the coating must be thin and uniform to avoid wrinkling (Ref. 89).

Tube-Bending Precautions. 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. Under such conditions pressure-die forces and the amount of elongation required to form the parts increase. This results in high failure rates.

Bending Limits. The bending limits depend mainly on the relationship of the bend radius to the tube diameter. The angle of the bend is not important for 90-degree or larger bends. The uniform elongation of the material is affected by the wall thickness of the tubing so that a decrease in formability in bending can be expected for tubing with a wall thickness of less than 0.035 inch.

The position of the neutral axis during bending influences the tensile strain in the outer tube fibers and the compressive strain in the inner tube fibers. Figure 90 shows the calculated tensile strain in the outer tube fibers when the neutral axis is located a distance of 1/2 and 1/3 diameter from the inner fibers of the tube. As shown in this graph the strain in the outer fibers decreases as the neutral axis moves away from the inside tube fibers for any given ratio of bend radius to tube diameter. Consequently, equipment that shifts the neutral axis away from the inner tube fibers during bending permits smaller bend radii to diameter ratios in a given material. The position of the neutral axis during rotary draw bending is usually between 1/3 D and 1/2 D. The exact position depends on the tooling and fit of the tubing on the tooling.

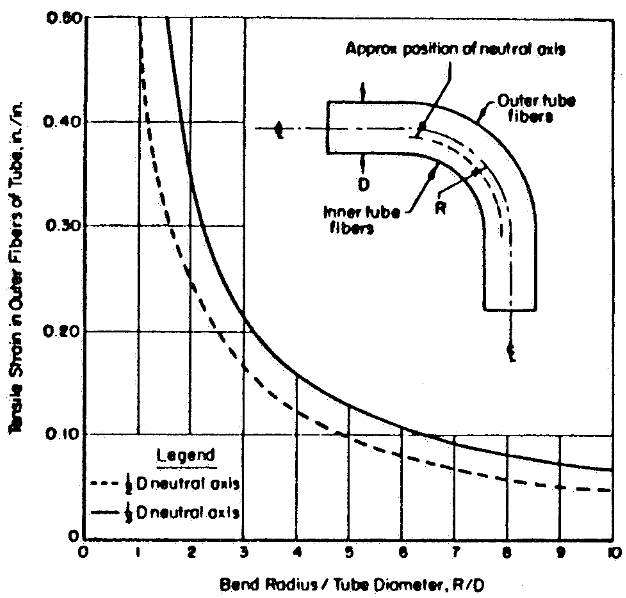


FIGURE 90. STRAIN IN THE OUTER TUBE FIBERS FOR A 90-DEGREE BEND WHEN THE NEUTRAL AXIS IS AT 1/3 D OR AT 1/2 D MEASURED FROM THE INNER TUBE WALL

Figure 90 may be used to determine the minimum ratio of bend radius to tube diameter for a given tube material and condition provided the tensile-elongation value of the material at the same thickness as the tube is known. For example, the A-286 alloy in the annealed condition has a tensile elongation of approximately 48 per cent. Tubing of this material could therefore be bent to a minimum ratio between 1 and 1-1/2 D depending on the position of the neutral axis in the bending procedure.

As the wall thickness of the tubing is decreased, the limiting factor in tube bending changes from elongation to compression stability. Buckling of the thin wall material on the inner tube fibers becomes more of a problem as the wall thickness is decreased and this condition is accentuated by a shift of the neutral axis away from the inner tube fibers. The minimum bend radii ratio should be increased by at least one number when the material thickness is 0.035 inch or less.

Post-Forming Operations. The tubing is generally trimmed to final length after forming where precise assembly work is required. The tubes are then cleaned to remove any lubricant or foreign material. For tubing that can be heat treated, the bending operation is generally carried out with the material in the solution-treated condition. The tubes are then aged after forming to obtain the final desired mechanical properties.

Tube Bulging. Introduction. In bulging, an internal pressure is applied to form a 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 most precipitation-hardenable stainless steels, the process is limited to forming in the annealed or solution-treated conditions.

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 slow 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 91, so that a hydrostatic pressure is approached. The behavior of the filler material will control how closely hydrostatic conditions prevail during forming operations. When the ram shown in Figure 91 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.

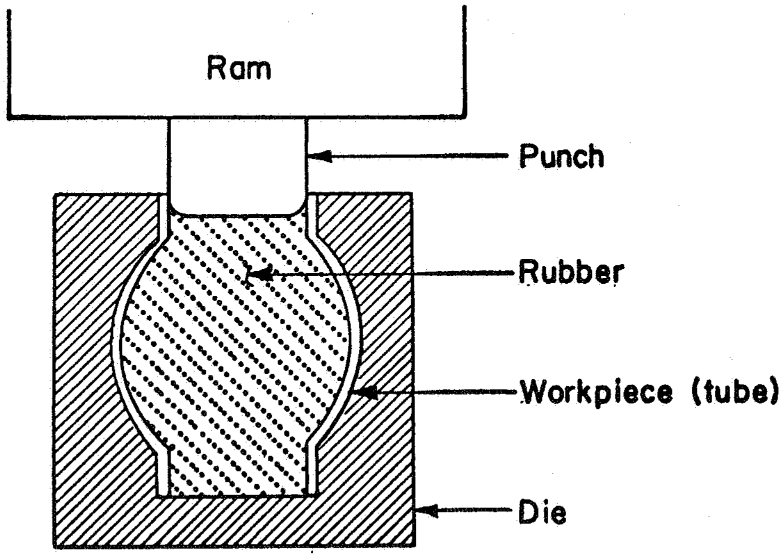


FIGURE 91. RUBBER-BULGING SETUP (REF. 34)

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 efficiency complicate sealing. The volume 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

$$p = 2TS/d \tag{22}$$

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. Both seamless and welded tubing of the precipitation-hardenable stainless steels are generally available in diameters from 0.012 to 4.5 inches and wall thicknesses from 0.004 to 0.148 inch. Larger size tubing has generally been made from roll- or brake-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 92, 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.

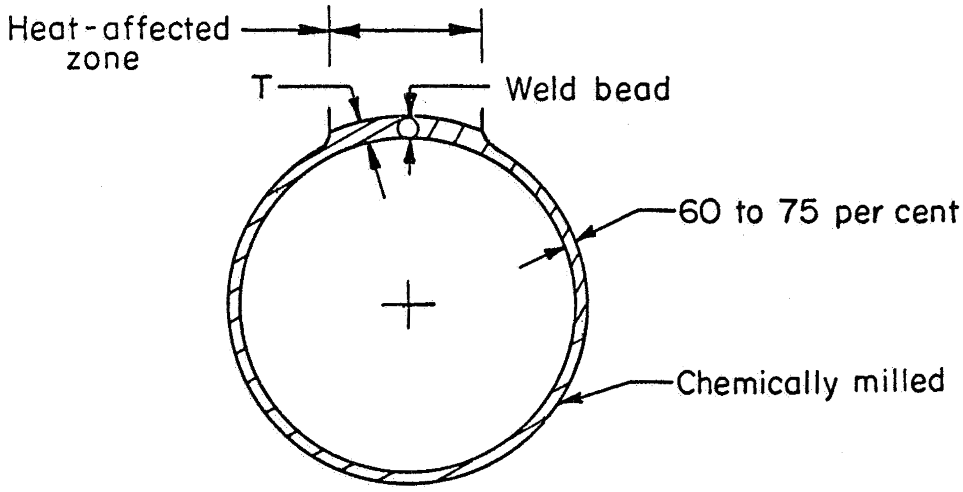


FIGURE 92. METHOD OF EQUALIZING STRENGTH BETWEEN WELD AND WALL AREAS FOR DIE-FORMED TUBES (REF. 35)

Bulge-Forming Limits. Two limitations must be considered in bulge-forming operations: ductility of the workpiece material and design of the tooling. The final part shape determines the maximum percentage increase in diameter. This can be calculated:

$$\text{Per Cent Increase} = \frac{d_f - d_o}{d_o} \times 100, \qquad (23)$$

where

d_o = original diameter

d_f = final diameter.

If no material is drawn in along the tube axis during forming, this may also be considered as the percentage stretch. 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 expansion 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 tube expansion is possible. The per cent increase in diameter 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 93. The minimum bend radii in tube forming should not be less than that used in other forming operations such as brake forming.

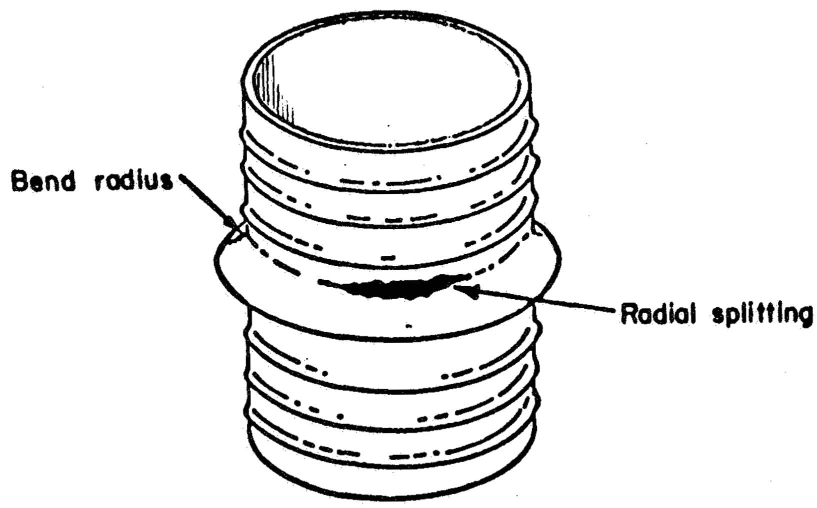


FIGURE 93. EXAMPLE OF FAILURE IN TUBE BULGING (REF. 35)

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 94. 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. Figure 95 may be used to determine E_A when the R_1/W ratio is known. 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.

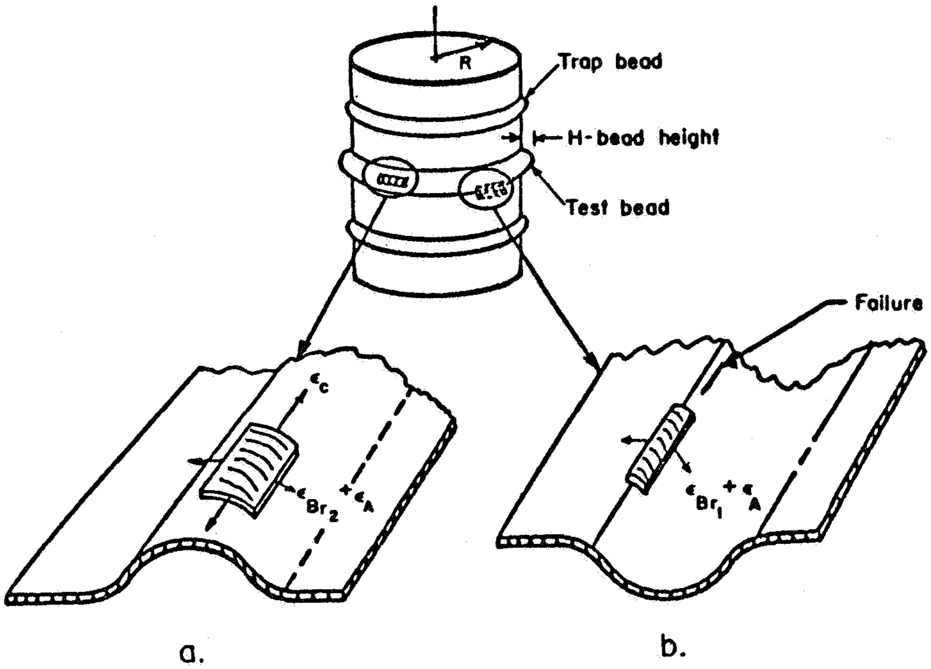


FIGURE 94. STRAIN CONDITIONS IN BULGE FORMING (REF. 35)

Figure 96 shows the limiting permissible amounts of stretching and bending strain for PH 15-7 Mo, AM-350, and A-286 in the annealed condition. The curves are based on tube-bulging experiments with 0.020 and 0.063-inch-thick material. Fracture would be expected to occur if attempts were made to bulge these materials to larger strains than those indicated by the trend lines. For example, the curves indicate that a part with a stretching strain of 0.2 in./in. should not be bent to a strain of more than 0.225 in./in. for A-286, 0.260 in./in. for AM-350, or 0.265 in./in. for PH 15-7 Mo. The end-forming limits result from geometrical restraints.

When materials are to be deformed dynamically by one of the high-velocity techniques, the uniform strain for the materials under this type of beading condition must be determined. Wood and associates (Ref. 35) have found that a maximum dynamic uniform strain ϵ_u correlates with the maximum axial or stretching strain ϵ_A in tube bulging. Thus, AM-350 alloy has a maximum ϵ_u of 0.39 in./in. and ϵ_A of 0.345 in./in., A-286 has an ϵ_u of 0.35 in./in. and an ϵ_A of 0.32 in./in., and PH 15-7 Mo has an ϵ_u of 0.40 in./in. and an ϵ_A of 0.35 in./in. The ϵ_A values can then be used in Figure 96 with the bending strain.

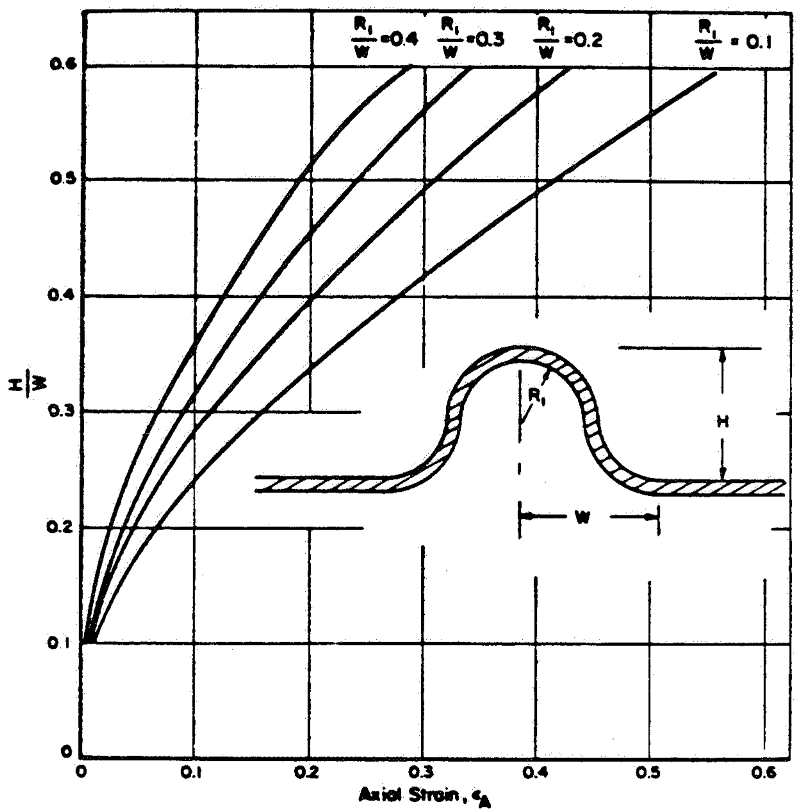


FIGURE 95. H/W VERSUS AXIAL STRAIN ϵ_A FOR VARIOUS VALUES OF R_1/W (REF. 35)

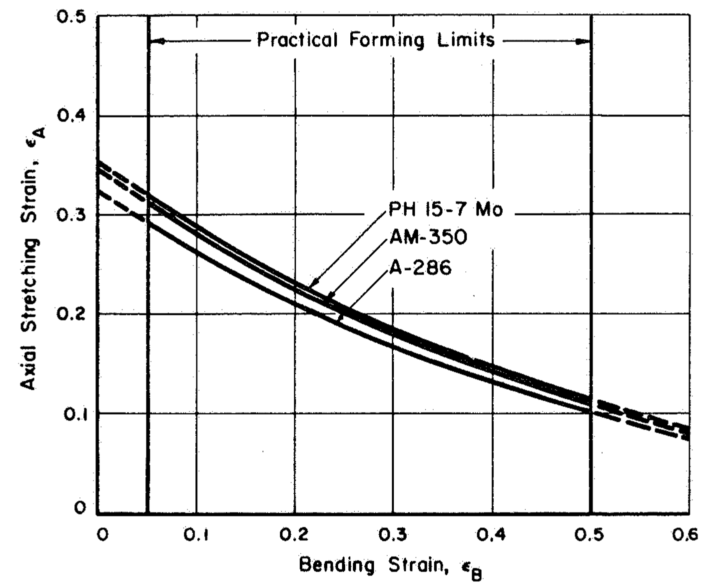


FIGURE 96. BENDING AND STRETCHING LIMITS FOR BULGE FORMING PH 15-7 MO, AM 350, AND A-286 TUBING (REF. 35)

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 that 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 discusses two types of secondary rolling operations used to change the shape of sheet or strip metal. 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 first process, roll forming, usually refers to a continuous process performed progressively by a series of contoured rolls in a special machine. With equipment of this kind (Figure 97), which can operate at speeds to 300 rpm, 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. The process is best suited to shapes made in large quantities.

