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MACHINING AND GRINDING OF TITANIUM AND ITS ALLOYS

C. T. Olofson, F.W. Boulger, J.A. Gurklis

Prepared Under the Supervision of the
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MACHINING AND GRINDING OF TITANIUM AND ITS ALLOYS

By

C. T. Olofson, F. W. Boulger, and J. A. Gurklis*

ABSTRACT

This report covers the state of the art of metal-removal operations for titanium and its alloys. It describes the methods currently employed for conventional machining, grinding, electrolytic, and chemical machining processes. The precautions which should be taken to avoid troubles resulting from the characteristics typical of titanium are pointed out. Ten machining, two grinding, two cutting, and two unconventional metal-removal operations are discussed separately. In other sections, the mechanics of chip-forming processes, the response to machining variables, costs, and precautions desirable from the standpoint of safety are discussed.

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*Principal Investigators, Battelle Memorial Institute, Contract DA-01-021-AMC-11651(Z).

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PREFACE

This report on practices used for removing metal from titanium and its alloys is intended to provide information useful to designers and fabricators. The detailed recommendations are considered to be reliable guides for selecting conditions, tools, and equipment suitable for specific operations. The causes of common problems are identified and precautions for avoiding them are mentioned.

The report summarizes information collected from equipment manufacturers, technical publications, and reports on Government contracts, and by interviews with engineers employed by major aircraft companies. A total of 86 references, most of them covering the period since 1958, are cited. Detailed data available prior to that time, mostly on unalloyed titanium, were covered by TML Report No. 80 issued by the organization now known as the Defense Metals Information Center. A large part of the more recent information on alloyed titanium was collected on a program for the Federal Aviation Agency. It appears in an abridged form in DMIC Memorandum 199.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

TECHNICAL MEMORANDUM X-53312

MACHINING AND GRINDING OF TITANIUM AND ITS ALLOYS

SUMMARY

Problems in machining titanium originate from three basic sources: high cutting temperatures, chemical reactions with tools, and a relatively low modulus of elasticity. Unlike steel, titanium does not form a built-up edge on tools, and this behavior accounts for the characteristically good surface finishes obtained even at low cutting speeds. Unfortunately, the lack of a built-up edge also increases the abrading and alloying action of the thin chip which literally races over a small tool-chip contact area under high pressures. This combination of characteristics and the relatively poor thermal conductivity of titanium results in unusually high tool-tip temperatures.

Titanium's strong chemical reactivity with tool materials at high cutting temperatures and pressures promotes galling and tool wear.

Mechanical problems result from titanium's relatively low modulus of elasticity, half that of steel. The low modulus coupled with high thrust forces required at the cutting edge can cause deflections in slender parts. Distortion of that kind creates additional heat, because of friction between the tool and workpiece, and problems in meeting dimensional tolerances. Because of differences in thermal and mechanical properties, titanium parts may "close in" on steel drills, reamers, and taps.

These difficulties can be minimized by following recommendations given in the report. When proper techniques are employed, machining of titanium is not an unusually difficult or hazardous operation. Although fires and explosions may possibly occur when finely divided titanium is improperly handled, simple precautions insure safety.

INTRODUCTION

Fifteen years ago titanium alloys were considered to be very difficult to machine compared with common constructional materials (Ref. 1). However, subsequent research and experience in machine shops has progressively improved the situation. Generally speaking, there have been no radical innovations; the steady improvement has resulted from gradual refinements in tool materials, tool geometries, and cutting fluids. Current experience indicates that more consistent machining results can be obtained with titanium than with some grades of steel (Ref. 2). For instance, surface roughness values as low as 20 to 30 microinch rms can be obtained on titanium without much trouble (Refs. 3-5).

MACHINING BEHAVIOR

Machinists commonly assert that titanium machines like austenitic stainless steel. However, comparing titanium directly with stainless steel seems justifiable only to the extent that both materials produce a tough, stringy chip (Ref. 1). The situation is different from the viewpoint of feed (Ref. 6) and cut depth. Austenitic stainless steel usually requires heavier feeds in order to penetrate the uncut metal below a heavily strain-hardened skin. Conversely, titanium, a material which does not strain harden as severely, does not necessarily require heavy feeds. In fact, tool wear per unit volume of metal removed increases with feed (Ref. 6).

The relative ease of metal removal for equal tool lives can be expressed in terms of the machinability ratings of metals. In this light, the machinability of unalloyed titanium does resemble that of annealed austenitic stainless steel, while the titanium alloys would be more comparable to 1/4-hard and 1/2-hard stainless steels. Table I shows the approximate machinability ratings of titanium alloys, stainless steel, and other alloys of interest to the aerospace industry (Refs. 7,8).

Principles of Titanium Machining.

Chip Formation. Three physical processes occur sequentially when a metal is machined. Initially, the metal at the tool point is compressed; then the chip is formed by displacement or

TABLE I. MACHINABILITY RATINGS OF TITANIUM AND ITS ALLOYS RELATIVE TO OTHER SELECTED MATERIALS(a)

Alloy	Type	Condition(b)	Rating(c)
2017	Aluminum alloy	T4	300
B1112	Resulfurized steel	HR	100
1020	Carbon steel	CD	70
4340	Alloy steel	A	45
Titanium	Commercially pure	A	40
302	Stainless steel	A	35
Ti-5Al-2.5Sn	Titanium alloy	A	30
Ti-8Mn	Titanium alloy	A	25
Ti-6Al-4V	Titanium alloy	A	22
Ti-8Al-1Mo-1V	Titanium alloy	A	22
Ti-6Al-6V-2Sn	Titanium alloy	A	20
Ti-6Al-4V	Titanium alloy	HT	18
Ti-6Al-6V-2Sn	Titanium alloy	HT	16
Ti-13V-11Cr-3Al	Titanium alloy	A	16
Ti-13V-11Cr-3Al	Titanium alloy	HT	~12
HS25	Cobalt base	A	10
René 41	Nickel base	HT	6

(a) Refs. 7, 8.

(b) T4. Solution-heat-treated and artificially aged condition
HR: Hot-rolled condition
A: Annealed condition
HT: Solution-treated-and-aged condition
CD: Cold-drawn condition.

(c) Based on AISI B1112 steel as 100.

deformation of metal along a very narrow shear plane extending from the tool edge to the unmachined work surface; finally the chip flows over the face of the tool under heavy pressure and high frictional resistance (Refs. 9,10). As the tool ploughs through the workpiece, the shear plane moves to maintain a "constant" shear angle (ϕ in Figure 1) throughout the entire cut (Ref. 11). The shear angle can fluctuate with cutting conditions. For example, if chip friction against the tool face increases, the shear angle will decrease, and vice versa (Ref. 12).

The characteristically large shear angle producing a thin chip, and the small tool-chip contact area constitute two of the three unique cutting characteristics for titanium (Refs. 4,13). Schematic drawings of chips being formed for the same size cut and tool angles in titanium and steel are compared in Figure 1.