Similar products can be made by drawbench forming. This technique involves pulling the strip through a series of heads or stands containing undriven, or idling, rolls similar to a Turks head. Such methods have been used to produce limited quantities of square pipe and other shapes from the precipitation-hardenable stainless

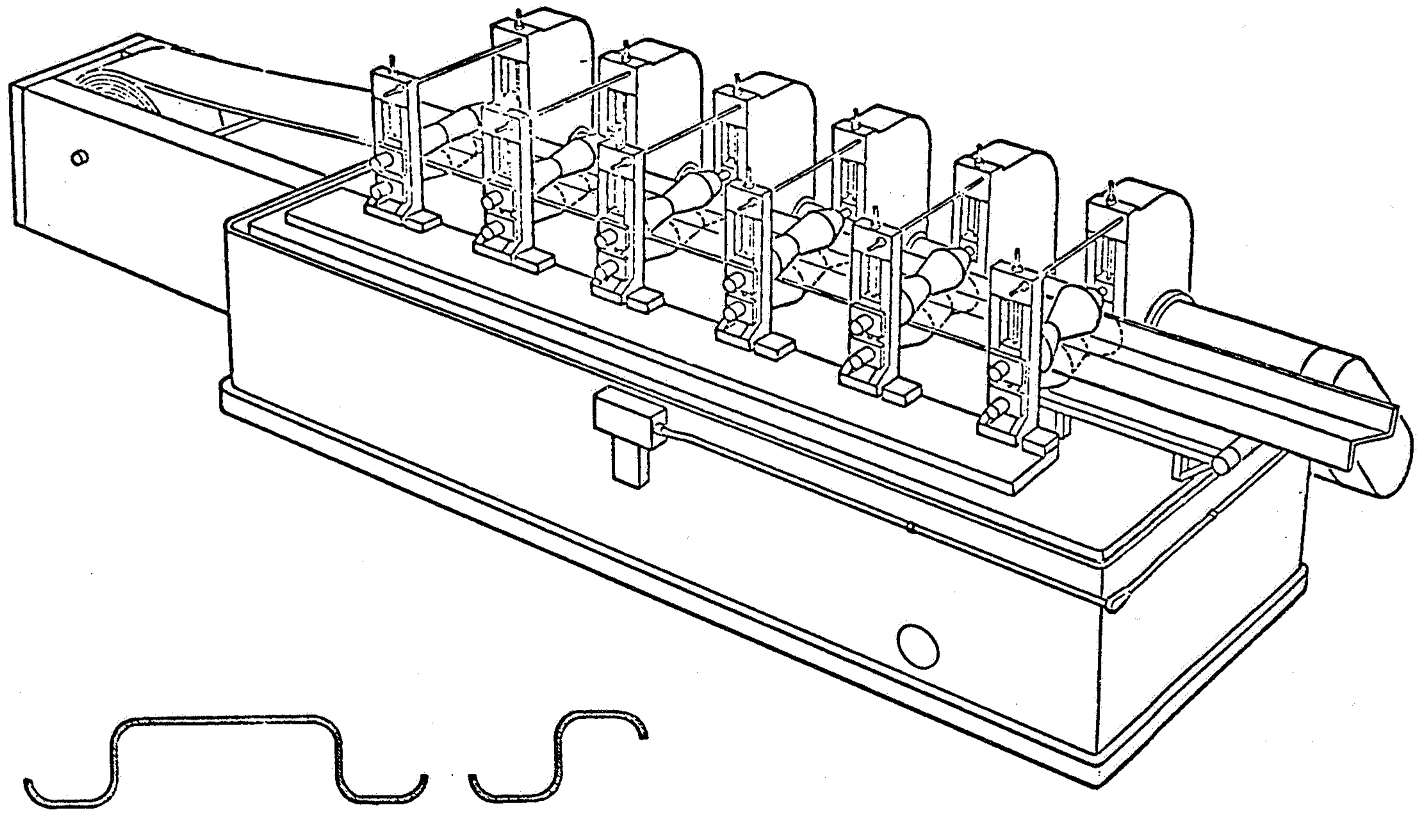


FIGURE 97. SCHEMATIC DRAWING OF ROLL-FORMING MACHINE

Courtesy of North American Aviation, Inc., Los Angeles, California.

steels. Both methods, roll forming and drawbench forming, are used to form the precipitation-hardenable stainless steels into structural hat sections, angles, tee sections, and channels. Normally these operations are performed at room temperature. Parts formed on drawbenches sometimes show excessive twisting and bowing and generally require subsequent contour stretching.

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 30 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 roll-forming machine is shown in Figure 97. The strip enters from the left, passes through the series of six rolls, and emerges from the machine at the right side as a rolled shape. Sometimes auxiliary equipment for cutting the roll-formed shape to length or for welding and straightening roll-formed tubing is added to complete the production line. Figure 98 is a sketch that shows the various stages of bending that were used to produce a completed stainless steel shape by roll forming (Ref. 91). In all, 20 roll-forming stages were required.

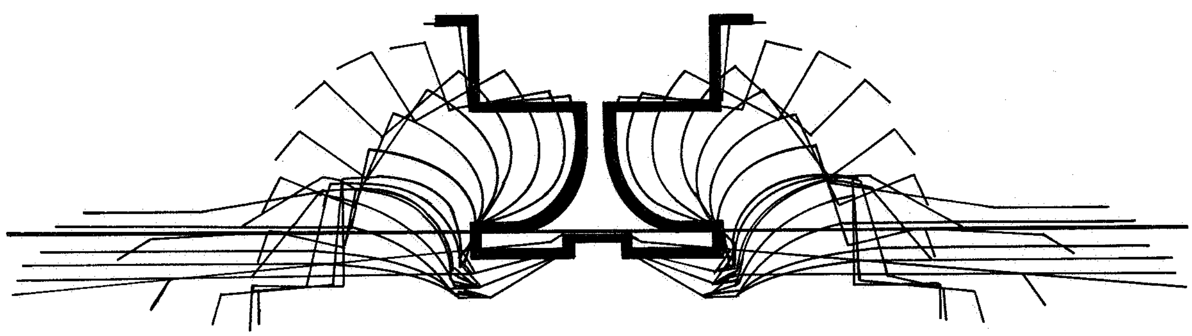


FIGURE 98. A COMPLEX SHAPE MADE FROM STAINLESS STEEL BY ROLL FORMING ON A 20-STATION MACHINE (REF. 91)

Intermediate forming shapes are shown.

Roll forming has many advantages over other methods. For example, parts made by roll forming have lower internal stresses than similar parts produced by impact or brake forming. Sometimes parts can be bent to a radius 1 T less than the minimum bend radius in brake forming. Since roll forming is a high-speed, fast-production process, man-hour savings may be substantial compared with brake-forming and other competitive forming methods.

Equipment. Equipment for roll forming is available from a number of manufacturers in a range of sizes and capacities. Table XXXIX gives comparative data on roll-forming machines produced by one manufacturer. The physical meaning of the dimensions used in this table is illustrated by Figure 99. The machines

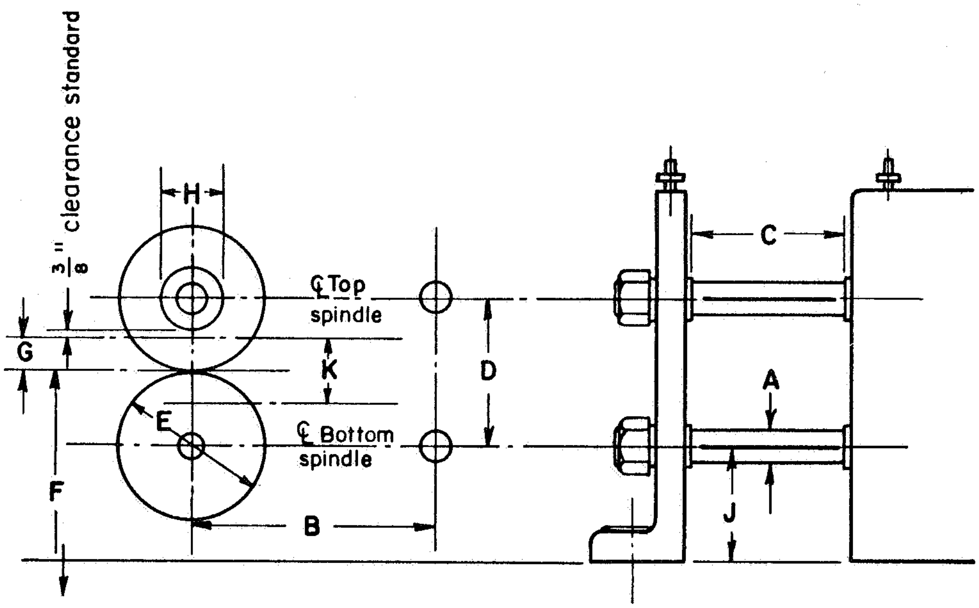


FIGURE 99. SKETCH SHOWING DIMENSIONS IN ROLL-FORMING STAND MENTIONED IN TABLE XXXIX

Courtesy of Tishkin Products Company, Detroit, Michigan.

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 stands. By running machines in tandem, as many as 50

TABLE XXXIX. COMPARATIVE CHART OF CAPACITIES OF VARIOUS ROLL-FORMING MACHINES PRODUCED BY ONE MANUFACTURER[(a)]

Reference to Figure 99		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, Detroit 37, Michigan.

stations have been used (Ref. 91). Relatively simple bending contours can be accomplished by using six or less rolls. Equipment manufacturers should be consulted on equipment requirements for specific applications.

Tooling. The rolls used in roll-forming equipment may be made from a variety of materials. Case-hardened steel rolls are normally used (Ref. 92); oil-hardened tool steels also may be used. For high-production applications where long-wearing characteristics are desirable, rolls of steels containing about 1 to 2.25 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 with only the working surfaces made of hardened tool steel are used. They are especially suitable for wide rolls with shallow contours. In other applications where severe forming is involved, rolls are sometimes faced with a 1/8-inch-thick overlay of bronze to reduce "pickup" (Ref. 92).

Lubricants. Lubricants are nearly always used for roll forming the precipitation-hardenable stainless steels. Since the forming is generally carried out at room temperature, viscous fluids such as SAE 60 oil or its equivalent function both as lubricants and coolants. These lubricants should be free of chlorine. However, the exact composition of the roll-forming lubricants are proprietary. The lubricant may be applied by passing the strip between wipers before it enters the first set of rolls, or the lubricant may be piped to the rolls and allowed to flow on the strip.

Material Preparation. The general precautions given in the section on blank preparation should be observed. The precipitation-hardenable stainless steels generally are not as sensitive to the presence of grinding marks and scratches parallel to the length of the strip as are the titanium-, nickel-, and cobalt-base alloys.

Variations in the thickness of the metal strip results in dimensional inaccuracy of roll-formed parts. Improvements in thickness-shape control by the metal rolling mills have minimized this problem.

Roll-Forming Procedures. Shapes such as channels, hat sections, and tubing are being produced routinely from the precipitation-hardenable stainless steels. Procedures used for the regular grades of stainless steel are used, with modifications, for roll forming the precipitation-hardenable grades. Small-diameter, welded aircraft tubing is commercially available in a variety of sizes up to 1-1/8-inch diameter in Grades AM-350, PH 15-7 Mo, and 17-7 PH. Such materials are roll formed in the annealed condition and welded as an additional step in the continuous production line by equipment such as is shown in Figure 100. The 12-stand roll former at the right produces tube of the desired size from strip that is then automatically welded, trimmed, sized, straightened, and cut off. The number of rolls used for roll forming depends on the strength and work-hardening rate of the particular alloy involved. The critical step that limits the production of tubing in many cases is the welding operation since the roll-forming equipment can produce tubing for welding speeds up to about 200 feet per minute. Generally automatic welders have not yet achieved such speeds.

The limiting bend radius of the material is an important parameter in determining the number of rolls that must be used in forming a particular shape. Such data coupled with experience gained in working with similar materials enable the successful production of shapes by roll forming of strip stock.

Post-Forming Treatments. After forming, sections are sheared to desired lengths and the forming lubricant is removed. This may be done by rinsing or wiping with solvents, vapor blasting individual pieces, or by using a suitable cleaning-bath or pickling cycle. Hydrogen pickup during pickling normally is not a severe problem with the stainless steels. Inspection for cracks is done by the fluorescent die-penetrant method and/or visually under a low-power microscope.

Roll Bending. Roll bending is an economical process for producing single-contoured skins from sheet materials. 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. The channels may initially have been produced by roll forming, on a press brake, 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. Curved angle sections may be produced by bending channel sections to the desired contour and then splitting the channels to form the angle sections.

Figure 101 is a sketch of a typical setup for the linear roll bending of channels (Ref. 44). The upper roll in the pyramid-type roll configuration can be adjusted vertically as shown in the figure

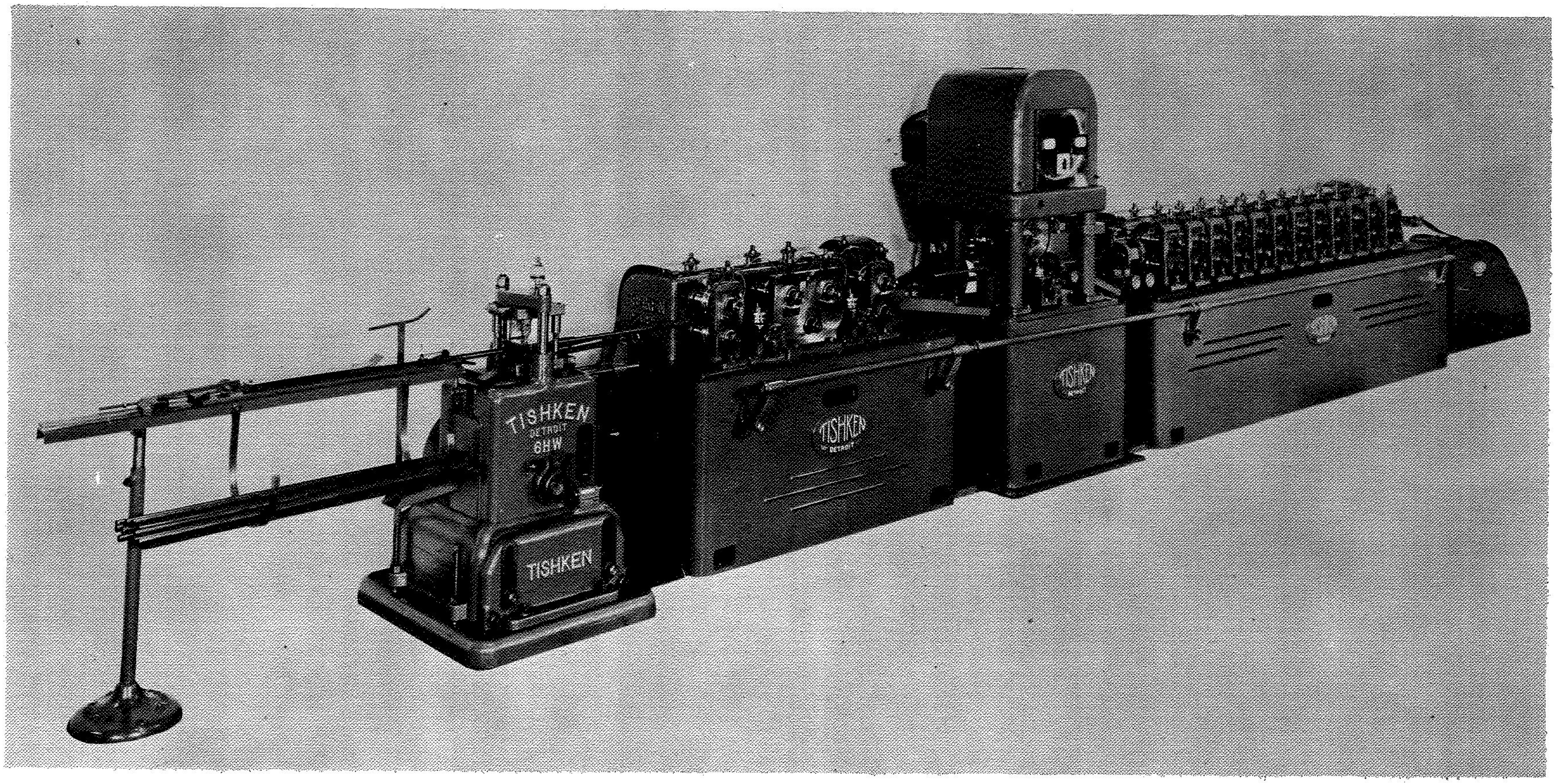


FIGURE 100. PRODUCTION LINE FOR PRODUCING WELDED TUBING

Courtesy of Tishkin Products Company, Detroit, Michigan.

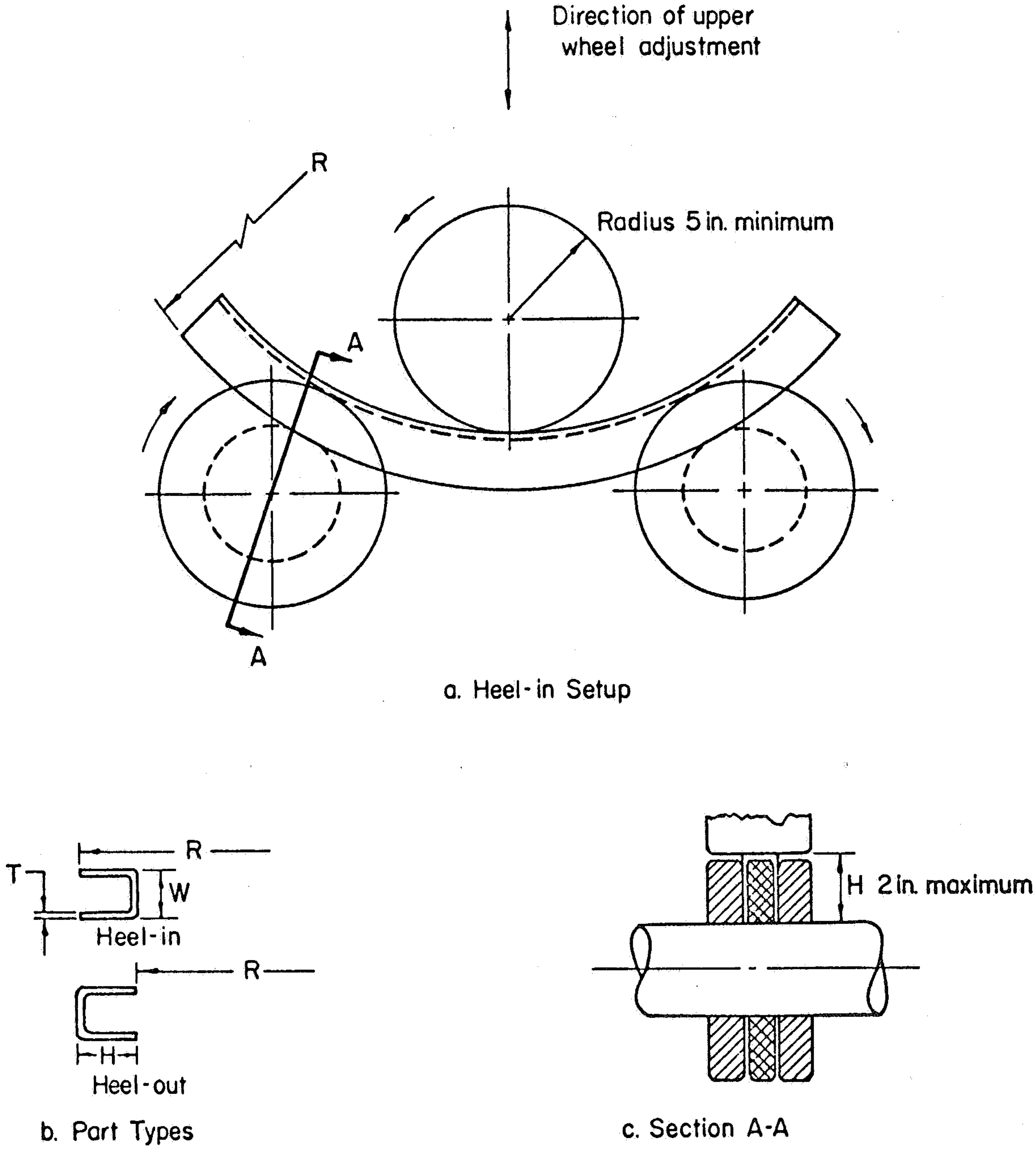


FIGURE 101. PART TYPES AND SETUP FOR ROLL BENDING (REF. 44)

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.

Roll bending is a process that depends greatly on 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. 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 102 shows a vertical roll bender of the type used by Wood, et al. (Ref. 44) 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 91. 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 103 for changing the bend radius.

Table XL 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.