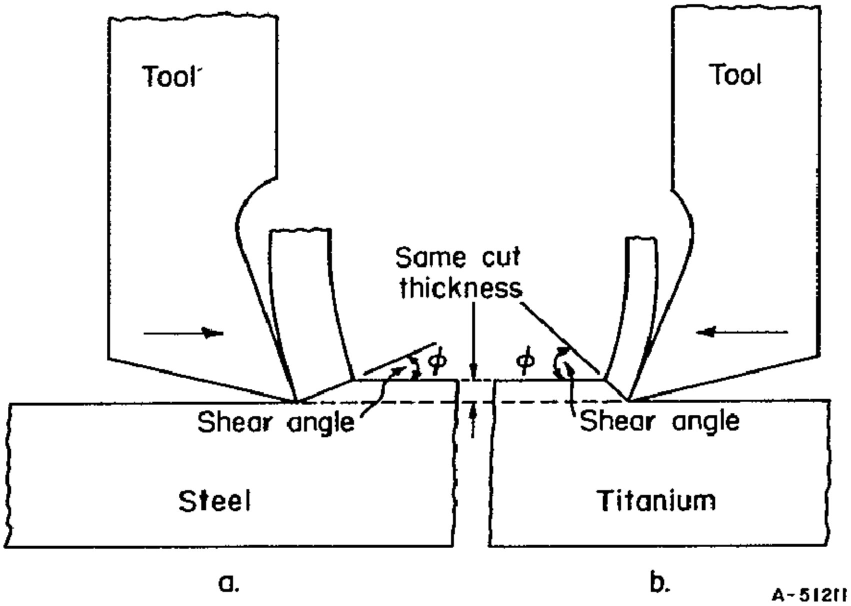


FIGURE 1. CHIP-FORMING PROCESS FOR STEEL AND TITANIUM (REF. 4)

The small shear angle shown for steel produces a long shear plane and a thick chip. Conversely the larger shear angle for titanium produces a shorter shear plane (Ref. 9). The long thin chip suffers less deformation (Ref. 12) and flows across the tool face at a higher velocity for any particular surface speed (Ref. 4).

The smaller contact area shown for titanium results in higher unit pressures for the same cutting force. These higher pressures coupled with the characteristically high-velocity chip generate more heat on the tool-chip contact area (Refs. 4,14). Other factors of chip formation characteristic of titanium have been identified by different investigators (Refs. 15-17).

Effects of Properties.

Thermal Properties. Almost all of the useful energy expended in machining is converted into heat. The amount of heat liberated depends on the tool forces, which are high during machining operations in difficult materials. The temperatures at the tool point depend partly on the rate at which heat is generated at the tool point and partly on the rate at which it is removed by the chip, the cutting fluid, and by conduction through the tool.

The heat-transfer characteristics of a material depend on thermal diffusivity, which is a function of density, specific heat, and thermal conductivity. Since titanium exhibits poor thermal diffusivity, as indicated in Table II, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided by suitable cutting fluids.

TABLE II. PHYSICAL PROPERTIES AND RELATIVE HEAT-TRANSFER PROPERTIES OF COMMERCIALLY PURE TITANIUM, 75ST ALUMINUM ALLOY, AND AISI 1020 STEEL

Property	Commercially Pure Titanium	75ST Age-Hardened Aluminum	AISI 1020 Steel
Density, ρ, lb/in.^{3}	0.163	0.101	0.290
Thermal Conductivity, k, Btu/(ft^2)(hr)(F)(in.)	105	845	390
Specific Heat, C_p, Btu/(lb)(F)	0.13	0.21	0.117
Volume Specific Heat, ρ C, Btu/(in.^{3})(F)	0.021	0.021	0.031
Thermal Diffusivity	4950	39,800	11,500

Chemical Reactivity. Titanium reacts with nearly all metals and refractory materials, and this, of course, includes cutting tools (Ref. 14). Because of the high temperatures and pressures developed during machining, an alloy is formed continuously between the titanium chip and the tool material. This alloy passes off with the chip producing tool wear (Ref. 14). Titanium reactivity shows up in another way. If the tool dwells in the cut, even momentarily as in drilling, the cutting temperature will drop, causing the chip to freeze to the tool. When cutting is resumed, the chip is released, leaving a layer of titanium on the cutting edge. This layer then picks up additional titanium to form an "artificial" built-up edge. This undesirable situation can be prevented by not permitting the tool to dwell in the cut, or by dressing the tool to remove the titanium layer before cutting is resumed.

Modulus of Elasticity. The stiffness of a part, which is affected by the modulus of elasticity of the workpiece material, is an important consideration when designing fixtures and selecting machining conditions. This is one of the more important factors in machining of titanium since the thrust force, which deflects the part being machined, is considerably greater for this metal than for steel (Ref. 4). Since the modulus of elasticity for titanium is only about half that of steel, a titanium part may deflect several times as much as a similar steel part during machining (Ref. 4).

GENERAL MACHINING REQUIREMENTS

The difficulties inherent in machining titanium can be minimized considerably by providing the proper cutting environment. The basic requirements include rugged machine tools in good condition; vibration-free, rigid setups; high-quality cutting tools; and suitable speeds, feeds, and cutting fluids (Refs. 2,3,13,18).

Machine Tools. Machine tools used for machining operations on titanium need certain minimum characteristics to insure rigid, vibration-free operation (Refs. 4,13,19). They are:

- Dynamic balance of rotating elements
- True running spindles
- Snug bearings
- Rigid frames
- Wide speed/feed ranges

- Ample power to maintain speed
- Easy accessibility for maintenance.

Milling machines and lathes also should possess backlash elimination and snug table gibs.

Vibration Effects. Vibration-free operation can be obtained by eliminating excessive play in power transmissions, slides, or screws of machine tools (Refs. 13, 18,19). Undersized or underpowered machines should be avoided. Certain aisle locations of machines near or adjacent to heavy traffic also can induce undesirable vibration and chatter during machining. Last, but not least, insufficient cutter rigidity and improper tool geometry can contribute to vibration (Refs. 13,18,19).

Rigidity Considerations. Rigidity is achieved by using stiff tool-tool holder systems, and adequate clamps or fixtures to minimize deflection of the workpiece and tool during machining.

In milling operations, large-diameter arbors with double arm supports; short, strong tools; rigid holding fixtures; frequent clamping; and adequate support of thin walls and delicate workpieces are desirable (Ref. 18).

Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, using a short tool overhang, and providing steady or follow rests for slender parts (Ref. 18).

Drilling, tapping, and reaming require short tools, positive clamping, and backup plates on through holes (Refs. 2,13,18,19).

Cutting-Tool Requirements. High-quality cutting tools are needed for all machining operations. They should be properly ground and finished. The face of the tool should be smooth, and the cutting edges sharp and free of burrs (Ref. 18).

Milling cutters, drills, and taps should be mounted to run true. Lathe tools usually should cut on dead center. In a multiple-tooth cutter like a mill or a drill, all teeth should cut the same amount of material (Ref. 2).

Tool Materials. Carbide, cast alloy, and high-speed steel cutting tools are used. The choice depends on seven basic factors including:

- The condition of the machine tool
- The over-all rigidity situation
- The type of cut to be made
- The surface condition of the titanium
- The amount of metal to be removed
- The metal removal rate
- The skill of the operator.

Carbide tools require heavy-duty, amply powered, vibration-free machine tools and rigid tool-work setups to prevent chipping. If these two basic conditions cannot be met, then high-speed steel tools give better results.

Carbide Tools. Carbide cutting tools are normally used for high-production items, extensive metal-removal operations, and scale removal. The so-called nonferrous or cast iron grades of carbides are used for titanium. These have been identified as CISC Grades C-1 to C-4 inclusive by the Carbide Industry Standardization Committee. A partial list of companies producing these grades of carbide cutting tools is given in Table III.

Although competitive brands of cutting tools classified as belonging to the same grade are similar, they are not necessarily identical. Variations in life should be expected from tools produced by different manufacturers and between lots made by the same producer. For this reason, some aircraft companies specify their own lists of interchangeable carbide tools made by approved manufacturers.

High-Speed Steel. High-speed steel tools can be used at low production rates. Tool life is low by ordinary standards.

Both the tungsten and molybdenum types of high-speed steel have been used. The hot hardness of tungsten high-speed steels results from a reluctance of the dissolved tungsten carbide in tempered martensite to precipitate and coalesce at elevated temperatures, a phenomenon which causes softening of hardened steel. Molybdenum carbides, as found in molybdenum high-speed steel, dissolve more readily in austenite than do tungsten carbides, and at lower solution temperatures. However, molybdenum carbides show somewhat greater tendencies to precipitate at tempering temperatures. Most

TABLE III. TOOL MATERIAL GUIDE FOR CARBIDES

CISC[b] Grade	Adamas	Carmet	Carboloy	Firth Loach	Firthite	Kenna-metal	Newcomer	Sandvik Coromant	Talide	Tungsten Alloy	Valenite	VR/Wesson	Willey
	Partial List of Carbides[a] Made by Various Manufacturers												
C-1	B	CA3	44A	FA5	H	K1	N10	H20	C89	9	VC1	2A68, VR54	E8, E13
C-2	A	CA4	883, 860	FA6	HA	K6	N20	H1P	C91	9H	VC2	2A5, VR54	E6
C-3	AA	CA7	905	FA7	HE	K8	N30	H1P	C93	9C	VC3	2A7	E5
C-4	AAA	CA8	999	FA8	HF	K11	N40	H05	C95	9B	VC4	2A7	E3
C-5	DD	CA51	78C	FT3	TQA	KM	N50	S6	S88	11T	VC5	EE, VR77	945
C-5A	43A	CA610	370	FT41, FT5	TXH	K21	--	S1P	S88X	9S	VC125	VR77, VR75	8A
C-6	D	CA609	78B	FT4	TXH, TA	K2S	N60		S90	10T	VC6	VR75	710
C-7	C	CA608	78	FT6	TXL	K5H	N70	S1P	S92	8T	VC7	E, VR73	606
C-7A	548	CA606	350	FT61	T16, TAL	K4H	--	--	S92X	5S	--	VR73	6A
C-8	CC	CA605	330	FT7	T31, WF	K7H	N80	F02	S94	5S	VC8	EH	509, 4A

(a) For the same CISC grade, there seem to be no truly equivalent carbides of different brands. Where two carbide grades from the same manufacturer are shown for the same CISC grade, the first is sometimes recommended.

(b) Carbide Industry Standardization Committee.

Notes: (1) The following chip-removal applications have been used for the CISC grade indicated. It will be noted that some grades specify the type of metal removal for which they are best suited.

C-1	Roughing Cuts – cast iron and nonferrous materials
C-2	General Purpose – cast iron and nonferrous materials
C-3	Light Finishing – cast iron and nonferrous materials
C-4	Precision Boring – cast iron and nonferrous materials
C-5	Roughing Cuts – steel
C-5A	Roughing Cuts and Heavy Feeds – steel
C-6	General Purpose – steel
C-7	Finishing Cuts – heavy feeds – steel
C-7A	Finishing Cuts – line feeds – steel
C-8	Precision Boring – steel

(2) This chart can function only as a guide. The so-called "best grade" may differ for each specific job even if the material being machined is the same. The final selection can be made only by trial and error. Instructions regarding the specific use and application of any competitive grade should be obtained directly from the manufacturer.

molybdenum high-speed steels utilize both tungsten and molybdenum in suitable ratios to obtain the advantages of both elements.

Cobalt is often added to both tungsten and molybdenum high-speed steels to increase their red hardness above 1000 F. Ordinary high-speed steels become too soft to cut effectively much in excess of this temperature. Figure 2 shows this loss in hardness as temperature rises. It also shows that the cobalt grades exhibit the best hot-hardness values at temperatures above 850 F.

Certain precautions must be observed when cobalt high-speed steels are used. They are sensitive to checking and cracking from abrupt temperature changes such as might occur during grinding. Consequently, steps should be taken against any kind of sharp, localized, overheating or sudden heating or cooling of these steels. They are more brittle than cobalt-free high-speed steels, and hence are not usually suitable for razor-edged quality tools. In addition, precautions must be taken to protect cobalt high-speed steels from excessive shock and vibration in service.

Table IV shows the wide choice of compositions of high-speed steels available to the tool engineer. There is little difference in properties between the molybdenum and tungsten types of high-speed steel. Although each group has its supporters, extensive laboratory and production comparisons of comparable grades of the two types have not consistently established any outstanding superiority for either group.

Cast Alloy. Cast cobalt-chromium-tungsten alloys are used for metal cutting at speeds intermediate between carbide and high-speed steel. The three main constituents of these alloys, cobalt, chromium, and tungsten, are combined in various proportions to produce different grades, as shown in Table V.

Cutting Speed. Cutting speed is the most critical variable affecting metal-removal operations on titanium. Cutting speed has a pronounced effect on the tool-chip temperature as shown in Figure 3. Since excessive speeds cause overheating and poor tool life, cutting speeds should be limited to relatively low levels unless the cutting site is properly cooled (Refs. 4,6,13). Rotating cutters or workpieces should be at the desired speed when cutting starts.

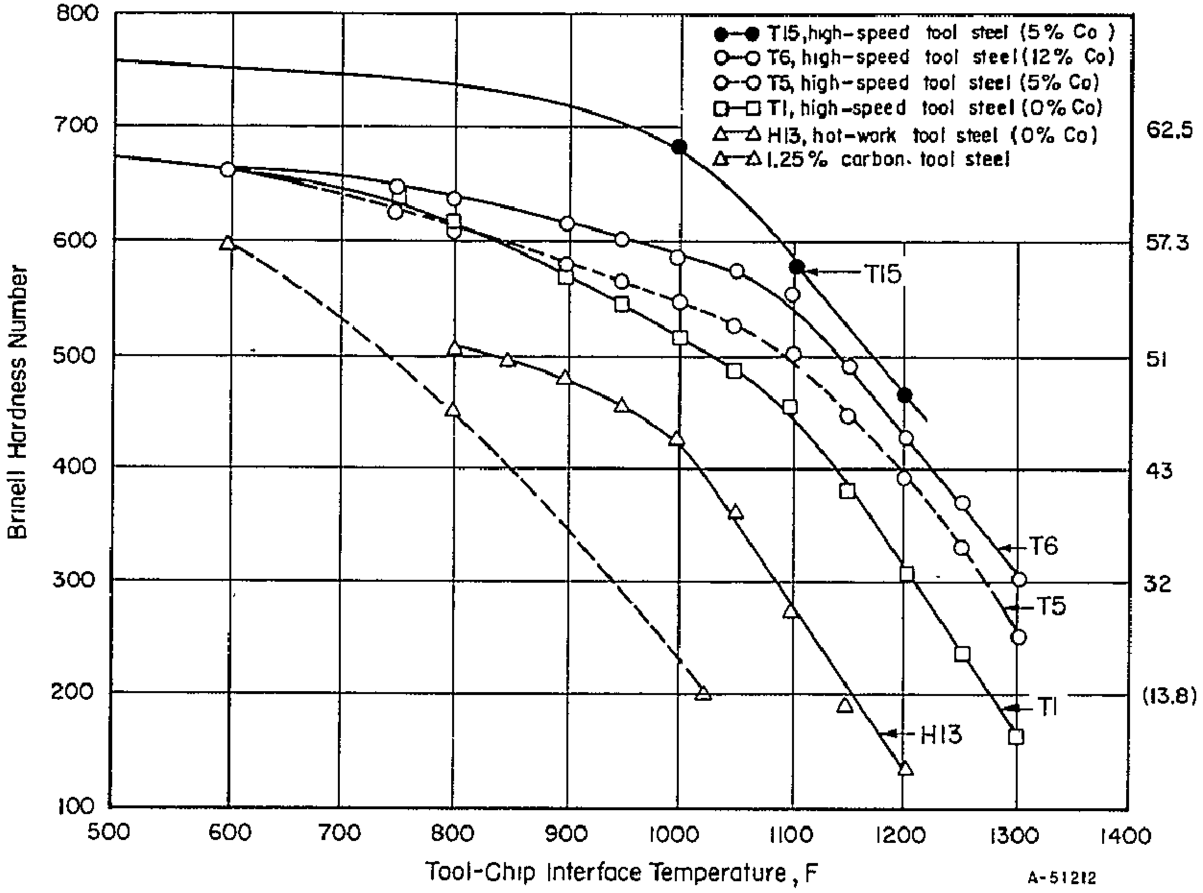


FIGURE 2. EFFECT OF TEMPERATURE ON THE HARDNESS OF VARIOUS TYPES OF TOOL STEEL

Source: Harder, O. E., and Grove, H. A., Hot-Hardness of High-Speed Steels and Related Alloys, Trans. Amer. Inst. Met. Eng., 105, 88-124 (1933).