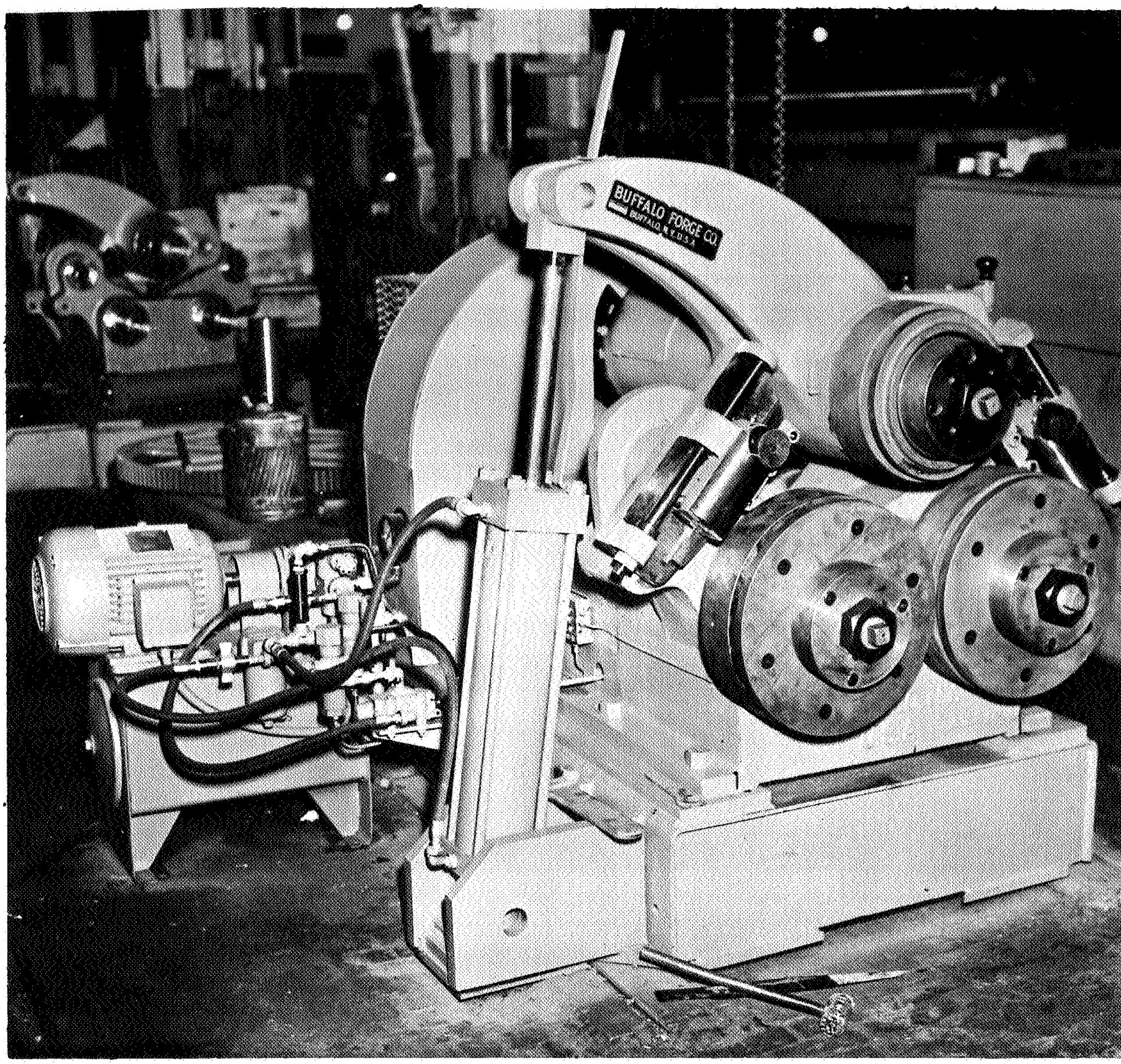


FIGURE 102. THREE-ROLL PYRAMID-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

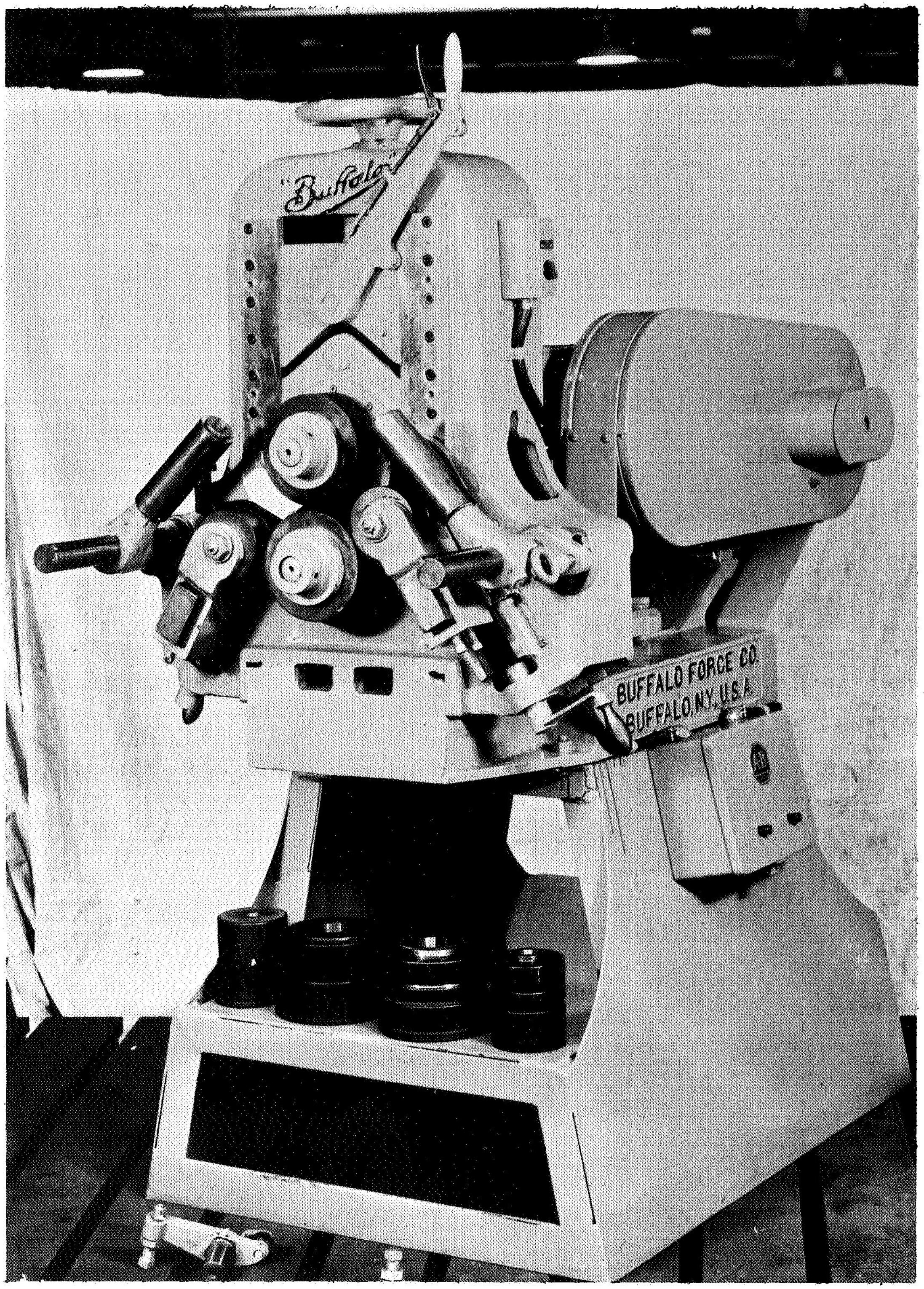


FIGURE 103. CONFIGURATION OF ROLLS IN AIRCRAFT PINCH-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

TABLE XL. PERTINENT DATA ON ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[a]

Type Model No.	Vertical Bending 1/2	Vertical Bending 1	Vertical Bending 2	Vertical Pinch 00	Vertical Pinch 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 104 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 used to bend such aircraft parts as wing-leading edges, doors, aircraft skins, etc. Table XLI gives data on the sizes and other characteristics of sheet-bending rolls produced by one manufacturer. One characteristic of this type of equipment is that the diameter of the rolls is rather small, frequently 1-1/2 to 2 inches. The rolls are backed up, as can be seen in Figure 104, 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 XLII gives data on the sizes and other pertinent characteristics of these slip-roll-bending machines. In general, power ratings of bend rolls used for precipitation-hardenable stainless steels should be 50 to 60 per cent greater than those required for carbon steel (Ref. 57).

Tooling. Rolls for linear contour bending of shapes have been made from a variety of materials. Sometimes the rolls are made from hard rubber or beryllium copper for use at room temperature with relatively soft materials or for short runs with harder materials. Rolls on roll-bending machines are commonly made from tool steels. These may range from Grade 0-2 for room-temperature application to Grades H-11 and H-13 for elevated-temperature use. Rolls for the sheet-roll-bending machines, such as are shown in Figure 104, may also be made of low-alloy steels such as Grade 4130 with flame or case-hardened surfaces. The surfaces usually have a hardness of about 50 R_C.

Lubricants. Lubricants are almost always required for roll forming the precipitation-hardenable stainless steels. For roll forming at room temperature, fluids such as SAE 60 oil, castor oil, lard oil, sperm oil, and mixtures of mineral oil and water function both as lubricants and coolants. When the forming forces are high,

TABLE XLI. 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	7-1/3
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	16-1/12	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
2410-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., Buffalo, New York.

TABLE XLII. 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		Diameter of Rolls, in.	Speed of Rolls, fpm	Approximate Range of Shipping Weight, pounds	
			Longest, in.	Shortest, in.			Longest	Shortest
1-1/2-1	2	24 to 30 gage	20	16	1 or 1-1/2	(b)	85	40
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	1,960
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, Buffalo, New York.
(b) Hand operated.
(c) Available also as hand-operated machines.

FIGURE 104. PHOTOGRAPH SHOWING THREE SIZES OF SHEET ROLL-BENDING EQUIPMENT RANGING IN CAPACITY FROM 4 TO 15 FEET

Courtesy of North American Aviation, Inc., Columbus, Ohio.

lubricants with higher viscosities give best results. The exact compositions of lubricants used are proprietary. Solid lubricants are often used for roll forming at elevated temperatures. The lubricants may be applied by spraying, dipping, brushing, or wiping.

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. 44). The principal parameters, shown in Figure 105 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 105.

The equation for the inflection line is

$$\frac{H}{R} = 0.0146 \left(\frac{H}{T} \right)^{1/2} . \tag{24}$$

The equation for the elastic buckling line below the inflection line

$$\frac{H}{R} = \frac{E_t}{S_{ty}} \left[\frac{0.025}{\left(\frac{H}{T} \right)^2} \right] . \tag{25}$$

The equation for the buckling line above the inflection line is:

$$\frac{H}{T} = \left[1.713 \frac{E_t}{S_{ty}} \right]^{2/5} . \tag{26}$$

Similar equations were developed for the linear roll bending of heel-out channels.

The equation for the inflection line is

$$\frac{H}{R} = 0.0209 \left(\frac{H}{T} \right)^{1/2} . \tag{27}$$

The equation for elastic buckling below the inflection line is

$$\frac{H}{R} = \frac{E_c}{S_{cy}} \left[\frac{0.02116}{\left(\frac{H}{T} \right)^2} \right] . \tag{28}$$

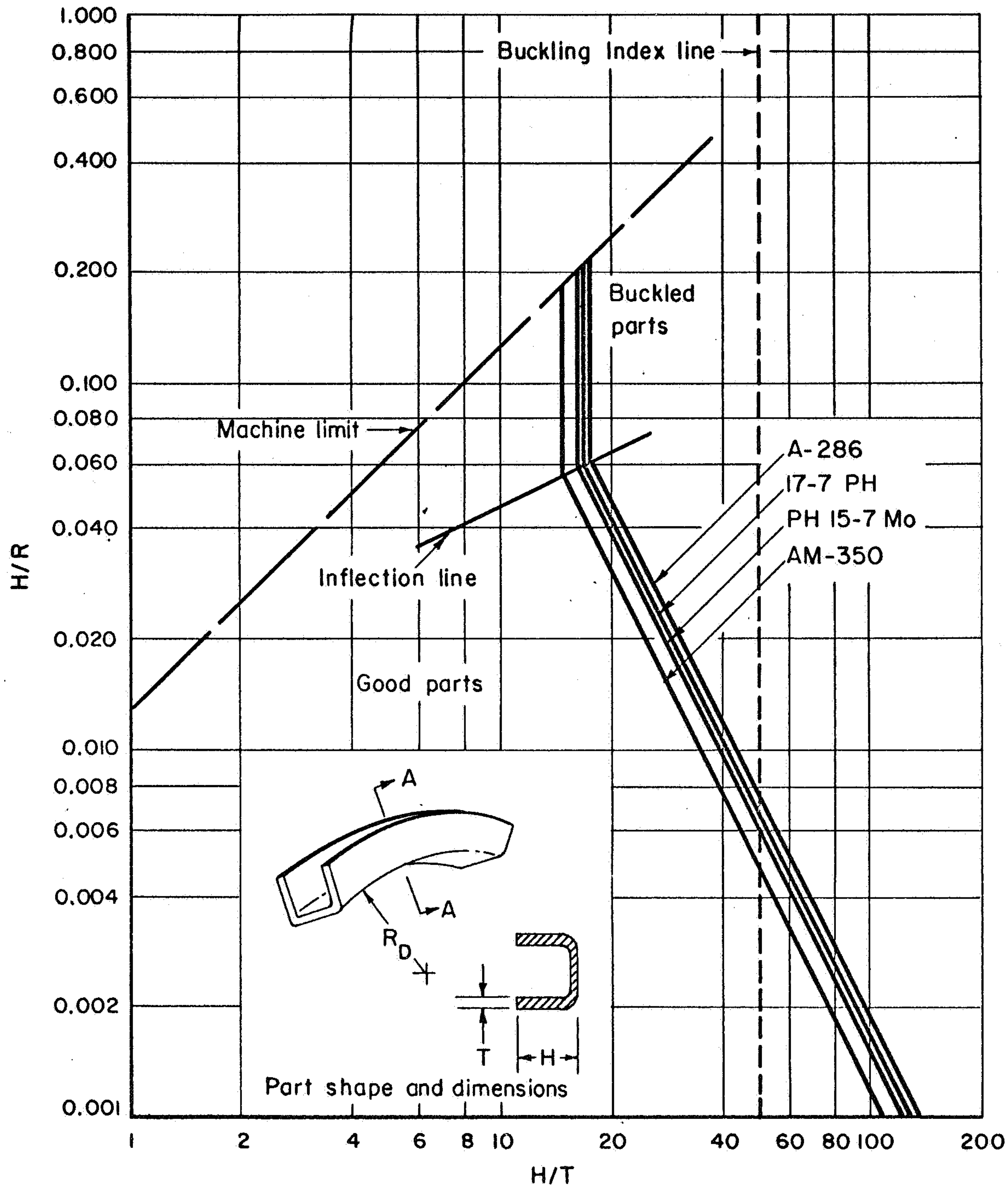


FIGURE 105. LINEAR ROLL-BENDING LIMITS FOR PRECIPITATION-HARDENABLE STAINLESS STEELS (HEEL-IN CHANNELS) (REF. 44)

The equation for buckling above the inflection line is

$$\frac{H}{T} = \left[1.01 \frac{E_c}{S_{cy}} \right]^{2/5} . \tag{29}$$

The formability curve for heel-out channels is shown in Figure 106.

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. Typical room-temperature values of tensile yield strength and elastic modulus found in the literature are listed in Table XLIII. These values may be used to calculate the E/S_{ty} and E/S_{cy} ratios required to solve Equations (25), (26), (28), and (29). It is here assumed that the compressive yield strengths, S_{cy}, required for Equations (28) and (29), will not differ significantly from the tensile yield strengths given so that the values may be used for both cases.

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 temperatures. 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.

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

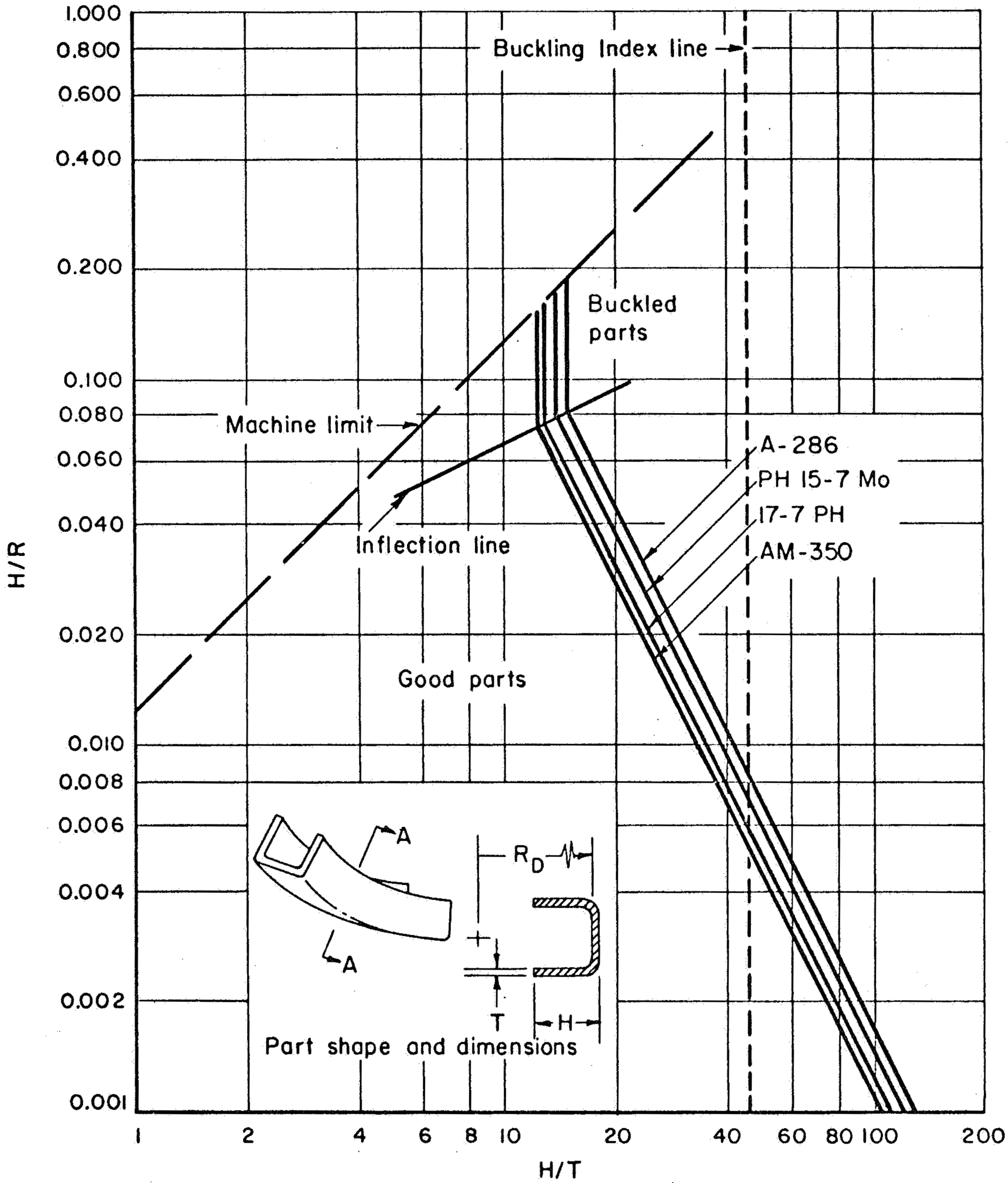


FIGURE 106. LINEAR ROLL-BENDING LIMITS FOR PRECIPITATION-HARDENABLE STAINLESS STEELS (HEEL-OUT CHANNELS) (REF. 44)

TABLE XLIII. TYPICAL ROOM-TEMPERATURE VALUES OF MODULUS OF ELASTICITY AND TENSILE YIELD STRENGTH FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS

Alloy	Condition	Elastic Modulus, E x 10^6 psi	Tensile Yield Strength, S_{ty}, 1000 psi	E/S_{ty}	Reference
		Martensitic Types			
17-4 PH[a]	Annealed	28.5	110	259	93
17-4 PH[a]	Annealed	28.5	110[b]	259	93
Stainless W	Solution treated	30.7	95	323	47
ALMAR 362	Annealed	28.5	105-115	271-248	29
		Austenitic Types			
A-286	Solution annealed	29.1	36	808	93
		Semiaustenitic Types			
17-7 PH	Solution annealed	29.0	40	725	93
PH 15-7 Mo	Solution annealed	28.0	55	509	93
AM-350	Solution treated	29.4	60	490	32
AM-355[a]	Solution treated	29.3	56-60[c]	523-489	32

(a) Normally not available as sheet or strip.
(b) Compressive yield strength.
(c) Properties for plate.