TABLE IV. TOOL-MATERIAL GUIDE FOR HIGH-SPEED STEELS(a)

Group	AISI Code(b)	Composition, weight per cent				
		Tungsten	Chromium	Vanadium	Cobalt	Molybdenum
Tungsten	T-1	18	4	1	--	--
	T-4	18	4	1	5	--
	T-5	18.5	4	1.75	8	--
	T-6	20	4	2	12	--
	T-8	14	4	2	5	--
	T-15	14	4	5	5	--
Molybdenum	M-1	1.5	4	1	--	8
	M-2	6	4	2	--	5
	M-10	--	4	2	--	8
	M-3	6	4	2.75	--	5
	M-3, Type 1	6.25	4	2.50	--	5.70
	M-3, Type 2	5.6	4	3.3	--	5.50
	M-4	5.50	4	4	--	4.50
	M-6	4	4	1.5	12	5
	M-7	1.75	3.75	2	--	8.75
	M-30	2	4	1.25	5	8
	M-33	1.75	3.75	1	8.25	9.25
	M-15	6.5	4	5	5	3.5
	M-34	2	4	2	8	8
	M-35	6	4	2	5	5
	M-36	6	4	2	8	5
	M-41	6.25	4.25	2	5	3.75
	M-42	1.5	3.75	1.15	8	9.5
	M-43	1.75	3.75	2	8.25	8.75
	M-44	5.25	4.25	2.25	12	6.25

(a) Data from Metals Handbook, Eighth Edition, American Society for Metals (1961), p 672. For commercial listings, reference can be made to "A Guide to Tool Steels and Carbides", Steel (April 21, 1958), Cleveland 13, Ohio; or to "Directory of Tool, Die Steels and Sintered Carbides", Twenty-Seventh Edition (1959), The Iron Age, Philadelphia 39, Pennsylvania.

(b) When greater than average red hardness is needed, cobalt-containing grades are recommended. So-called parallel grades in the molybdenum and tungsten groups are not necessarily comparable. For example, special-purpose steels such as T-6, T-8, T-15, and M-6, M-35, and M-36 seem to have no close counterparts in the opposite group. The unique compositions and properties of these steels often suit them to certain applications without competition.

TABLE V. TOOL-MATERIAL GUIDE FOR CAST ALLOYS

	Composition, per cent									Hardness, R_C
	Co	Cr	W	C	Ni	Fe	Ta	B	Others	
Stellite 19(a)	50.6	31	10.5	1.9	--	3.0 max	--	--	3.0	55
Stellite 3(b)	46.5	30.5	12.5	2.45	3.0 max	3.0 max	--	--	2.0	60
Tantung G(c)	46	28	16	2.0	--	2.0	5	0.2	2.0	--
Stellite Star-J(d)	40.5	32	17	2.5	2.5 max	3.0 max	--	--	2.5	61
Stellite 98M2(e)	37.5	30	18.5	2	3.5	2.5 max	--	--	6	63

(a) Possesses the highest resistance to shock loading or intermittent-cutting effect, but the lowest red hardness of the stellites listed.

(b) Possesses higher hardness, but lower impact strength than Stellite 19. If Stellite 3 can handle the shock conditions of cutting, it is preferable to Stellite 19.

(c) A good compromise of hardness and shock resistance.

(d) Among the stellites, the hardness of Star-J is second only to 98M2. It should machine metal faster than Stellites 3 and 19 under moderate impact conditions. Stellite Star-J is suitable for milling cast iron.

(e) Possesses the highest hardness of all stellites, but only fair impact strength.

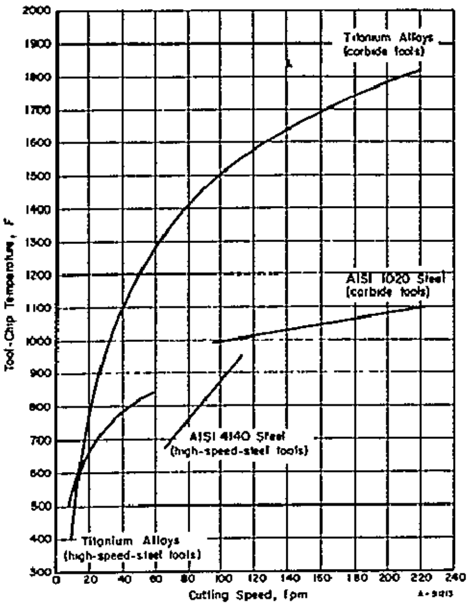


FIGURE 3. EFFECT OF CUTTING SPEED ON CUTTING TEMPERATURE FOR CARBIDE AND HIGH-SPEED STEEL

Feed. All machining operations on titanium require a positive, uniform feed. The cutting tool should never dwell or ride in the cut without removing metal (Refs. 4,13). As an added precaution, all cutters should be retracted when they are returned across the work (Ref. 18).

Cutting Fluids (Ref. 8). Cutting fluids are used on titanium to increase tool life, to improve surface finish, to minimize welding of titanium to the tool, and to reduce residual stresses in the part. Soluble oil-water emulsions, water-soluble waxes, and chemical coolants are usually employed at the higher cutting speeds where cooling is important. Low-viscosity sulfurized oils, chlorinated oils, and sulfochlorinated oils are used at lower cutting speeds to reduce tool-chip friction and to minimize welding to the tool. These cutting fluids have been identified as follows for use in some of the subsequent machining tables:

Fluid Code Number	Cutting Fluid Type
1	Soluble oil-water emulsion (1:10)
2	Water-soluble waxes
3	Chemical coolants (synthetics; barium hydroxide, etc.)
4	Highly chlorinated oil
5	Sulfurized oil
6	Chlorinated oil
7	Sulfochlorinated oil
8	Rust-inhibitor types (like nitrite amine)
9	Heavy-duty soluble oil (a chlorinated extreme pressure additive type)

Although chlorinated oils are being used in some cases on titanium and its alloys, they should be avoided if nonchlorinated fluids satisfy the machining requirements (Ref. 8). Residual chloride from these fluids may lead to possible stress-corrosion cracking of parts in service. When chlorinated fluids are used on titanium, the residues must be removed promptly with a nonchlorinated degreaser like methyl ethyl ketone (MEK). Fundamentally, it is always good practice to remove all cutting-fluid or lubricant residues from workpieces, especially before any heating operation.

SCRAP PREVENTION (REF. 2)

Since titanium is a relatively expensive metal, every effort should be made to avoid waste. Table VI illustrates the common sources of scrap and their importance in different machining operations, and suggests ways of preventing scrap.

Any scrap-prevention program requires emphasis on following the basic recommendations for machining titanium stated previously. In addition to using those practices, parts should be handled and transported with reasonable care. Nicks and scratches must be avoided, both on parts in process and on finished parts. Suitable containers or paper separators should be used for parts in process to prevent damage in handling and storage.

The machining and grinding of titanium normally require closer supervision than do operations on other metals, not only to prevent scrap, but also to detect defective parts early in the processing schedule.

TABLE VI. SOURCES OF SCRAP FOR VARIOUS MACHINING OPERATIONS AND THE CORRECTIVE ACTIONS NEEDED

	Sources of Scrap							
	Burned Surfaces	Rough Finish	Chatter Marks	Dimensional Discrepancies	Residual Stresses	Distortion	Broken Tools	Handling Scratches
	Incidence of Scrap for Machining Operation Shown							
Operation								
Turning		x	x	x	x	x		x
Milling		x	x	x				x
Drilling				x			x	x
Tapping		x		x			x	x
Grinding	x	x		x	x	x		x
Belt grinding	x				x			x
Cut-off	x							
Sawing				x				x
	Corrective Action Needed to Avoid Defects Indicated Above							
Corrective Action								
Strong, sharp tools		x		x	x	x	x	
Dressed wheels	x					x		
Positive chip removal		x	x					
More rigid setups		x	x	x				
Modern machine tools			x	x				
Speed/feed/cutting fluid		x		x	x	x	x	
Careful handling								x
Stress relief					x	x		

HAZARD AND HEALTH CONSIDERATIONS (REFS. 20-22)

Some potential fire and explosion hazards are associated with machining and grinding operations for titanium. However, no confirmed adverse physiological reactions have been attributed to titanium in this country (Ref. 22).

From the standpoint of fire and explosion, titanium chips and dust under certain conditions can be hazardous (Ref. 22). The following comments illustrate this situation:

- Fine chips from sawing and filing operations and turnings from fine finishing cuts can be ignited with a match, and will continue to burn after the heat source is removed (Refs. 20,21). Heavy chips and coarse turnings present only a slight fire hazard (Refs. 20,23).
- Occasionally, titanium turnings may ignite when the metal is cut at high speeds without the adequate use of a proper coolant (Ref. 22). The situation is similar when titanium is ground dry because of the intense spark stream (Ref. 22).
- Very finely divided titanium dispersed in air in proper proportions can create an explosion hazard (Ref. 21).
- The explosion hazards of titanium, according to the U. S. Bureau of Mines, may exceed that of finely divided magnesium (Refs. 21,24).

In regard to health considerations, a number of investigators have demonstrated experimentally that titanium is not toxic (Refs. 25-28). In fact, its physiological inertness, corrosion resistance, lightness, and low modulus of elasticity suggest uses in orthopedic surgery (Ref. 29). However barium compounds like barium hydroxide when used as cutting fluids for titanium may be hazardous to personnel unless suitable precautions are taken to protect machine operators. Barium compounds may possess both acute and chronic toxicity if inhaled at high concentrations. Consequently positive measures must be taken to exhaust all fumes and mist from the machining area. The recommended maximum atmospheric concentration per 8-hour day is 0.5 milligram per cubic meter of air (Refs. 7,88).

SAFETY PROCEDURES

Safety procedures are concerned with both preventive and emergency measures.

Preventive measures generally mean that good housekeeping practices must be maintained at all times (Refs. 20-22,24). Specifically they involve the following:

- Regular chip collection, and storage in covered containers (once a day)
- Removal of containers when one-half full to an outside location
- Keeping machine ducts and working area clean of titanium dust, chips, and oil-soaked sludge
- Cleaning area and equipment of all oil and grease, and removal of rags and waste subject to spontaneous combustion.

If a fire starts, it should be smothered by using dry powders developed for combustible metal fires (Refs. 21-23,25). These include graphite powder, powdered limestone, absolutely dry sand (Refs. 21,23,25), and dry compound extinguisher powder (Refs. 21, 23,25) for magnesium fires.

Carbon tetrachloride or carbon dioxide extinguishers should not be used (Refs. 21-23,25).

Water or foam should never be applied directly to a titanium fire. Water accelerates the burning rate and may cause hydrogen explosions (Refs. 20,25). However, water can be applied to the surrounding area up to the edges of the fire to cool the unignited material below the ignition point (Refs. 20,25).

COST COMPARISONS

Very little comparative information on machining costs is available from fabricators experienced in machining both titanium and aluminum. Cost ratios assignable to materials are difficult to establish and vary between machining operations (Ref. 30).

Machining titanium usually takes more time than machining conventional materials because lower machining speeds and feeds are needed (Ref. 7). On the basis of equal volumes of metal removed, different machining operations performed on Ti-8Al-1Mo-1V probably will require an over-all range of 1.2 to 3.5 times the number of man-hours needed for a similar aluminum part (Ref. 7). Specific ratios of different machining operations are shown in Table VII.

TABLE VII. ESTIMATED DIRECT-LABOR-HOUR RATIOS(a) FOR MACHINING SIMILAR TITANIUM(b) AND ALUMINUM(c) AIRFRAME DETAILS(d) (REF. 7)

Machining Operation	Titanium to Aluminum Man-Hour Ratios(e)		
	Probable	Minimum	Maximum
Turning	1.7 to 1	1 to 1	3 to 1
Drilling	2.6 to 1	1.3 to 1	2.7 to 1
End milling	2.7 to 1	2 to 1	3.3 to 1
Straight milling	1.2 to 1	1.1 to 1	2 to 1
Profile milling	1.6 to 1	1.5 to 1	1.8 to 1
Hole preparation	3.5 to 1	2 to 1	4.5 to 1
Over-all machining	2.7 to 1	1.5 to 1	3.5 to 1

(a) Machining and setup times expected in 1970-1975.
(b) Ti-8Al-1Mo-1V.
(c) 2000 and 7000 series aluminum alloys in 1964-1965.
(d) A production of 100 airframes is assumed.
(e) Ratios do not reflect the rates of improvement that could occur for aluminum by 1970-1975.

These ratios are not necessarily valid where a titanium part of one design is substituted for an aluminum part of another design to perform the same function, at a savings in weight. Furthermore, while these ratios reflect possible improvements in metal-removal rates for titanium by 1970, they do not reflect similar improvements in machining aluminum parts (Ref. 7). Nevertheless, they can be helpful in extrapolating the extensive experience, information, and data available on machining aluminum parts in order to estimate probable costs of future titanium parts. Before these ratios can be converted to labor costs, however, items such as complexity factors and learning curves should be taken into consideration (Ref. 7).

Generally speaking, experience in machining titanium does not appear to be extensive enough to permit precise titanium/aluminum cost ratios. Estimates, however, have been made. A summary of estimates on comparative machining costs collected from several shops experienced in machining is shown in the following tabulation (Ref. 30).

Process	Cost of Machining Titanium Versus Aluminum
Turning	1 to 3:1
End milling	2:1
Straight milling	1.2 to 4:1
Drilling	2.5:1
Routing and sawing	4 to 6:1

MILLING-TYPE OPERATIONS

Introduction. Milling is an intermittent cutting operation which can be difficult to control because of the large number of variables involved (Ref. 31). Welding, edge chipping, and subsequent tool failure are the basic problems (Refs. 3,13). Additional problems include heat, deflection, abrasion, and distortion.

The amount of titanium smeared on cutter edges by welding is proportional to the thickness of the chip as it leaves the cut. The welded-on metal and a small part of the underlying edge of the tool later chips off when the tooth re-enters the cut. This starts the wearland. Welding and chipping continue to cause gradual wear until the tool fails suddenly (Ref. 18). As the tool wears, the surface finish deteriorates, and it soon becomes more difficult to control dimensions.

Gradual tool wear can be minimized by climb milling (Refs. 4, 32,33). This practice results in a shorter tool path and a thinner chip when the tooth leaves the workpiece. Both factors reduce the amount of metal adhering to the cutting edge, and wear from that source. Slower speeds and smaller feeds minimize chipping caused by impact and lower the cutting temperature.

The presence of oxides or contaminated layers on titanium can cause localized wear or notching of the tools at the depth-of-cut line. Etching the workpiece in a suitable acid mixture will alleviate abrasion of this kind.

Some problems result from the deflection of thin parts or slender milling cutters (Ref. 18) and the distortion of workpieces accompanying the mechanical relief of residual stresses (Ref. 32). In the latter case, thermal-stress-relieving treatments in fixtures prior to machining is desirable.

In spite of the potential difficulties mentioned, milling operations produce titanium parts to aircraft standards of finish and accuracy at production rates comparable to those attained on aircraft constructional steel (Ref. 32). A surface finish of 63 microinch or better is readily achieved and finishes as good as 17 microinch are possible in finishing cuts (Ref. 32).

Basic Milling Operations. Milling operations can employ either the face or peripheral milling approach. Face-milling operations employ the combined action of cutting edges located on the periphery and face of the cutter. The milled surface is generally at right angles to the cutter axis, and is flat except when milling to a shoulder. Face mills and end mills represent the tools used in this operation.