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 105 and 106 give limits for the linear roll bending of heel-in and heel-out channels, respectively, for four precipitation-hardenable stainless steel alloys, as treated by Wood, et al. (Ref. 44). All four of the alloys show similar behavior. Of the alloys, the A-286 alloy is the easiest to form by linear roll binding, whereas the AM-350 alloy is the most difficult to form.

TABLE XLIV. LINEAR ROLL-BUCKLING LIMITS (REF. 34)

Alloy	Critical Ratio, R_D/T		Buckling Limits, H/T, for H/R Ratios of 0.001	0.005	0.010	0.020	0.030	0.040	0.050	0.060
			Heel-In Channels							
17-7 PH	60	H/T	125	57	40	29	23	20	18	--
		R_D/T	124,815	11,343	3,960	1,421	744	480	342	--
AM-350	60	H/T	107	48	34	24	20	17	15	--
		R_D/T	106,893	9,552	3,366	1,176	647	408	284	--
PH 15-7 Mo	60	H/T	121	54	39	27	22	19	17	--
		R_D/T	120,879	10,746	3,861	1,323	712	456	323	--
A-286	60	H/T	133	60	43	30	25	22	19	18
		R_D/T	132,867	11,940	4,257	1,470	809	528	361	282
			Heel-Out Channels							
17-7 PH	86	H/T	110	50	36	25	20	18	16	15
		R_D/T	110,110	10,050	3,636	1,275	687	468	336	275
AM-350	86	H/T	105	48	34	28	20	17	15	14
		R_D/T	105,105	9,648	3,434	1,428	687	442	315	247
PH 15-7 Mo	86	H/T	120	54	39	27	22	19	17	16
		R_D/T	120,120	10,580	3,939	1,377	756	494	357	283
A-286	86	H/T	130	59	42	30	24	21	19	17
		R_D/T	130,130	11,859	4,242	1,530	824	546	399	300

The data in Figures 105 and 106 can also be presented in tabular form (Ref. 34). Table XLIV gives roll-forming limits for heel-in and heel-out channels. These data can be used as follows:

(1) Calculate R_D/T ratio from given dimensions

(2) Compare the R_D/T ratio with the critical R_D/T ratio given in the table

(a) If the calculated R_D/T ratio is less than the critical ratio, the part cannot be formed due to machine limitations. This is based on the capacity of a Kane-Roach three-roll machine used to determine the values in the table.

(b) If the calculated R_D/T ratio is greater than the critical R_D/T ratio in the table, interpolate the tabular R_D/T ratios and corresponding H/T values for buckling to determine the required H/T ratio. Multiply H/T by the material thickness, T, to determine the maximum flange height, H_{max}.

Example 1. Determine the maximum flange height for roll forming a channel of 0.100-inch-thick AM-350 stainless steel to a 5-inch heel-in contour radius (use Table XLIV).

R_D = 5 in., T = 0.100 in., R_D/T = 5/0.100 = 50, which is less than the critical R_D/T ratio of 60.

Therefore, it is not possible to form the part because of machine limitations.

Example 2. Determine the maximum flange height for roll forming a channel 0.025-inch-thick, PH 15-7 Mo stainless steel to a 10-inch heel-out contour radius (use Table XLIV).

R_D = 10 in., T = 0.025 in., R_D/T = 400, which is greater than the critical R_D/T ratio of 86. For R_D/T = 494, H/T = 19 and for R_D/T = 357, H/T = 17. Interpolating for R_D/T = 400, H/T = 17.63. H_{max} = H/T = 17.63 x 0.025 = 0.441 in.

Graphs similar to Figures 105 and 106 and tables similar to Table XLIV can be constructed from experimental values of E/S_{ty} and E/S_{cy} for alloys of interest.

Roll Bending of Sheet. Sheet of the precipitation-hardenable stainless steels have been contoured by rolling, but no systematic study such as that conducted by Wood, et al., for the roll bending of channels has been reported. For successful roll bending of sheet, the sheet must be relatively flat.

The roll-bending equipment for contouring sheet is rated on the bending of mild steel or an aluminum alloy. The yield strength of mild steel is about 50,000 psi and that of aluminum alloys about 73,000 psi. The precipitation-hardenable stainless steels in the annealed or solution-treated condition range in yield strength from about 36,000 to 110,000 psi. When aged after solution treating, yield strengths ranging from about 120,000 to 220,000 psi are obtained.

The capacity of a given sheet-roll-bending machine can usually be estimated on the basis of the square of the thickness of sheet being formed. Thus, if a given piece of equipment is capable of bending 1/4-inch-thick aluminum plate (73,000 psi yield), it probably would only have the capacity to bend about 0.203-inch-thick annealed 17-4 PH alloy (110,000 psi). 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 in the above example were of the same thickness, then the stronger 17-4 PH alloy sheet would have to be reduced in length proportionately.

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 107 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, varies with the head diameter, D, of the fastener, the rivet diameter, 2R, and the bend angle, α, according to the relationship (Ref. 56)

$$e = \left(\frac{D}{2R} - 1 \right) \left(1 - \cos \alpha \right) \quad . \qquad (30)$$

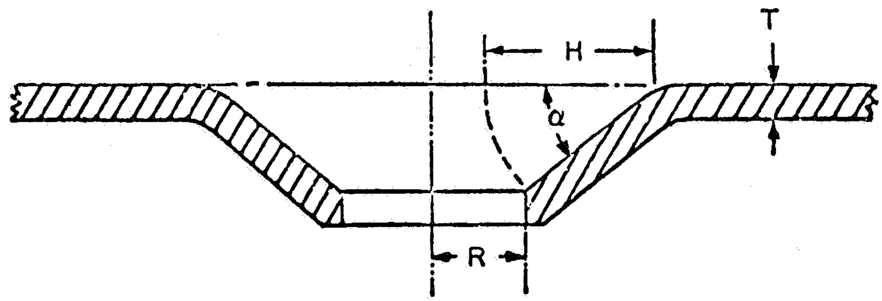


FIGURE 107. PARAMETERS FOR DIMPLING (REF. 44)

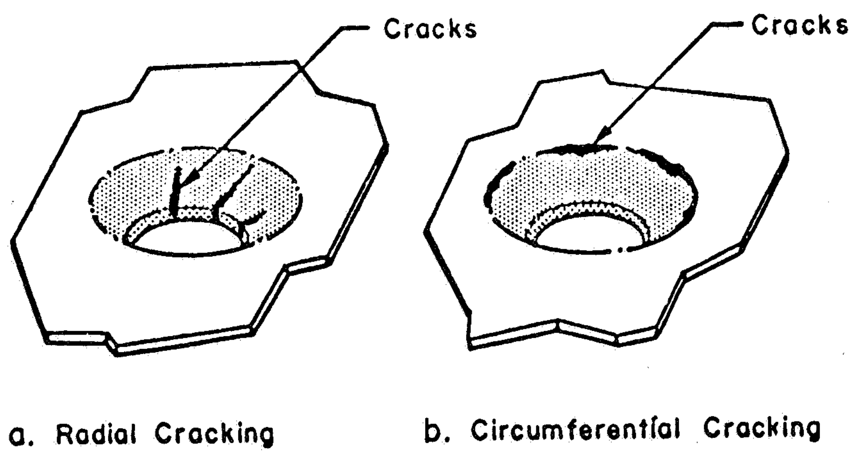


FIGURE 108. MAJOR FAILURES IN DIMPLING (REF. 34)

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 is shown in Figure 108. The latter type of failure is more prevalent in thinner sheets. Radial cracks are more common in thick stock.

The general equation developed by Wood and his associates (Ref. 44) for predicting dimpling limits from the parameters indicated in Figure 107 is

$$\frac{H}{R} = \frac{0.444(\epsilon_{2.0})^{0.253}}{1 - \cos \alpha} . \qquad (31)$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material and temperature of interest (e.g., $\epsilon_{2.0} = 0.5$ for 50 per cent elongation).

The standard dimple angle, α, in Figure 107 is 40 degrees although other angles may be used for special purposes. Dimpling requires a considerable amount of ductility and many of the precipitation-hardenable stainless steels are sufficiently ductile to be dimpled at room temperatures. Consequently, elevated temperatures may be required to dimple only some of the stronger and less ductile materials. 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 operation are indicated in Figure 109. In this process a pressure in excess of

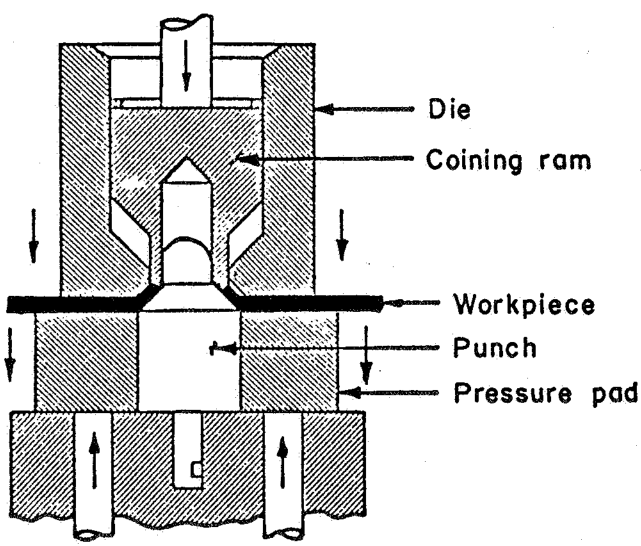


FIGURE 109. CROSS SECTION OF RAM-COIN DIMPLING (REF. 34)

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. 94):

3/32- to 1/8-inch rivets	Up to 10,000 lb
5/32-inch rivet	10,000 - 20,000 lb
3/16-inch rivet and screw	15,000 - 25,000 lb
1/4-inch rivet and screw	18,000 - 40,000 lb
5/16-inch screw	25,000 lb and up.

The capacities of four commercially available dimplers are given in Table XLV. A photograph of the Chicago Pneumatic CP 450EA Dimpling Machine Frame equipped with a hot, triple-action, ram-coin-die unit is shown in Figure 110. A competitive machine in which the dies are heated by induction coils is shown in Figure 111.

TABLE XLV. CAPACITIES AVAILABLE IN COMMERICALLY AVAILABLE DIMPLING MACHINES (REF. 94)

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

Tooling. A typical sequence of operations for dimpling is shown in Figure 112. The five positions shown for a triple-action ram-coin-dimpling machine are the approach, preform, coining, end of stroke, and retraction.

Some precipitation-hardenable stainless steels 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.

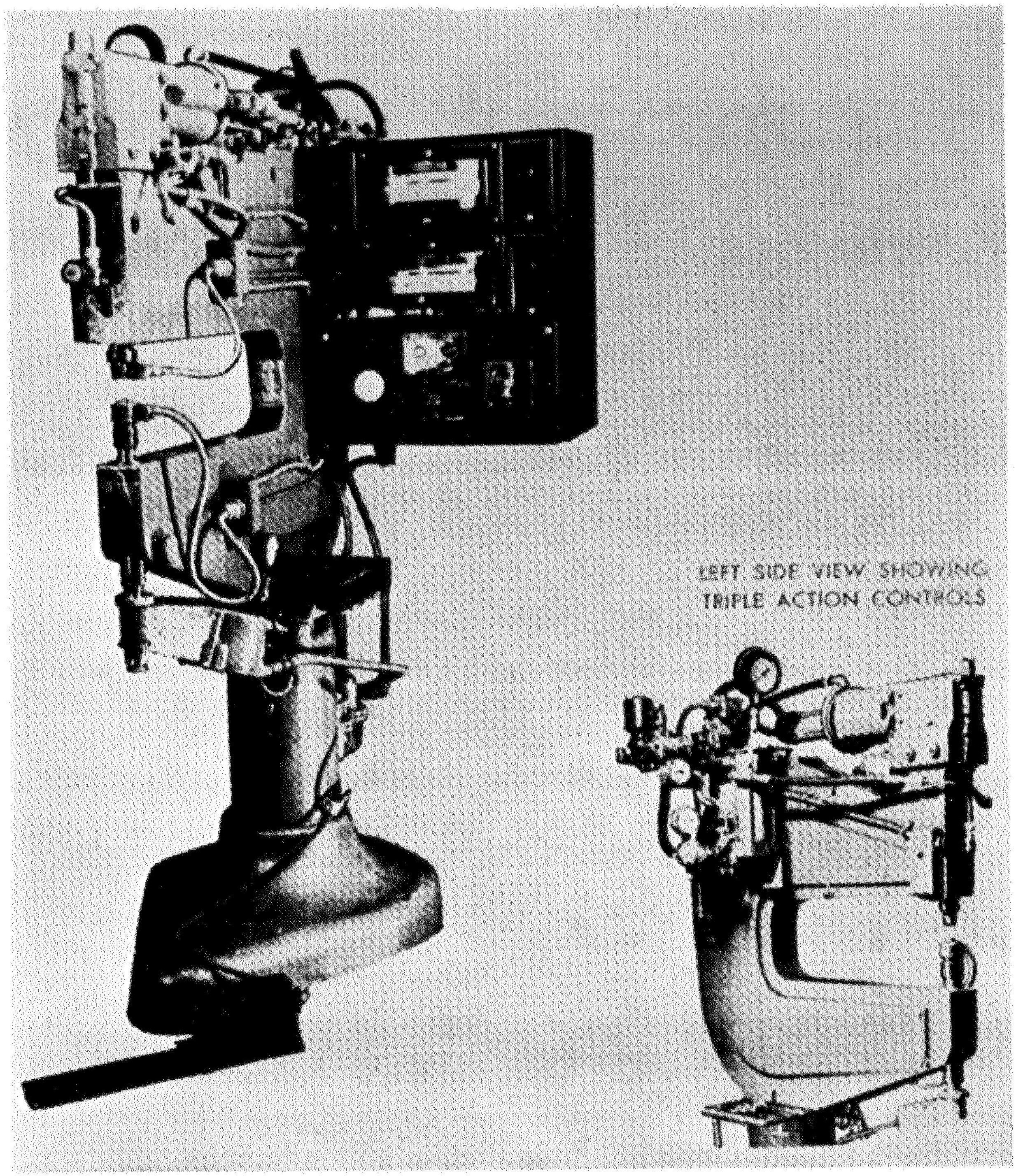


FIGURE 110. CP450EA HOT, TRIPLE-ACTION RAM-COIN DIMPLER

Fully automatic electric and pneumatic controls.

Courtesy of Zephyr Manufacturing Company, Inglewood, California.

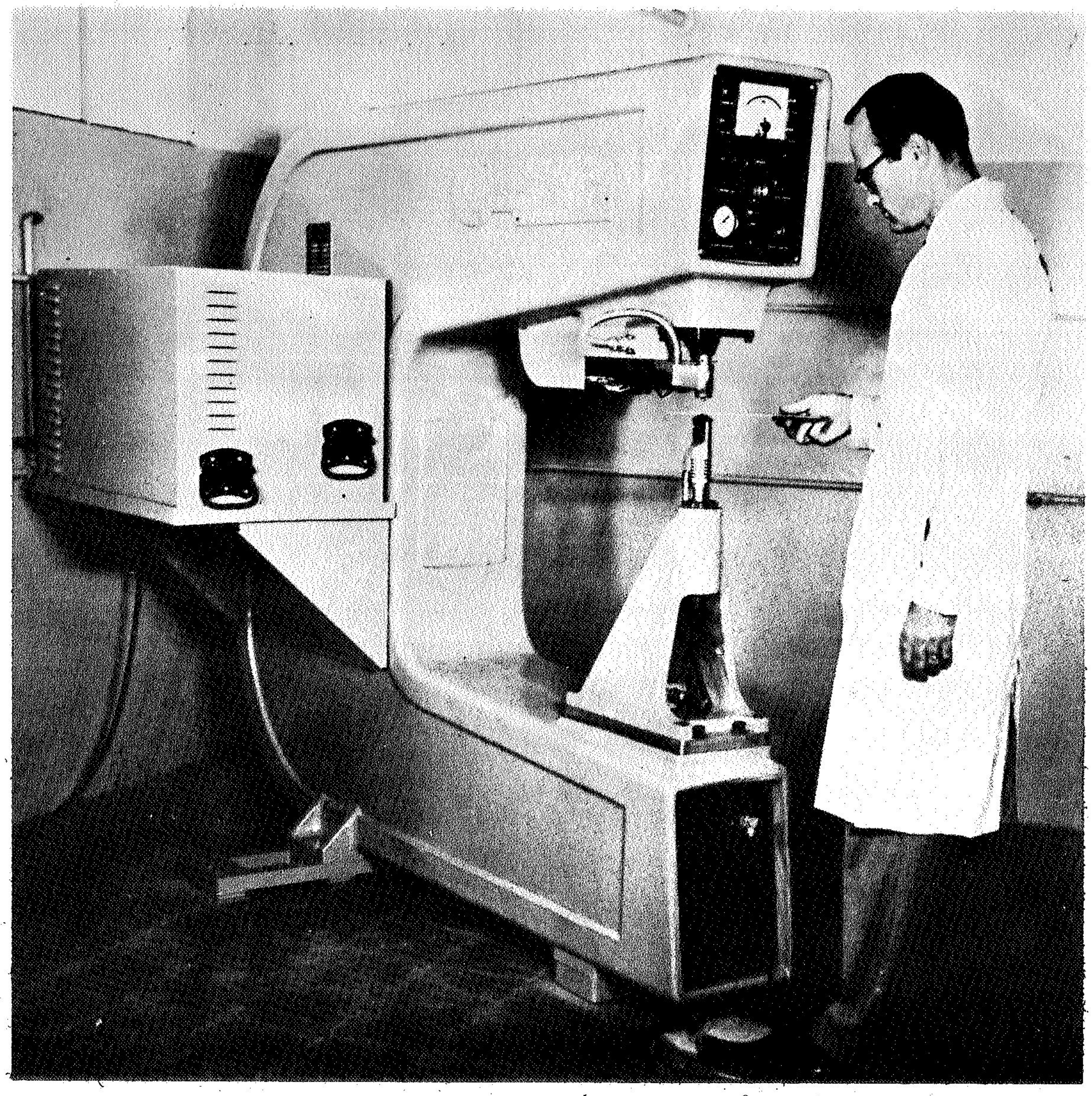


FIGURE 111. INDUCTION-COIN-DIMPLING MACHINE

Courtesy of Aircraft Tools, Inc.,
El Segundo, California.