In peripheral or arbor milling the cutting teeth are located on the perimeter of the cutter body. The types of arbor-mounted cutters used include plain mills, helical mills, slab mills, side mills, and slotting cutters.

Face mills produce flat surfaces more efficiently and accurately than plain milling cutters do. Faster feed rates are also possible with face mills because they are more rugged. In addition, the complicated supports usually required for arbor-mounted cutters are unnecessary when face mills are used. Face milling is preferred whenever it is practical.

Machine Tool Requirements. Heavy-duty milling machines produce the best results in milling titanium (Ref. 32). Horizontal or vertical knee-and-column milling machines, as well as fixed-bed milling machines, are used on various face- and end-milling operations. Numerically controlled or tracer controlled milling machines are used for profile- and pocket-milling operations.

Generally speaking, 10 to 15 horsepower is usually sufficient for milling titanium. This means, for example, a Number 2 heavy-duty or a Number 3 standard knee-and-column milling machine. However, the machines needed to accommodate large parts may have as much as 25 to 50 horsepower available (Ref. 34).

Milling Cutters. The choice of the milling cutter depends on the type of machining to be done (Refs. 7,8). Face mills, plain milling cutters, and slab mills are usually selected for milling plane surfaces. End mills are suitable for light operations such as profiling and slotting (Ref. 35). Form cutters and gang-milling cutters are used for shaped cuts. Helical cutters are preferred because they promote a smoother cutting action. The use of the smallest-diameter cutter with the largest number of teeth without sacrificing necessary chip space minimizes chatter and deflection (Refs. 2,36). All cutters, however, need adequate body and tooth sections to withstand the cutting loads developed in the particular machining operation.

Cutter Design. Tool angles of a milling cutter should be chosen to facilitate chip flow and immediate ejection of the chip. The controlling angles are the axial rake, radial rake, and corner angles.

Rake Angles. Rake angles are not especially critical (Refs. 3,13,36). Boston (Ref. 4) indicates in his report that radial rake angles between +7 and -7 degrees should give the most consistent performance (Ref. 4) for carbide tools. Other investigators have reported that tool life progressively improves as the radial rake is reduced from +6 to 0 degrees and down to -10 degrees (Ref. 13).

Positive rake angles are generally used on high-speed steel cutters, but occasionally it is necessary to reduce the rake to zero to overcome a tendency for the cutter to "dig-in", or to chip prematurely. K-lands are practical for reducing rake angles (Ref. 18).

Inclination Angle. The axial-radial rake-angle combination should be balanced with the corner angle to produce a positive angle of inclination. Positive inclination angles lift the chip up and away from the machined surface and thus prevent scratching (Ref. 11). Angles of inclination (as well as true rake) can be determined from the intersection of an axial rake/radial rake line with a given corner angle on the nomographs shown in Figure 4. The angles involved are 0 degrees axial rake, -10 degrees radial rake, and a 30-degree corner angle.

Corner Angle. The use of a corner angle not only encourages positive angles of inclination but also provides a longer cutting edge to distribute cutting forces over a greater area (Refs. 13, 36). This results in lower cutting pressures and temperatures and less smearing (Refs. 4,13).

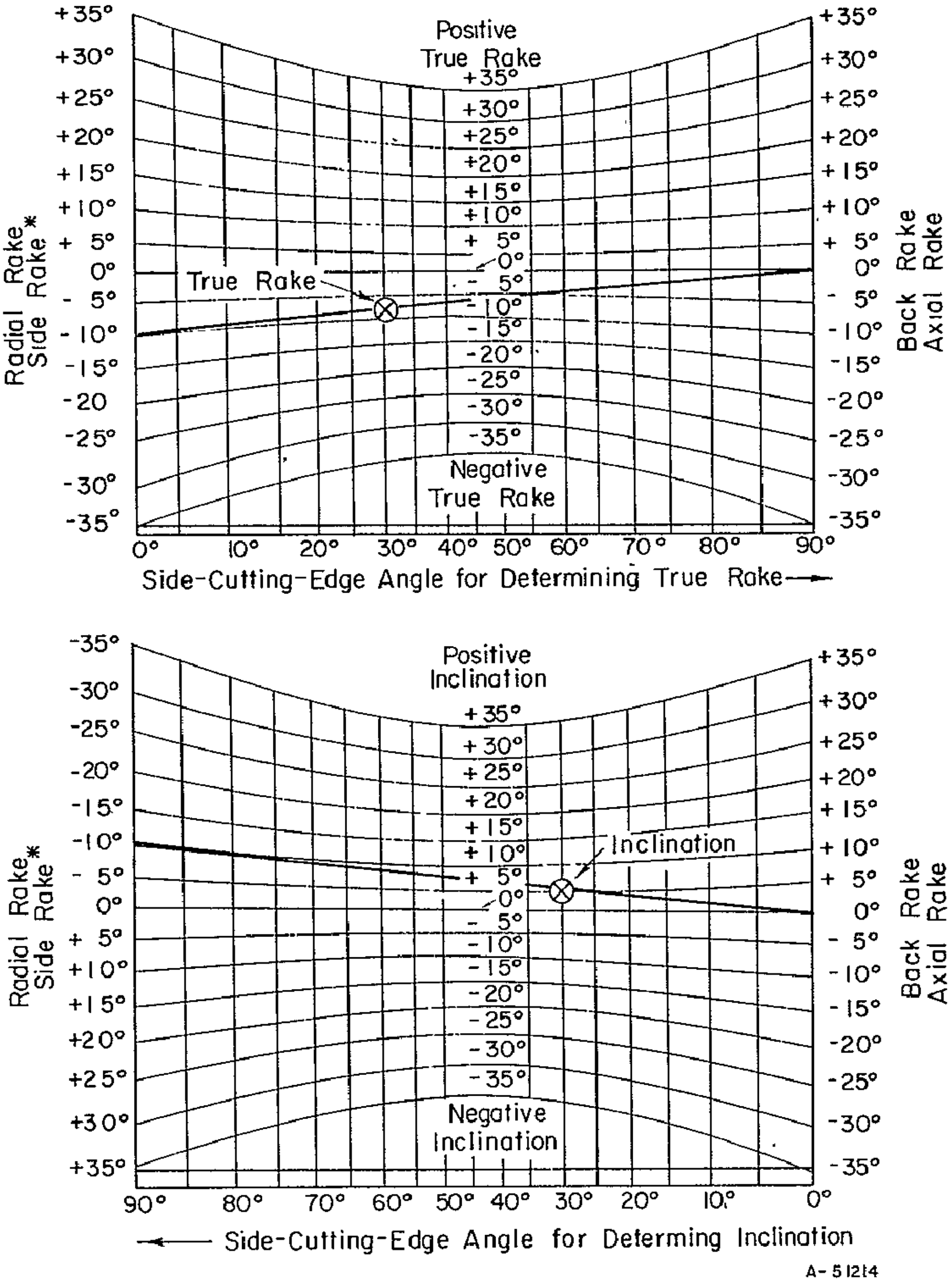


FIGURE 4. NOMOGRAPHS FOR DETERMINING TRUE RAKE AND INCLINATION ANGLES FOR MILLING CUTTERS (REF. 35)

A 30 to 45-degree chamfer also produces a longer cutting edge and a wider, thinner chip. However, a corner angle is more effective than a chamfer (Ref. 3).

Relief Angles. Relief angles are probably the most critical of all tool angles when milling titanium (Ref. 8). Generally, relief angles of less than 10 degrees lead to excessive smearing along the tool flank, while angles greater than 15 degrees weaken the tool and encourage "digging in" and chipping of the cutting edge (Refs. 2, 13,18,36). At lower speeds, relief angles of around 12 degrees give longer tool life than do the standard relief angles of 6 or 7 degrees (Ref. 4). If chipping occurs, the 12-degree angles should be reduced toward the standard values.