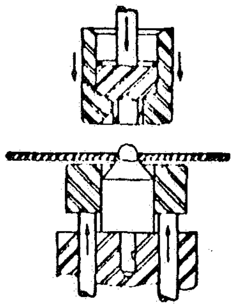
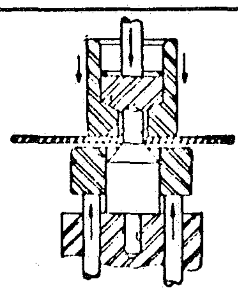
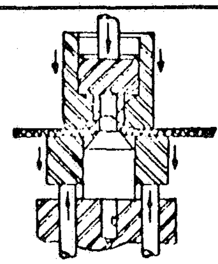
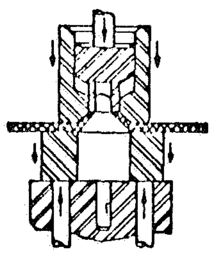
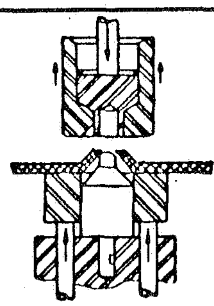
Position 1		**a. Approach** Sheet is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading force on coining ram is at preselected value
Position 2		**b. Preform** Die assembly has just contacted work, and *timed heating stage* is beginning; controlled 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 con*formation 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 112. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING

Courtesy of Convair, General Dynamics Corporation, San Diego, California.

Elevated-temperature dimpling is usually done with heated dies. The sheet to be dimpled may be heated by contact with the heated dies, as shown in Figure 113. 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 114. The tooling consists of a solid die and a two-piece punch assembly. The die is made of high-temperature resistant steel. This punch cone is a composite of Kentanium and steel base. Sometimes punches also are made of tungsten carbide. The pad is a special high-alumina composition. 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 direction of current flow from the punch to the die used to heat the sheet metal to the dimpling temperature is shown in Figure 114. The dies also may be heated by induction, and such systems have been produced by one or more suppliers of dimpling dies (see Figure 111).

Material Preparation for Dimpling. Sheet Quality. Factors that permit maximum formability in dimpling are consistent yield strengths from sheet to sheet, minimum thickness and flatness variations between sheets, and high-quality surface finishes.

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.

TABLE XLVI. RECOMMENDED PILOT-HOLE SIZES FOR RESISTANCE DIMPLING (REF. 96)

Fastener Diameter[a], in.	Drill Size, No. (inch)
3/32	54 (0.055)
1/8	50 (0.070)
5/32 or No. 8	40 (0.098)
3/16 or No. 10	30 (0.128)
1/4	10 (0.193)
5/16	1/4 inch (0.250)

(a) Fastener diameter, not head configuration, determines the hole size.

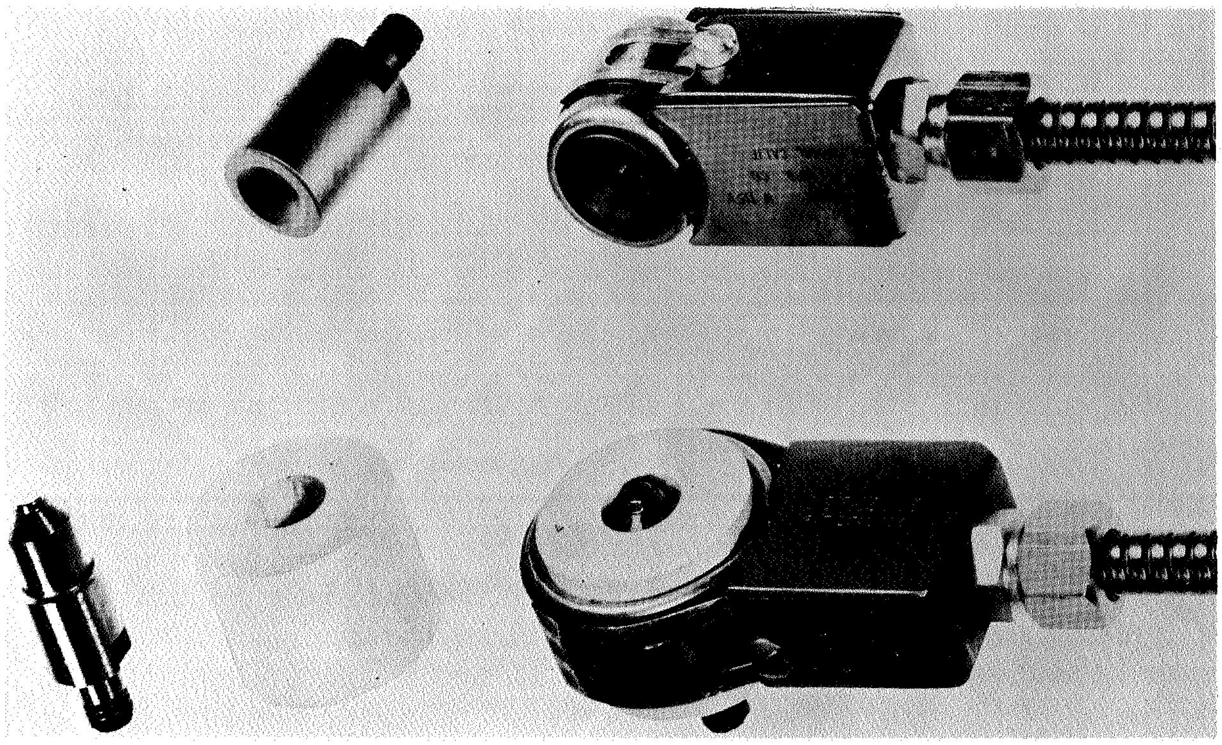


FIGURE 113. RESISTANCE-HEATED DIMPLING TOOLING

Courtesy of Zephyr Manufacturing Company, Inglewood, California.

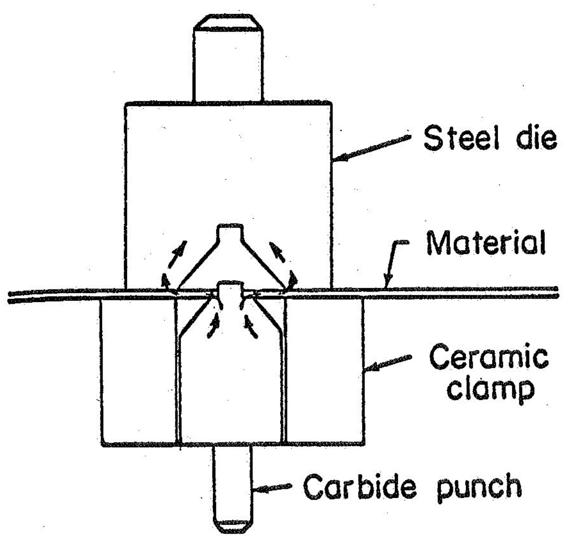


FIGURE 114. CURRENT FLOW FROM PUNCH TO DIE USED TO HEAT SHEET MATERIAL TO THE DIMPLING TEMPERATURE BY RESISTANCE (REF. 95)

Ceramic clamp heated between 500 and 600 F by a strap resistance heater so that the ceramic does not act as a chill ring.

Pilot-hole sizes should conform to specifications applicable to aluminum alloys. The pilot holes should be drilled with suitable stub drills to produce holes with straight sides. Such holes are satisfactory for dimpling. Table XLVI lists pilot-hole sizes recommended for fasteners with several diameters.

Deburring Drilled Holes. Care must be taken in deburring holes for dimpling. Only the material turned up by the drill at the edges of the hole should be removed. Hand deburring with a countersink cutter has proven satisfactory (Ref. 94). Power-driven countersinks that chatter are not satisfactory since chatter marks are potential sources of radial cracks.

A power-driven microstop tool with a special facing cutter* has been used successfully in production (Ref. 94). 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 leaves a smooth hole edge.

Lubricants. Dimpling is done dry at both room and elevated temperatures.

Calculated Dimpling Limits. The general theoretical predictability equation (Ref. 44) for dimpling based on the parameters indicated in Figure 107 is

$$\frac{H}{R} = \frac{(0.444)\,(\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} \quad .$$

The value of $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material at the temperature of interest. Table XLVII gives typical elongation values for a number of precipitation-hardenable stainless steels in several conditions of heat treatment. Greatest ductility in the aged condition is found in the A-286 alloy, which is easier to dimple than some of the other alloys.

Figure 115 shows the relationship between ductility and temperature for the mill- or full-annealed AM-350, A-286, and PH 15-7 Mo alloys (Ref. 35). At room temperature, the A-286 alloy is slightly more ductile than the other two alloys. Both AM-350 and the PH 15-7 Mo alloys exhibit slightly better ductility up to 500 F than room

*Tool Number ZP339, The Zephyr Manufacturing Company, Inglewood, California.

TABLE XLVII. TYPICAL ROOM-TEMPERATURE VALUES OF ELONGATION IN A 2-INCH GAGE LENGTH FOR SELECTED CONDITIONS OF PRECIPITATION-HARDENABLE STAINLESS STEELS

Alloy	Condition	Per Cent Elongation in 2-Inch Gage Length	Reference
	Martensitic Types		
17-4 PH[a]	A (solution annealed)	10.0	93
	H 900	14.0	93
	H 925	14.0	93
	H 1025	15.0	93
	H 1075	16.0	93
	H 1150	19.0	93
Stainless W	Solution annealed (1850 to 1950 F)	3.0-5.0	47
	Solution annealed and aged (950 F)	3.0-5.0	47
	Solution annealed and aged (1000 F)	3.0-5.0	47
	Solution annealed and aged (1050 F)	4.0-7.0	47
	Solution annealed (1850 to 1950 F) and solution annealed at 1300 F	5.0-7.0	47
	Solution annealed (1850 to 1950 F), solution annealed (1300 F), and aged (950 F)	5.0-7.0	47
	Solution annealed (1850 to 1950 F), solution annealed (1300 F) and aged (1000 F)	5.0-7.0	47
	Solution annealed (1850 to 1950 F), solution annealed (1300 F) and aged (1050 F)	5.0-7.0	47
Almar 362	Solution annealed	10.0-20.0	29
	Solution annealed and aged (1000 F)	15.0-17.0	29
	Solution annealed and aged (900 F)	13.0	29
	Solution annealed and aged (1050 F)	18.0	29
	Semiaustenitic Types		
17-7 PH	A	35.0	93
	T	9.0	93
	TH 1050	9.0	93
	C	5.0	93
	CH 900	2.0	93
	A 1750	19.0	93
	R 100	9.0	93
	RH 950	6.0	93
PH 15-7 Mo	A	30.0	93
	T	7.0	93
	TH 1050	7.0	93
	C	5.0	93
	CH 900	2.0	93
	A 1750	12.0	93
	R 100	7.0	93
	RH 950	6.0	93
AM-350	H (solution treated - 1900 to 1975)	40.0	32
	SCT (850 F)	13.5	32
	SCT (1000 F)	15.0	32
	L plus DA (1375 and 850 F)	13.5	32
	H plus DA (1375 and 850 F)	12.5	32
AM-355[a, b]	H (solution treated 1950 F)	26.0	32
	SCT (850 F)	14.0	32
	SCT (1000 F)	17.0	32
	Austenitic Types		
A-286	A (solution annealed at mill)	48.0	93
	STA (solution annealed and aged at 1325 F)	24.0	93

(a) Normally not supplied as sheet or strip.
(b) Value given is for plate.

temperature and then decrease in ductility to 1000 F. The PH 15-7 Mo alloy continues to decrease in ductility, but the AM-350 alloy increases in ductility above 1000 F having an elongation of 50 per cent at 2000 F. The ductility of the A-286 alloy decreases with increasing temperature up to 1500 F, then improves as the temperature is raised in the range from 1500 to 2000 F. The elongation value at 2000 F was 40 per cent.

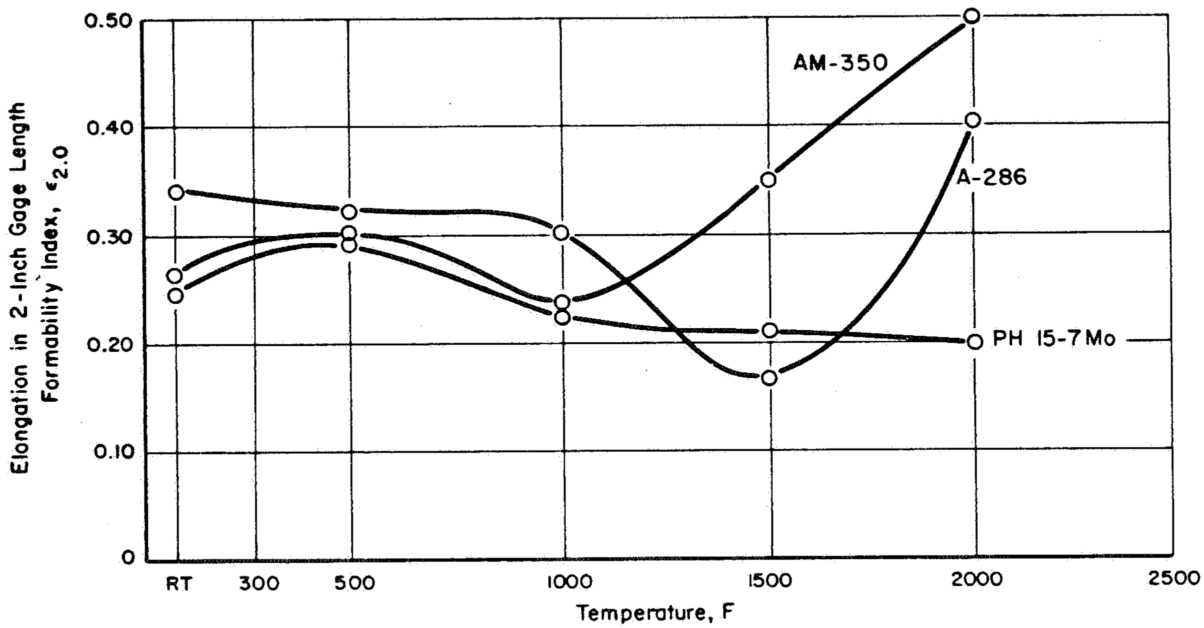


FIGURE 115. RELATIONSHIP BETWEEN ELONGATION AND TEMPERATURE AS DETERMINED IN TENSILE TESTS ON FULLY ANNEALED ALLOYS (REF. 35)

The slight increase in ductility from room temperature to 500 F, indicated in Figure 115 for both AM-350 and PH 15-7 Mo stainless steels (12 per cent), does not justify dimpling at 500 F unless the alloys cannot be successfully dimpled at room temperature. Dimpling at high temperatures in the range of 2000 F is beset by problems in tooling.

Figure 116 and Table XLVIII show the relationships between the H/R ratio and the bend angle as determined by Wood, et al. (Refs. 34, 35) for four precipitation-hardenable stainless steels. As expected, the alloys are easier to dimple as solution treated than when aged. These data predict that good parts will be formed for values

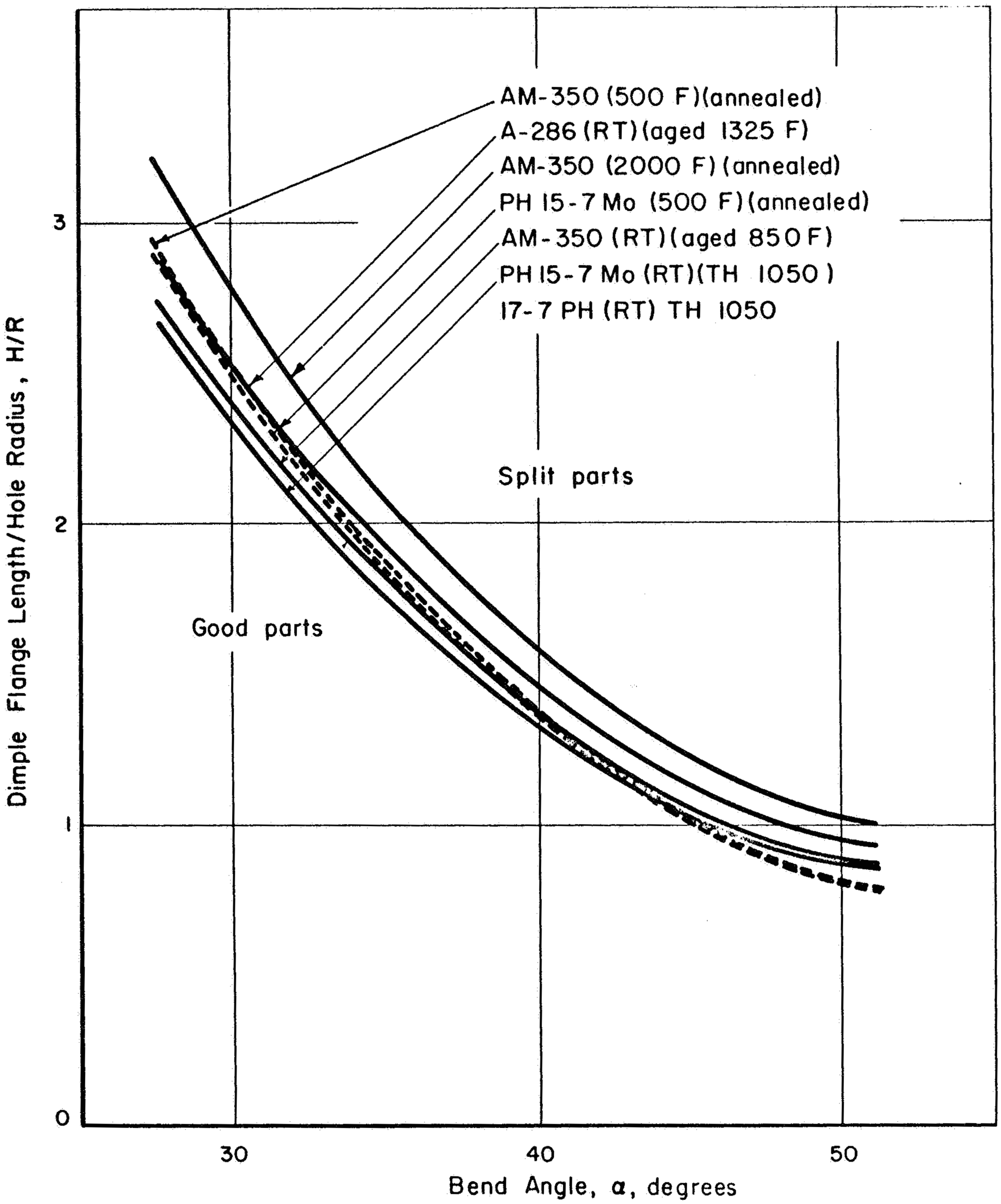


FIGURE 116. THEORETICAL RELATIONSHIP BETWEEN H/R RATIO AND BEND ANGLE FOR THE DIMPLING OF SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS (REFS. 34, 35)

of H/R under the curves while splitting will occur if the experimental H/R values fall above the curves. Similar charts can be prepared for other alloys using Equation (31) and appropriate elongation values such as those given in Table XLVII.

TABLE XLVIII. ROOM-TEMPERATURE DIMPLING LIMITS FOR SELECTED PRECIPITATION-HARDENABLE STAINLESS STEELS TO PREVENT RADIAL SPLITTING AT EDGE OF HOLE (REFS. 34, 35)

Alloy	Condition	Temperature, F	Dimpling Limits, H/R, for Various Bend Angles, α				
			30 Deg	35 Deg	40 Deg	45 Deg	50 Deg
17-7 PH	TH 1050	RT	1.78	1.32	1.02	0.80	0.65
AM-350	Aged at 850 F	RT	1.88	1.40	1.08	0.85	0.68
AM-350	Annealed	500	2.46	1.87	1.43	1.10	0.93
AM-350	Annealed	2000	2.78	2.09	1.58	1.23	1.03
PH 15-7 Mo	TH 1050	RT	1.78	1.32	1.02	0.80	0.65
PH 15-7 Mo	Annealed	500	2.43	1.84	1.40	1.07	0.90
A-286	Aged at 1325 F	RT	2.26	1.67	1.30	1.03	0.82

Conditions of heat treatment and dimpling temperatures affect the limits given in Table XLVIII. The usefulness of Table XLVIII can be illustrated in the following example (Ref. 34):

Problem: Determine the maximum length of dimple flange, H_{max}, that can be produced at room temperature for the AM-350 stainless steel alloy in the solution-treated condition using a hole radius of 1/8 inch and a bend angle of 42 degrees.

α = 42 degrees; R = 0.125 inch.

By interpolation, H/R = 0.988 when α = 42 degrees

$H_{max} = (H/R)(R) = 0.988 \times 0.125 = 0.124$ inch.

Dimpling Experience. Work at McDonnell Aircraft Corporation (Ref. 49) appears to agree with the findings of Wood, et al. (Refs. 34, 35, 44) regarding the room-temperature dimpling of some of the precipitation-hardenable stainless steels. Both the AM-350 alloy (SCT 850 condition) and the PH 15-7 Mo alloy (TH 1050 condition) were successfully dimpled for 5/32 Hi Shear rivets in 0.063-inch-thick sheet. The dimpled test strips had the same strength as adjacent strips in which pilot holes were drilled but no dimples made. Difficulties were encountered in attempting to dimple these materials at higher temperatures, as the data of Wood predicted. However, attempts to produce dimples in these same two materials for 1/4-inch fasteners at room temperature were not successful. Practically speaking, the use of fasteners with diameters greater than about 3/16 inch for relatively thin sheet is seldom warranted. When thicker sheet is used, countersinking is customarily utilized to produce the recesses for the fasteners.

The AM-350, PH 15-7 Mo, and 17-7 PH alloys were successfully dimpled, in the heat-treated condition, at 1300 to 1400 F at Northrop Aircraft (Ref. 97). The sheet was heated by conduction from the lower die that was heated by induction. This elevated-temperature dimpling, however, resulted in a 30 to 35 per cent reduction in hardness in the area of the dimple. The lower hardness, no doubt, was the result of overaging the sheet prior to dimpling by heating it to the dimpling temperature. In another program, the 17-7 PH alloy sheet could be successfully dimpled at room temperature only after overaging the TH 1200 condition (Ref. 98).

Attempts at Boeing (Ref. 99) to test dimple 0.014- and 0.020-inch-thick sheet of AM-355 CRT by conventional methods at die temperatures of -20 F, room temperature, and 800 F were not successful. Dimples were made for No. 10 screws and for 5/32- and 3/16-inch-diameter rivets. All of the dimples formed had circumferential cracks and most of the screw dimples had radial cracks.

Another Boeing study investigated the feasibility of dimpling PH 15-7 Mo (RH 950) sheet, 0.010, 0.020, 0.032, and 0.040 inch thick by the Lemert Spin-Impact Method (Ref. 100). This dimpling method does not depend as much on material ductility but rather forms the dimple by the peening action of a rotating die. Results were erratic and inconsistent. The hole to be dimpled was punched on the Lemert machine and the hole area was annealed rapidly with an oxyacetylene torch operated manually. Dimpling on the Lemert machine is a two-step operation. In the first step, a 0.040-inch-thick aluminum strip is inserted under the sample sheet. In the second step, the backing strip is removed, and the dimple is completed. The dimples thinned too much in the side walls and several alternative procedures did not completely solve the problem. However, radial cracking appeared to be a problem mainly in the 0.040-inch-thick sheet, but circumferential cracking occurred also in thinner sheet. Hardness data indicated that a substantial loss of strength also occurred. This process must be developed further to be useful as a production tool.

Post-Dimpling Treatments. Normally the precipitation-hardenable stainless steel sheet is dimpled in the condition in which it is to be used. 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 normally is not required.

Flash occurs at the edges of the dimple for all types of dimpling. Figure 117 shows an enlarged section of a dimple and illustrates the

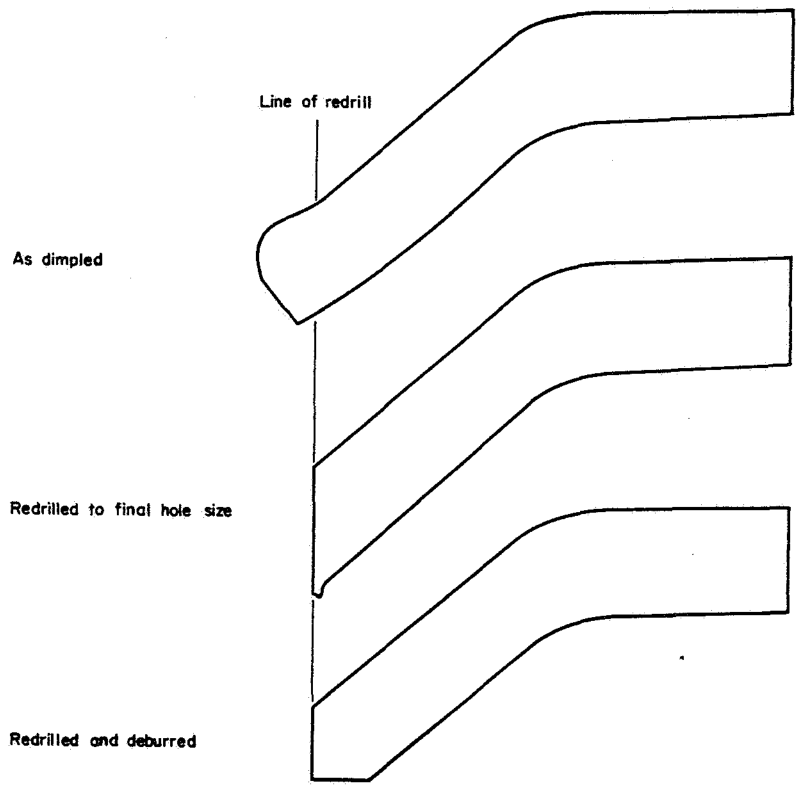


FIGURE 117. ENLARGED SECTION OF DIMPLE SHOWING POST-DIMPLING OPERATIONS (REF. 96)

Courtesy of Zephyr Manufacturing Company, Inc., Inglewood, California.

redrilling and deburring that usually is necessary after dimpling (Ref. 96). The deburring is done with a special facing cutter equipped with a microstop tool. The width of the flat surface on the back side of the dimple should be about 1/2 the material thickness. However, when deburring sheet 0.060 inch thick and thicker, the flat width should not exceed 0.030 inch.

Stress-Corrosion Cracking in Dimples. There is a possibility of stress-corrosion cracking when the precipitation-hardenable semiaustenitic stainless steels are used for airframe applications in the heat-treated condition. Kowalski and Kritzer (Ref. 101) report that AM-350 (SCT 850), AM-355 (SCT 850), and PH 15-7 Mo (RH 950) are all very susceptible to stress-corrosion cracking in 20 per cent salt spray at stress levels of 40, 60, 80, and 100 per cent of tensile yield. The 17-7 PH alloy, heat treated to the TH 1075 condition, however, was not susceptible in the same test. Dimpling at 1300 F considerably decreased the stress-corrosion susceptibility of PH 15-7 Mo (RH 950) at all stress levels. However, the stress-corrosion susceptibility of AM-355 (SCT 850) was only slightly decreased at the lower stress level (40 per cent tensile yield stress) by dimpling at 1300 F.

It is known that shot peening, under certain conditions, will reduce a material's susceptibility to stress corrosion by inducing a compressive stress in the outer fiber of the material. No measurable benefit in corrosion was detected when both AM-350 (SCT 850) and PH 15-7 Mo (RH 950) were peened with glass beads.

JOGGLING

Introduction. A joggle is an offset in a flat plane produced by two bends 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 118. 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 sections by a variety of techniques. Whenever possible, the joggle is formed as part of another forming operation but at times a separate operation is used to produce a joggle.

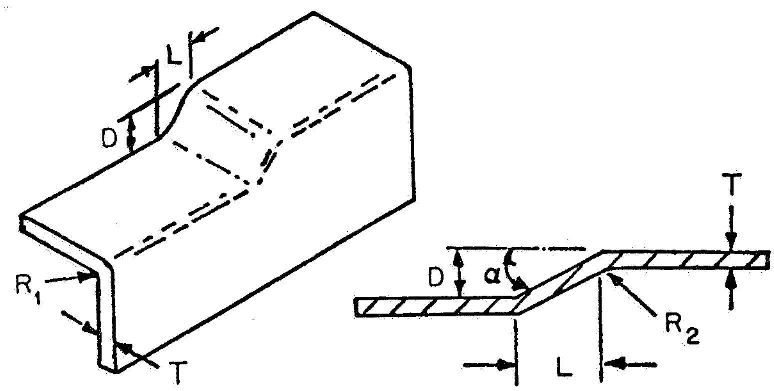
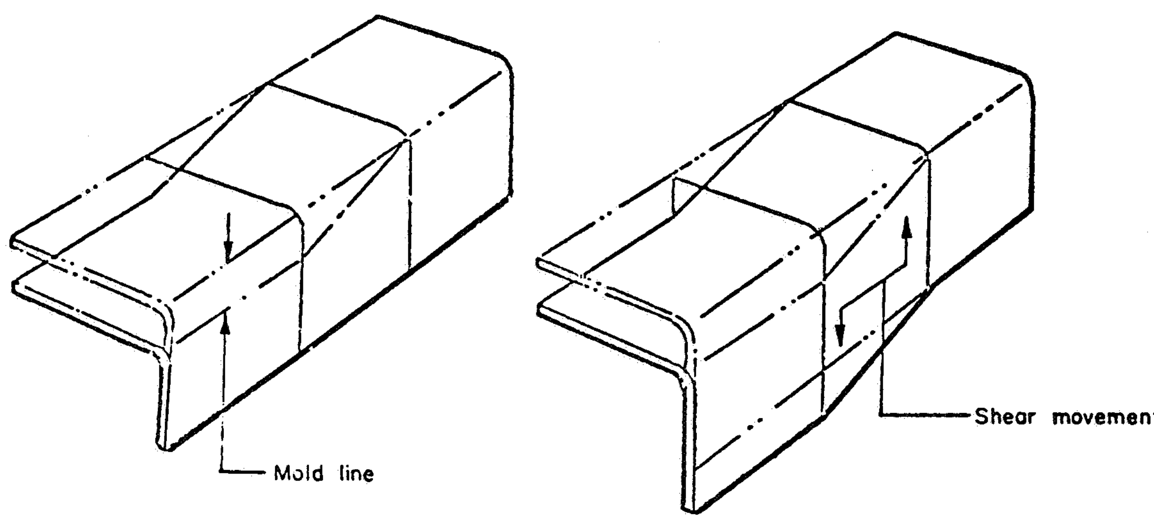


FIGURE 118. JOGGLE IN AN ANGLE (REF. 44)

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 119. BASIC METHODS OF FORMING JOGGLES (REF. 44)

Presses with special joggle dies are often employed for forming joggles in angles and channels. 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 119.

Tooling. The precipitation-hardenable stainless steels are often joggled at room temperature. Nickel-chromium-molybdenum tool steels will give satisfactory service as joggle dies when heat treated to R_C 50-55. For higher temperatures, tooling constructed from high-strength, heat-resistant alloys or ceramic materials must be used.

A schematic drawing of a universal joggle die, similar to that used by Wood, et al. (Ref. 44) in their studies is shown in Figure 120. This type of tooling requires an additional hydraulic cylinder to apply horizontal forces to clamp the side of the angle specimen to the die. Suitable shims are added to the die to produce the shape desired in the part. For production runs, mated, rather than universal, adjustable joggle dies are usually used.

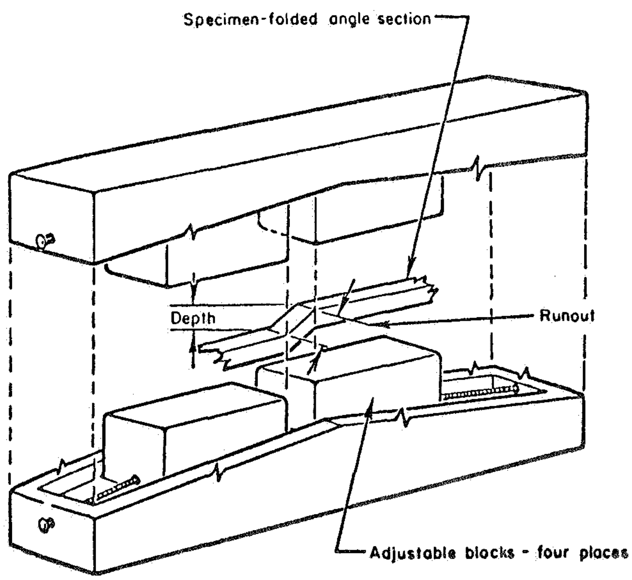


FIGURE 120. UNIVERSAL JOGGLE DIE (REF. 44)

Courtesy of North American Aviation, Inc., Inglewood, California.

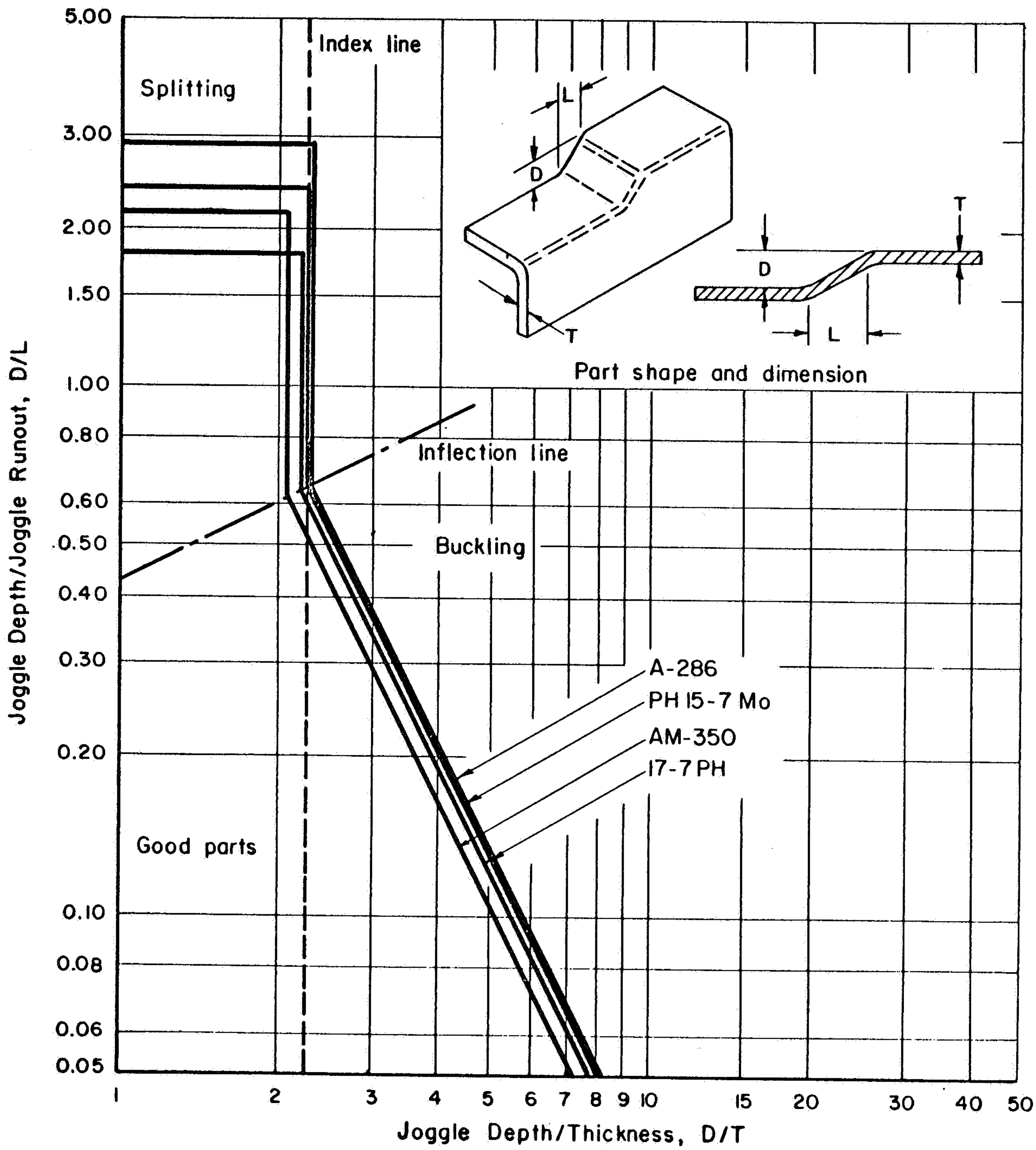


FIGURE 121. FORMING LIMITS FOR JOGGLING OF PRECIPITATION-HARDENABLE STAINLESS STEELS IN THE SOLUTION-TREATED OR ANNEALED CONDITION (REF. 44)

Material Preparation. Precautions covered in the section on blank preparation apply to the preparation of sheet for joggling.

Lubricants. Lubricants are generally used in the production joggling of precipitation-hardenable stainless steel sheet metal. The high-pressure drawing lubricants containing inert filler and having high film strength would be satisfactory. To prevent carburization, all lubricants must be completely removed before any thermal treatment is used on the parts.

Joggling Limits. Wood and his associates (Ref. 44) included experiments on 17-7 PH, PH 15-7 Mo, AM-350, and the A-286 alloy in their study of the relationships between the properties of the workpiece and the formability limits in joggling. Formability limit charts, based on data for these alloys in the solution-treated condition, were constructed from a knowledge of the properties of the material and joggling geometry (Ref. 44). These are shown in Figure 121. The A-286 alloy is shown to have the best formability in joggling of the alloys shown. The joggle depth can be nearly three times the runout length for this alloy. The joggle-depth to material-thickness ratio is approximately the same for the A-286, PH 15-7 Mo, and 17-7 PH alloys. The common types of buckling and splitting failures encountered in joggling are illustrated in Figure 122.