Tool Quality. All cutters should be ground to run absolutely true (Refs. 2,4) to make certain that all teeth are cutting the same amount of material (Ref. 2). The total run out should not exceed 0.001-inch total indicator reading (TIR).

Tool Materials. The choice of the proper tool material is not a simple matter in milling, and depends on the various factors already described on page 8. Carbide and high-speed steel cutters are normally used.

Carbide. Carbide milling is recommended whenever possible for large lots, high-production rates, or extensive metal-removal operations, particularly in face-milling and slab-milling applications (Refs. 31,32). However, carbide cutters should not be used if a machine tool is not in good condition, or if a setup cannot be made rigid enough (Ref. 36). High-speed steel tools should be used instead.

High-Speed Steel. High-speed steel cutters are popular mainly because of their ready availability. The T4 and T5 cobalt grades are used for high-production milling of small parts, whereas the regular T1, T2, and M1 grades are suitable for low-production milling. High-speed steel can be used under conditions of insufficient rigidity, as well as for slots and formed cuts.

Tool life of high-speed steel cutters is low and quite sensitive to cutting speed when milling titanium. Furthermore, high-speed steels fail almost immediately when they encounter surface oxides or scale.

Some differences in the performance of high-speed steel cutters may exist between cutters of the same type and geometry supplied by different manufacturers. This difference can be attributed to the geometry, composition, and/or heat treatment of the tool. Hence, purchasing specifications should cover both the grade and the heat treatment of the steel (Ref. 31).

Setup Conditions. Fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture (rather than the clamps) should absorb the cutting forces (Ref. 19). Fixtures should be rugged enough to minimize distortion and vibration.

The selection of speeds, feeds, and depth of cut in any setup should take into account the rigidity of the setup, the optimum metal-removal rate/tool life values, and the surface finish and tolerances needed on the finished part.

Cutting Speed. Cutting speed is a very critical factor in milling titanium. When starting a new job, it is advisable to use a cutting speed in the lower portion of speed ranges suggested in Tables 8 through 11 (Refs. 4,13).

Sufficient flywheel-assisted spindle power should be available to prevent loss in cutting speed as the cutter takes the cutting load (Ref. 19).

Feed. Feed rates for milling titanium are usually limited to the range of 0.002 to 0.008 inch per tooth (ipt) to avoid overloading the cutters, fixtures, and milling machine. Lighter feeds reduce the tool/chip contact area, thereby reducing the incidence of welding and premature chipping (Refs. 2,4,36). Delicate types of cutters and flimsy or nonrigid workpieces also require lighter feeds (Ref. 31).

It is important to maintain a positive feed. Cutters must not dwell or stop in the cut for reasons stated on page 6. Climb milling is preferred for carbide and cast alloy tools except for scale-removal operations (Ref. 32). Conventional milling is more suitable for high-speed steel tools and for removing scale (Ref. 33).

Depth of Cut. The selection of cut depth depends on setup rigidity, part rigidity, the dimensions and tolerances required, and the type of milling operation undertaken. For skin-milling operations, light cuts (0.010 to 0.020 inch) seem to cause less warping than deeper cuts (0.04 to 0.06 inch) (Ref. 29). When cleaning up and sizing extrusions, a 0.05-inch depth is usually allowed (Ref. 32). Depths of cut of up to 0.15 inch can be used, however, if sufficient power is available (Ref. 4). When forging scale is present, the nose of each tooth must be kept below the hard skin to avoid rapid tool wear.

Cutting Fluids (Ref. 2). A wide variety of cutting fluids are used to reduce cutting temperatures and to inhibit galling. Sulfurized mineral oils are used extensively and are usually flood applied. Water-base cutting fluids are also widely used and are either flood or mist applied. Tool life seems to be significantly improved when a 5 per cent barium hydroxide-water solution is used as a spray mist. However, it seems advisable to exhaust the fumes from the cutting area to protect the operator (Ref. 37) as pointed out on page 17.

Good tool life can be obtained by using the spray-mist technique for all water-base coolants. The mist should be applied ahead of a peripheral milling cutter (climb cutting), and at both the entrance and exit of a face-milling-type cutter. Pressurizing the fluid in an aspirator system permits better penetration to the tool-chip area, better cooling, better chip removal, and better tool life by a factor of two (Ref. 37). With flood coolant, the chips tend to accumulate behind the cutter, and are occasionally carried through the cutter.

There are a number of proprietary fluids in each category that are producing excellent results.

General Supervision. Titanium-milling operations require reasonably close supervision. The supervisor should check all new milling setups before operations begin. Thereafter, he should spot-check for nicks and scratches to prevent potentially defective parts from being processed too far.

Milling cutters should be kept sharp (Refs. 2,18,32). Hence, they should be examined for early indications of dulling. When chips start to exhibit a dull-red color, the tool should be replaced immediately. Some companies recommend having at least two cutters available in case replacement is necessary for a given operation. Minimum downtime usually occurs when the entire cutter is replaced by a new one, rather than by waiting for a dull cutter to be resharpened.

The normal criterion of wear for replacing a cutter is considered to be a wearland of 0.010 inch (Ref. 32) for a carbide cutter and 0.015 inch for a high-speed steel cutter.

Face Milling. Face mills of normal design are used for milling relatively wide flat surfaces, usually wider than 5 inches (Ref. 35). Special face mills are also used and include the rotating insert and conical types (Refs. 37,39).

Diameters of face mills are important. They should be as wide as but not appreciably wider than the width of the cut (Refs. 2,13). If a smaller-diameter cutter can perform a given operation and still overhand the cut by 10 per cent, then a larger cutter should not be used. Conversely, it is not good practice to bury the cutter in the work (Ref. 13).

Face mills and shell-end mills range from 1 to 6 inches in diameter. Face mills are also available in diameters greater than 6 inches. A good surface finish and freedom from distortion are desirable qualities when machining wide surface like sheets. Surface finish, in the case of milling, improves significantly with decreasing feed but only slightly with increasing speed.

Table VIII contains typical data on feeds, speeds, depths of cut, and tool design. Figure 5 explains the tool-angle nomenclature and codes used.

End Milling. End milling, a type of face-milling operation, utilizes the cutting action of teeth on the circumferential surface and one end of a solid-type cutter (Ref. 35). End-milling cutters are used for facing, profiling, and end-milling operations; and include the standard end mills and two-lip end or slotting mills (Ref. 35). Chip crowding, chip disposal, and tool deflection are possible problems in some end-milling operations.

Due to an inherent lack of rigidity, end mills should be as short as practical (Ref. 18), and their shank diameter should equal their cutting diameters. The proper combinations of hand of helix and hand of cut should be considered to avoid deflection of the cutter in the direction of an increasing depth of cut (Ref. 35).

When milling slots where the end of the cutter is in contact with the work, the hand of the helix and the hand of the cut should be the

TABLE VIII. MILLING TITANIUM ALLOYS WITH HELICAL FACE MILLS[a]

Depth of Cut: 0.05 to 0.25 inch

		C-2 Carbide Tools[c]				High-Speed Steel Tools[c]				
Titanium Alloy	Alloy Condition[b]	Tool Geometry[d]	Cutting Fluid[e]	Cutting Speed[f], fpm	Feed, ipt	Tool Material	Tool Geometry[d]	Cutting Fluid[e]	Cutting Speed[f], fpm	Feed, ipt
Commercially pure	An	C	1,3,5	200-400	0.004-0.008	M1, T1	A	1,3,5	25-150	0.003-0.006
Ti-8Al-1Mo-1V	An	B, D	1,3	110-170	0.004-0.006	M3, T5, T15	A, G	1,3	30-40	0.003-0.006
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	A, B	1,2,3	170-200	0.002-0.008	M3, T5, T15	A, F	1,2,5	40-60	0.002-0.008
Ti-4Al-3Mo-1V	An	A, B	1,2,3	170-200	0.002-0.008	M3, T5	A, F	1,4, 5, 6,7	40-60	0.002-0.006
	HT	B, C	1,2,4	60-95		T15, M15	A, C		20-35	
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	A, C	1,3,4	125-170	0.004-0.008	M3, T15	A, C	1,4, 5, 6,7	40-60	0.002-0.006
	HT	C	1,4	80-110		T15	A, C		20-50	
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	B, C	1,3,4	110-150	0.004-0.008	M3, T15	A, C	1,4	30-60	0.004-0.006
	HT	C	1,4	80-100		T15	C	1,4	25-50	
Ti-13V-11Cr-3Al	An	B, C	1,3,4	100-125	0.003-0.006	T15	C, E	4	25-45	0.004-0.006
	HT	C, F	4	70-100		T15	C, E	4	20-30	