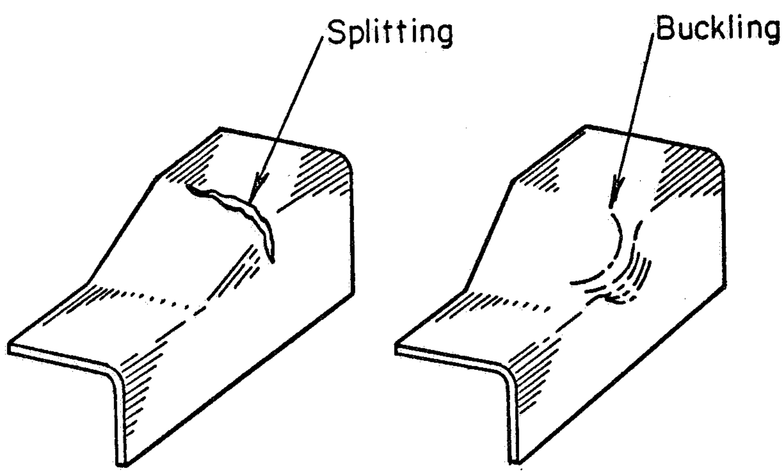


FIGURE 122. MAJOR JOGGLING FAILURES (REF. 34)

An empirical approach that may be used to choose joggle dimensions is described in a North American Aviation Specification (Ref. 102). The length or runout, L, of the joggle, shown in Figure 118, can be determined from the following formulas and the factors A, B, and C given in Table XLIX.

(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 $D > A$).

(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

$$L = \sqrt{D(C - D)} \text{ (when } D < A).$$

(3) For joggles in flat sheets, the projected distance between tangents may be determined from the equation for reverse curve as follows:

$$L = \sqrt{D(4R_2 + 2T - D)} \text{ (see Figure 117).}$$

TABLE XLIX. JOGGLE-FORMING-LIMIT FACTORS FOR SELECTED ANNEALED PRECIPITATION-HARDENABLE STAINLESS STEELS (REF. 102)

Alloy	Minimum Bend-Radii Factor, R/T[a]	Minimum Joggle-Runout Factors[b] A/T	B	C/T
AM-350	2	2.0	2	10
AM-355	2	2.0	2	10
PH 15-7 Mo	1	1.2	2	6
17-7 PH	2	2.0	2	10

(a) To obtain bend radii, multiply R/T value by material thickness, T.
(b) To obtain A and C, multiply A/T and C/T values by material thickness, T.

Values suggested for minimum runout and minimum bend radii are given in Table XLIX for several precipitation-hardenable stainless steels. Table L gives joggle-design specifications used at McDonnell Aircraft Corporation for both flat and flanged sheet joggled at room temperature in the solution-treated condition.

Post-Joggling Treatments. Springback in joggles formed at room temperature or slightly elevated temperatures may be 5 to 10 per cent. The parts are generally overbent to compensate for the springback.

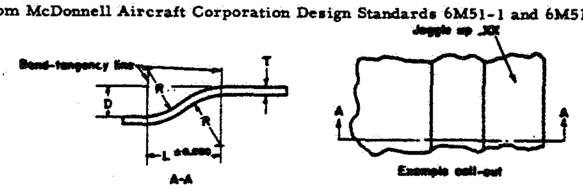
Joggled and formed parts generally are solution heat treated and aged after joggling. Clamping the parts in fixtures helps reduce distortion during the heat treatment. Any lubricant residue must be thoroughly and completely removed after joggling if the parts are to receive a thermal treatment.

TABLE L. JOGGLE-DESIGN SPECIFICATIONS FOR FLAT AND FLANGED SHEET OF PRECIPITATION-HARDENABLE STAINLESS STEELS(a)

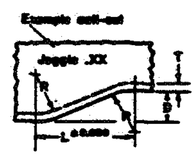
Depth of Offset, D	Joggle Length, L(b) for Indicated Sheet Thickness, T: Up to 0.022	0.023-0.027	0.028-0.035	0.036-0.044	0.045-0.054	0.055-0.068	0.069-0.075	0.076-0.084	0.085-0.097	0.098-0.113	0.114-0.139	0.140-0.172	0.173-0.219	0.220-0.262
Flat Sheet-Joggled Cold(c)														
Up to 0.022	0.14	0.16	0.17	0.18	0.19	0.21	0.22	0.23	0.24	0.26	0.27	0.30	0.34	0.37
0.023-0.027	0.15	0.17	0.19	0.19	0.21	0.23	0.24	0.25	0.26	0.28	0.29	0.34	0.37	0.41
0.028-0.035	0.16	0.18	0.20	0.20	0.22	0.25	0.26	0.27	0.29	0.30	0.32	0.37	0.41	0.44
0.036-0.044	0.17	0.20	0.22	0.22	0.24	0.27	0.28	0.30	0.31	0.33	0.36	0.40	0.45	0.49
0.045-0.054	0.20	0.21	0.24	0.24	0.26	0.29	0.31	0.33	0.34	0.37	0.39	0.44	0.49	0.54
0.055-0.068	0.21	0.24	0.25	0.25	0.28	0.32	0.34	0.35	0.37	0.40	0.43	0.47	0.54	0.58
0.069-0.075	0.22	0.25	0.26	0.26	0.29	0.33	0.35	0.37	0.39	0.43	0.45	0.50	0.57	0.62
0.076-0.084	0.22	0.26	0.27	0.27	0.30	0.35	0.37	0.38	0.41	0.44	0.47	0.53	0.60	0.66
0.085-0.097	0.23	0.27	0.30	0.30	0.31	0.36	0.38	0.40	0.42	0.46	0.48	0.55	0.63	0.69
0.098-0.113	0.23	0.27	0.31	0.31	0.32	0.37	0.39	0.42	0.44	0.48	0.51	0.58	0.66	0.72
0.114-0.139	0.24	0.29	0.33	0.33	0.37	0.40	0.43	0.45	0.48	0.51	0.55	0.63	0.71	0.79
0.140-0.172	0.24	0.30	0.35	0.35	0.39	0.46	0.47	0.51	0.53	0.57	0.62	0.69	0.79	0.87
0.173-0.219	0.24	0.31	0.36	0.36	0.41	0.48	0.52	0.53	0.56	0.61	0.66	0.74	0.85	0.94
0.220-0.262	0.24	0.31	0.37	0.38	0.44	0.53	0.57	0.60	0.64	0.70	0.76	0.84	0.96	1.07
Flanged Sheet(d)														
Up to 0.022	0.12	0.13	0.15	0.15	0.15	0.18	0.19	0.20	0.21	0.23	0.24	0.27	0.31	0.34
0.023-0.027	0.14	0.15	0.16	0.16	0.17	0.20	0.21	0.22	0.23	0.25	0.26	0.31	0.34	0.38
0.028-0.035	0.15	0.17	0.18	0.18	0.19	0.22	0.23	0.24	0.26	0.27	0.29	0.34	0.38	0.41
0.036-0.044	0.18	0.19	0.20	0.20	0.21	0.24	0.25	0.27	0.28	0.30	0.33	0.37	0.42	0.46
0.045-0.054	0.21	0.22	0.23	0.23	0.25	0.27	0.28	0.30	0.31	0.34	0.36	0.41	0.46	0.51
0.055-0.068	0.24	0.25	0.27	0.27	0.28	0.31	0.32	0.33	0.35	0.37	0.40	0.44	0.51	0.55
0.069-0.075	0.26	0.27	0.29	0.29	0.30	0.33	0.34	0.35	0.37	0.39	0.42	0.47	0.54	0.59
0.076-0.084	0.29	0.30	0.32	0.32	0.33	0.35	0.37	0.38	0.39	0.42	0.44	0.50	0.57	0.63
0.085-0.097	0.32	0.33	0.34	0.34	0.36	0.38	0.39	0.41	0.42	0.44	0.47	0.52	0.60	0.66
0.098-0.113	0.35	0.36	0.37	0.37	0.39	0.41	0.42	0.44	0.45	0.47	0.50	0.56	0.63	0.69
0.114-0.139	0.41	0.42	0.44	0.44	0.45	0.47	0.49	0.50	0.51	0.54	0.56	0.62	0.69	0.76
0.140-0.172	0.51	0.52	0.53	0.53	0.55	0.57	0.59	0.60	0.61	0.64	0.66	0.71	0.78	0.85
0.173-0.219	0.60	0.61	0.62	0.62	0.64	0.66	0.68	0.69	0.70	0.73	0.75	0.80	0.86	0.94
0.220-0.262	0.77	0.78	0.79	0.79	0.81	0.83	0.85	0.86	0.87	0.90	0.92	0.97	1.04	1.11

(a) Data taken from McDonnell Aircraft Corporation Design Standards 6M51-1 and 6M51-2 (June, 1963).

(b) Parameters:



a. Flat Sheet



b. Flanged Sheet

(c) Joggle dimensions are for all aluminum alloys and conditions except 7075-T6 and 7178-T6, annealed stainless steels including the precipitation-hardenable grades, annealed or normalized alloy steels, hot-formed magnesium alloys, and annealed Inconel. Tolerances for D are ±0.03 inch for sheet thicknesses of 0.068 inch or less; ±0.02 inch for sheet thickness of 0.069 inch or greater.

(d) Joggle dimensions for all aluminum alloys the O condition, also 2024-T-3, 6061-T6, and annealed stainless steels including the precipitation-hardenable grades. *Tolerances for D are +0.03, -0.01 inch for sheet thickness 0.044 inch or less and +0.02, -0.01 for sheet thickness 0.045 inch* or greater.

SIZING

Introduction. Sizing is a final forming operation used to bring preformed parts within the desired tolerances. When form tooling has been properly designed to account for the predictable springback in the precipitation-hardenable stainless steels, very little sizing should be required. Generally tolerances of ±0.030 inch can be obtained in forming these alloys. When fitup problems require closer tolerances, a sizing operation is usually required.

Sizing of the precipitation-hardenable stainless steels might be accomplished by benching, by hot sizing in desired fixtures, by die quenching, or by subzero sizing. Benching is the more commonly used method. Alloys that age near the hot-sizing temperature can cause considerable difficulty and sometimes require more than one operation to obtain the desired results. Such alloys sometimes are sized as part of the aging cycle.

Benching. Benching is a hand-forming operation used to bring parts produced by plastic deformation to the desired tolerance. It consists of placing a free-formed part over a male die of the desired dimensions and beating the part with lead strips. The term benching is used because the work is generally carried out with the die laying on a workbench.

Since most of the materials are work hardened by the previous forming operations, they require a considerable amount of benching time; sometimes they crack during benching. Best results are obtained by annealing or solution treating the materials after forming and before benching. Parts made from many materials can then be heat treated after benching to obtain the desired properties. Benching after heat treatment should be avoided because residual stresses may be developed in the part that may be detrimental to its structural function (or "integrity").

Hot Sizing. 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 sheet thickness and alloy should be used. Forces that approach the yield strength of the material at the forming temperature are applied.

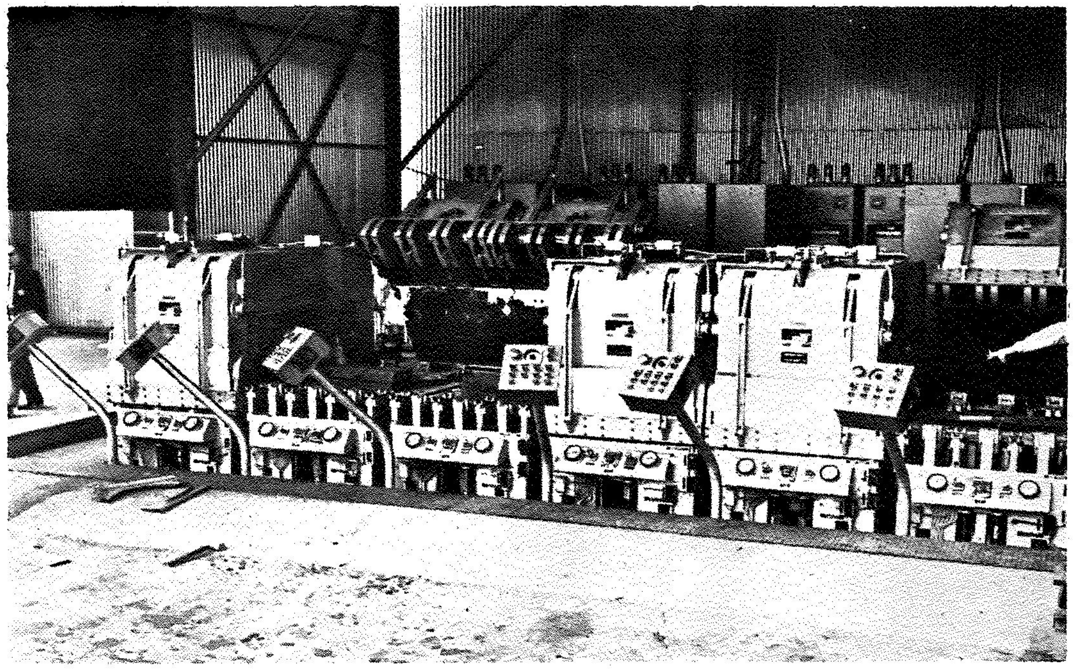
In the second process, parts are wedged in fixtures to obtain the necessary pressures, and then the assembly is heated in a conventional furnace. This method is simpler and cheaper because expensive hot-sizing presses are not required.

Temperatures from 900 to 1000 F are required to hot size the precipitation-hardenable stainless steels. The time required for sizing 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 are expected to retain the room-temperature shape of the sizing die.

Hot sizing may be used for parts cold formed to rough dimensions by brake-press, drop-hammer, rubber, hydropress-forming, or deep-drawing processes. The temperature used for hot sizing is either at the solution-annealing or below the aging temperature for the alloy.

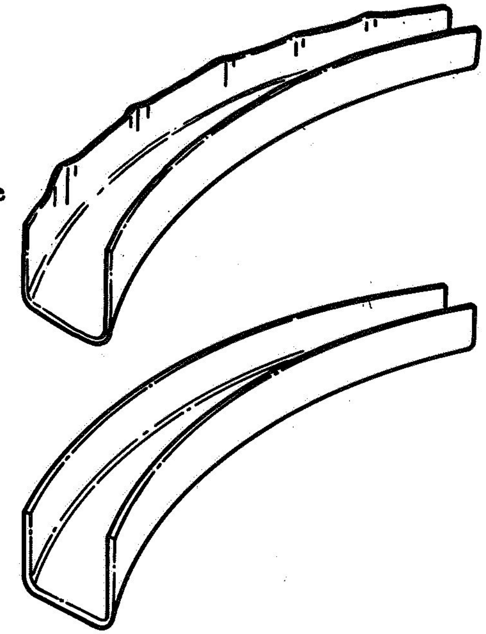
Equipment. A hot-sizing device consists of two heated platens, one mounted directly over the other. The upper platen is hinged so that it can be opened to expose the lower platen. The upper platen is operated by hydraulically actuated jack rams. The platens are heated either by gas firing or electrical-resistance heating.

Figure 123 shows an electrically heated hot-sizing press that has a bed 24 feet long by 4 feet wide. This press is 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 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 (not shown in Figure 123). 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 corner of Figure 123. Vertical pressures up to 120 tons are available with each unit, and horizontal cylinders apply side loads up to



Hot-size press

Part before



After

Principle - heat and pressure

Hydraulic cylinder pressure

Electrically heated platen

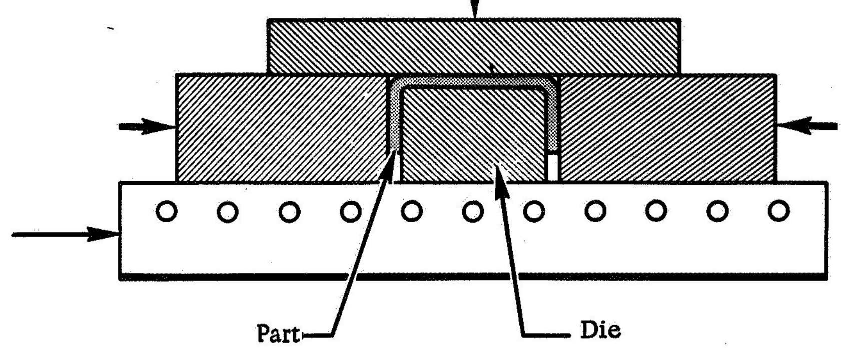


FIGURE 123. HOT-SIZING PRESS

Courtesy of North American Aviation, Inc., Inglewood, California.

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. This type of unit generally is used for hot sizing at temperatures below the aging temperature for the alloy.

No special equipment is necessary for hot sizing with wedge-type fixtures. Tooling can be made that will lock a part into position when wedges are driven between retaining rings and dies. Then the entire assembly is placed in a furnace. Figure 124 shows the principle of design of a number of hot-sizing fixtures. One of these fixtures contains electrically heated platens and can be used in a conventional arbor press as shown in Figure 119 (lower right corner).

Except for the wedge-type hot-sizing tool for use on an arbor press (see Figure 124), the pressure attainable in wedge sizing is limited and generally can be applied in only one direction. Wedge-type tooling is often used for sizing parts during solution-annealing treatments.

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 short-production lots, up to about 20 pieces, provided the sizing temperature does not exceed 1000 F. Scaling is a severe problem with these tools.

High-silicon cast iron (Meehanite) dies can be used for lot sizes up to 100 pieces at temperatures to 1100 F. Scaling restricts the use of this material at higher temperatures. Wire brushing after 35 to 50 parts and light sand blasting of the die surface after 100 parts removes scale.

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 LI with their probable limitations.

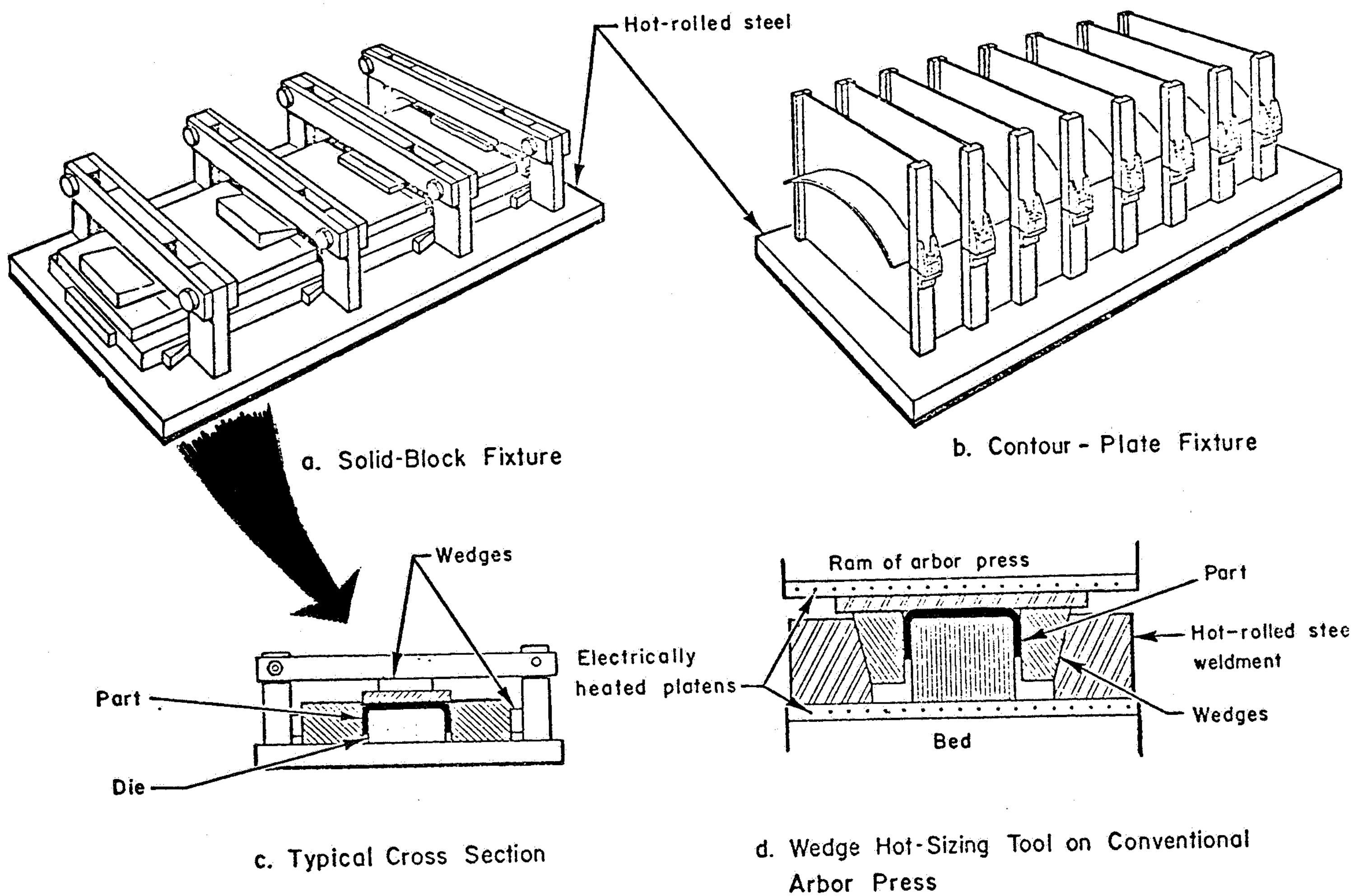


FIGURE 124. HOT-SIZING FIXTURES

Courtesy of North American Aviation, Inc., Ingelwood, California

TABLE LI. SUMMARY OF TOOLING MATERIALS FOR HOT SIZING[a]

Material	Number of Parts	Temperature Limit, F	Remarks
Hot-rolled steel	<20	1000	Not recommended for production tooling because of scale problems
Meehanite[b]	<100	1200	Wire brush at intervals of 35 to 50 parts; light sand blast after 100 parts; good resistance to oxidation
Nodular cast iron[c]	>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[d]		>1500	Ceramic dies are covered with stainless steel sheets, 0.050 inch thick
Modified H13[e]	>100	1300	Prehardened to R_C 32-36

(a) Courtesy of Chance Vought Aircraft, Inc., Dallas, Texas; Convair, General Dynamics Corporation, San Diego, California; and North American Aviation, Inc., Los Angeles, California.

(b) Meehanite is quality-controlled high-silicon cast iron.

(c) High-silicon, nickel, molybdenum nodular iron.

(d) Produced by Glasrock Products, Torrance, California.

(e) 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. Castable ceramics allow the holes for heater wires to be cast in the die. The ceramic faces of the die are covered with stainless steel sheets about 0.050 inch thick. Face temperatures higher than 1500 F can be used with these tools.

Material Preparation. It is sometimes necessary to apply a protective coating or lubricant to the surface of the part to aid in forming and to reduce oxidation, especially if the hot-sizing temperature is higher than 1000 F. Both the scale preventive compounds and lubricants must be of the nonsulfurized type to prevent contamination.

Sizing Conditions. Because the hot-sizing process is used mainly to correct springback and warpage in preformed parts, no definite forming limits can be given. The removal of springback and warpage in precipitation-hardenable stainless steel parts 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 temperature used for hot sizing the precipitation-hardenable stainless steels must be controlled within specific limits for the alloys. Hot sizing during aging has been quite successful on 17-7 PH (TH 1075) (Ref. 78). However, because of the lower aging temperature and higher mechanical properties, the PH 15-7 Mo (RH 950) alloy has not been sized as successfully during aging. Hot sizing at North American Aviation has been successfully accomplished in a furnace fixture or hot-sizing press at 1275 F in 1/2 hr with 17-7 PH, PH 15-7 Mo, and AM-350 (Ref. 78).

Table LII indicates ranges of temperature where precipitation-hardenable stainless steels in various conditions of heat treatment have lower ductilities than they possess at room temperature. These ranges were determined on the basis of elongation and reduction-in-area values. If the alloys are sized in these temperature ranges they are likely to crack.

TABLE LII. TEMPERATURE RANGES WHERE THE DUCTILITY OF PRECIPITATION-HARDENABLE STAINLESS STEELS IS LOWER THAN THAT AT ROOM TEMPERATURE (REFS. 32, 47, 93)

Alloy	Condition	Temperature Range, F
17-4 PH	H 900	Up to 1000
17-7 PH	TH 1050	100-900
	RH 950	100-650
	CH 900	100-800
PH 15-7 Mo	TH 1050	100-750
	RH 950	100-600
	CH 900	100-950
AM-350	SCT (850 F)	400-1000
AM-355	SCT (850 F)	400-1000
	SCT (1000 F)	400-1000
A-286	STA	1050-1425[a]
Stainless W	STA (1000 F)	100-800[b]

(a) Elongation does not change appreciably between room temperature and 1050 F; reduction in area does not attain its room-temperature value until it is at about 1500 F.

(b) Little change in ductility from room temperature to 800 F.

Die Quenching. Die quenching is a heat-treating procedure that is often used as a final sizing operation and for minimizing warpage in precipitation-hardenable stainless steel parts. It has been successfully used to control warpage in some aircraft parts made of 17-7 PH stainless steel (Refs. 103, 104). Warping of close-tolerance parts occurs usually on cooling from the conditioning temperature, 1400 F, after forming. It is caused by the transformation of austenite to martensite, which starts on cooling at about 200 F and is concluded at about 60 F. To prevent the warpage, the part is placed in a finish-size die when the metal is at about 600 F and removed when the die is below 125 F, but above 50 F. It is important not to cool the part below 50 F after conditioning and before precipitation hardening. The die is at a temperature of 50 to 100 F when it receives the part. After die quenching, the part is aged at temperatures ranging from about 1050 to 1200 F, depending on the properties desired. A high die pressure is not required and, in fact, is not desirable, since it tends to bind the part as it first shrinks and then expands in the die. Only enough pressure is needed to keep the part from warping away from the die contour.

The parts must be thoroughly cleaned by vapor degreasing and by abrasive cleaning prior to heating. They should be coated to minimize oxidation and then heated in air or an inert-gas atmosphere and not in a carbon-rich atmosphere. After die quenching, the parts are lightly grit blasted, recoated to minimize oxidation, and then aged.

Subzero Sizing. Another technique for improving the dimensional accuracy of formed parts of some of the precipitation-hardenable stainless steels is subzero sizing (cryoforming). By this method, the dimensional change that occurs when austenite transforms to martensite is utilized. The growth during transformation in the case of 17-7 PH and PH 15-7 Mo amounts to 0.004 to 0.005 inch per inch of metal (Ref. 105). Thus, on a 4-foot-long part, an increase in length of nearly 1/4 inch would occur.

A typical cycle in which subzero sizing is used as a production technique to produce close-tolerance parts of PH 15-7 Mo might consist of the following operations (Refs. 78, 106):

(1) Rough form the part to slightly less than the desired dimensions using a press brake, drop hammer, hydropress, or stretch wrap

(2) Hot size if required at 1225 to 1350 F to produce the desired configuration

(3) Condition by heating at 1750 F and cooling to about 125 F

(4) Place parts in dies or wedge-type fixtures that have been heated to 125 F

(5) Refrigerate the assembled parts and dies to -50 to -110 F to complete the transformation to martensite. This usually requires 40 to 60 minutes. Slow cooling to -110 F is desirable to avoid distortion of the tools

(6) Sometimes the parts are removed after being held in the fixture for about 10 minutes; they are then aged in batches at subzero temperature

(7) Age at 950 F to produce RH 950 condition.

The aging at 950 F after the subzero treatment does not distort the parts because no phase change is involved. Shrinkage during aging is only about 0.0005 inch per inch.

Figure 125 is a sketch of a flanged part in a die for subzero processing. The allowance for expansion at the edges of the flange are indicated. As for die quenching, only a minimum amount of pressure sufficient to keep the part against the die is required.

No expensive machined and hardened dies are required for subzero sizing. Any material that will withstand temperatures to -110 F is satisfactory, provided it has a low coefficient of expansion. Kirksite and plastic (Cerrobend) dies have been used successfully for subzero sizing. It is desirable to coat these dies, preferably with stainless steel to avoid surface contamination of the formed stainless steel parts. In addition to preventing contamination, the use of stainless steel die faces eliminates much of the die-storage problem because only the die faces need to be stored.

Figure 126 shows a Bomarc frame of 17-7 PH stainless steel that was sized by cryoforming. A silicone rubber punch and a steel female die were used. A preformed part was placed in a holding oven at 500 F and then cryoformed in a hydropress under 1500 psi. Acceptable tolerances were produced by this technique.

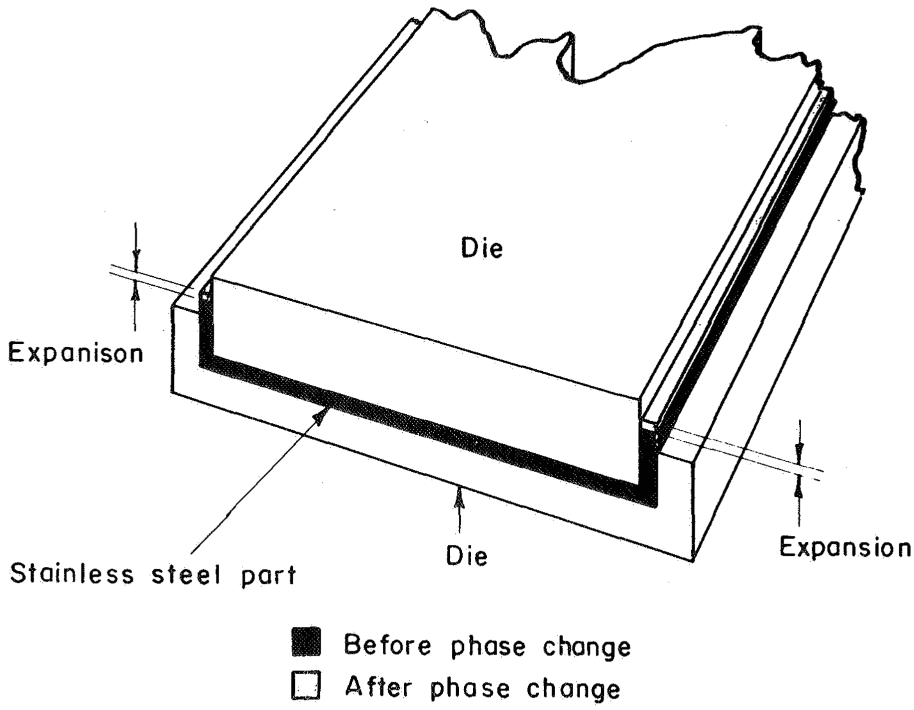


FIGURE 125. SKETCH OF FLANGED STAINLESS STEEL PART IN DIE FOR SUBZERO FORMING

Note expansion of stainless steel into flanges during phase changes.
Courtesy of Armco Steel Corporation, Middletown, Ohio.

The subzero-sizing process appears to be suitable for the economical production of close-tolerance, high-strength, precipitation-hardenable stainless steel details and assemblies. Since neither hot-sizing presses nor the development of elevated-temperature tools is needed, subzero sizing often can be accomplished on currently available facilities.

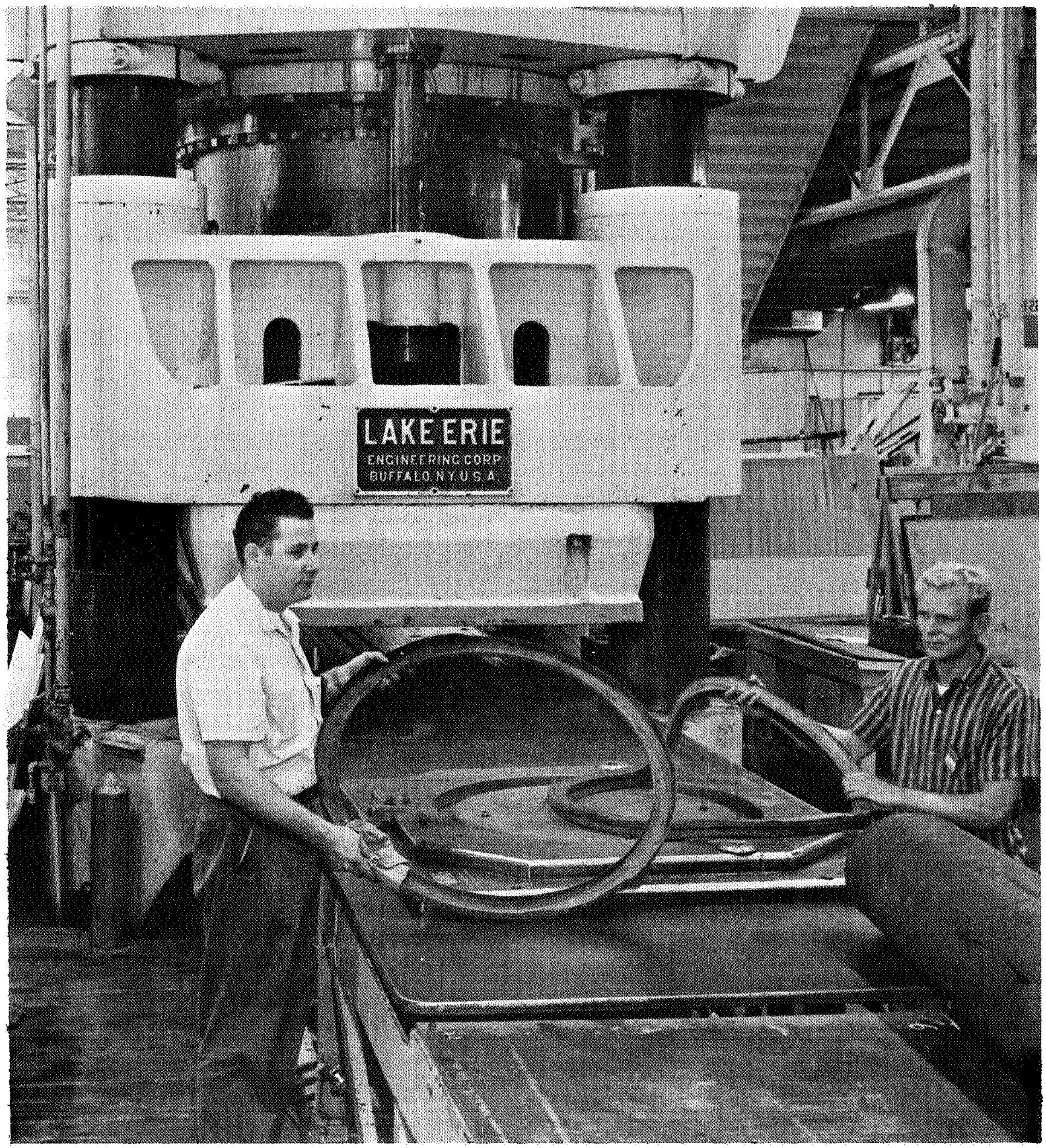


FIGURE 126. BOMARC FRAME OF 17-7PH STAINLESS STEEL CRYOFORMED USING A SILICONE-RUBBER PUNCH AND A STEEL FEMALE DIE

Preformed part was heated to 500 F and cryoformed in a hydropress under 500 psi.

CONCLUSIONS AND RECOMMENDATIONS

One of the major problems in deformation processing of precipitation-hardenable stainless steels is variation of properties between heats of the materials. The springback from forming might vary between 5 and 40 per cent while the yield strength of annealed or solution-treated material may vary by 30,000 psi. Research to determine the effect of chemistry and processing variables on the properties of these stainless steels should be undertaken. Information obtained from such studies might be used to obtain closer specifications for control of chemistry and processing methods.

Considering the commercial materials, various types of research are expected to advance the art of deformation processing. Developments in any of the areas mentioned below are expected to increase productivity and decrease the costs of components fabricated from the precipitation-hardenable stainless steels.

Since the aerospace industry primarily uses these steels, the desired formability characteristics for this industry have been considered. Rolling equipment for making wider sheet with reduced tolerance variation and consistent properties throughout the sheet is required. Wide rolling-mill capacities and techniques such as pack rolling to obtain thin sheets should be investigated. New methods for surface treatment to limit the amount of conditioning required during rolling or forging would reduce the cost of production.

Basic studies in the theoretical behavior of metals during rolling, forging, extrusion, or wire drawing would be of benefit in increasing the formability of precipitation-hardenable stainless steels. Similarly, studies in friction and lubrication should advance the forming technology of these materials.

The precipitation-hardenable stainless steels in secondary metalworking show only slight increases in formability with increasing forming temperature. Consequently studies in forming at elevated temperatures would be expected to have a very low yield for advancement of forming technology. Some benefit is obtained in forming sheet, plate, and tubing at high velocities. Research in both high-velocity forming and trapped-rubber impact forming would be expected to give significant benefits.

As with other materials, the collection of information on the mechanical properties that control the performance of sheet and plate in forming operations is necessary. Some of the tests suggested by Wood, et al. (Refs. 34, 35, 44) that are necessary to determine formability are not commonly performed. Tests that will give significant data on the most important parameters in metalforming should be undertaken. The routine tension and compression tests, although useful, do not give sufficient information to make reliable predictions of formability limits. Collection of data on the precipitation-hardenable stainless steels should be relatively easy since generally only room-temperature values are required.

Development of sizing techniques in conjunction with thermal and mechanical processing of these materials should be undertaken. More reliable parts with closer tolerances and more consistency and possibly higher mechanical properties could be expected from these studies. The thermal history of the precipitation-hardenable stainless steels also should be studied to ascertain its effect on formability.

Development work should also be directed toward improving equipment and tooling for forming precipitation-hardenable stainless steels by conventional processes. Major improvements in forming some part shapes, such as sheet and tubing, may result from applying a counterpressure to minimize tensile stresses developed at the surface during forming. Tube bulging, drawing, and flanging operations are possible examples.

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APPROVAL

DEFORMATION PROCESSING OF
PRECIPITATION-HARDENING STAINLESS STEELS

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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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