(a) From Refs. 2, 7, 8, 13, 18, 34, 37, 40, 87, 88

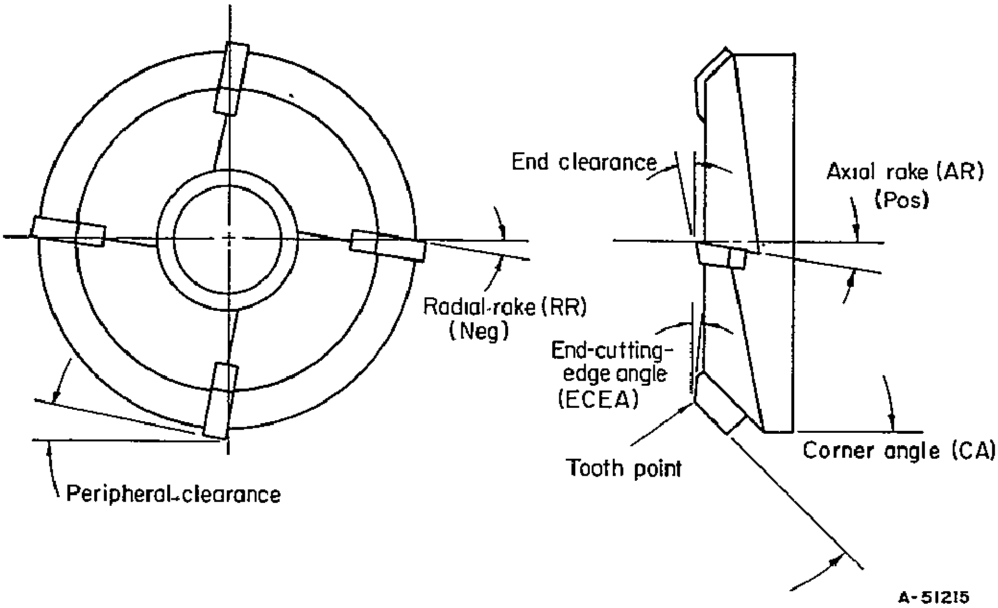
(b) An = annealed; HT = solution treated and aged.

(c) CISC designations for carbides, AISI designations for high-speed steels.

(d) See Figure 5 for tool angles involved.

(e) See page 54 for specific types. Remove all chlorinated oil residues with MEK.

(f) The lower speed in each range is used for the heavier feeds and depths of cut.



Tool Angles, degrees, and Nose Radius, inch	Tool Geometry Code							
	A	B	C	D	E	F	G	H
Axial Rake	0	0	0 (to +10)	+6 to -6	+10 (to 0)	0 to +10	0 to +6	15
Radial Rake	0 (to +10)	0 (to -10)	0	0 to -14	0 (to +10)	0 to +10	0 to +14	0
End Relief	12	12	10	6 to 12	10	10 to 12	6 to 12	12
Peripheral Relief	12	12	10	6 to 12	10	10 to 12	6 to 12	12
End-Cutting Edge	6 (to 12)	12 (to 6)	10	6 to 12	6 to 10	6 to 10	6 to 12	*
Corner	30	30	45	0 to 45	45	30 to 45	30	*
Nose Radius	0.04	0.04	0.04	0.04	0.04	0.04	0.04	*

*No data.

FIGURE 5. TOOL GEOMETRY DATA FOR FACE MILLS

same. This means a right-hand helix for a right-hand cut, or a left-hand helix for a left-hand cut (Ref. 35).

When profile milling, where the periphery of the cutter is doing the cutting, the opposite is true – i.e., left-hand helix for a right-hand cut and vice versa (Ref. 35).

Cutter diameter in profile or pocket milling depends on the radius needed on the pockets.

High-speed steel cutters are normally used for end-milling and profile-milling operations. Helical-style cutters give better performance than the straight-tooth designs do. The shank of end mills should be somewhat softer than the cutter flutes to avoid breakage between shank and flutes (Ref. 40).

Tables IX and X provide machining data for end-milling, profile-milling, and slotting operations. Figure 6 illustrates the tool nomenclature and codes used.

Slab or Spar Milling. Slab milling is used to improve the tolerances and surface finish on extrusions. The operation is usually done on a heavy-duty, fixed-bed mill.

Sections that are relatively long and thin (like spars) require special considerations (Ref. 32). In the first place, as-received extrusions may need straightening before machining, since extrusion straightness tolerances exceed mill-fixture and part tolerances (Ref. 32). Spars should not be forced into a fixture (Ref. 32). Spars may be straightened mechanically if the distortion is not too severe (Ref. 32). Otherwise they should be hot straightened in fixtures. This may include aging in fixtures at 1000 F (4 hours) for Ti-6Al-4V (Ref. 32).

Rigid setups are necessary. Arbor-mounted cutters require arbors of the largest possible diameter (Ref. 18). The arbor should have just the proper length required for the number of cutters mounted and the arbor support employed (Ref. 35). Arbor overhang beyond the outer support should be avoided since it is conducive to chatter and vibration (Ref. 35).

Cutters should be mounted as close to the column face of the milling machine as the work will permit (Ref. 35). The cutters of opposite hand to the cut should be used so that the cutting forces will

TABLE IX. SLOTTING TITANIUM ALLOYS WITH HELICAL END MILLS[a]

Depth of Cut: 0.05 to 0.25 inch

Titanium Alloy	Alloy Condition[b]	C-2 Carbide Tools[c] (Tool Geometry - E)			M-2 High-Speed Steel Tools[c] (Tool Geometry - D)		
		Cutting Speed[d], fpm	Feed[e], ipt		Cutting Speed[d], fpm	Feed[e], ipt	
			3/8-In. Diameter	3/4-In. Diameter		3/8-In. Diameter	3/4-In. Diameter
Commercially pure	An	100-190	0.0007-0.003	0.003-0.006	40-75	0.0007-0.003	0.003-0.005
Ti-8Al-1Mo-1V	An	75-140 200	0.0007-0.003	0.003-0.006 0.002-0.004	30-50	0.0007-0.003	0.003-0.005
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	90-175	0.0007-0.003	0.003-0.006	35-70	0.0007-0.003	0.003-0.005
Ti-4Al-3Mo-1V	An HT	90-175	0.0007-0.003 --	0.003-0.006 --	35-70 --	0.0007-0.003 --	0.003-0.005 --
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An HT	75-165 60-115	0.0007-0.003 0.0006-0.003	0.003-0.006 0.003-0.005	30-65 25-45	0.0007-0.003 0.0006-0.003	0.003-0.005 0.002-0.004
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An HT	75-140 60-115	0.0007-0.003 0.0006-0.003	0.003-0.006 0.003-0.005	30-55 25-45	0.0007-0.003 0.0005-0.003	0.003-0.005 0.001-0.004
Ti-13V-11Cr-3Al	An HT	75-140 50-115	0.0007-0.003 0.0004-0.002	0.003-0.006 0.002-0.004	30-55 20-45	0.0007-0.003 0.0004-0.002	0.003-0.005 0.001-0.003
Cutting Fluids	Use heavy duty soluble oil-water or chemical coolants, or highly chlorinated cutting oil. Remove all chlorinated oil residues with MEK.						

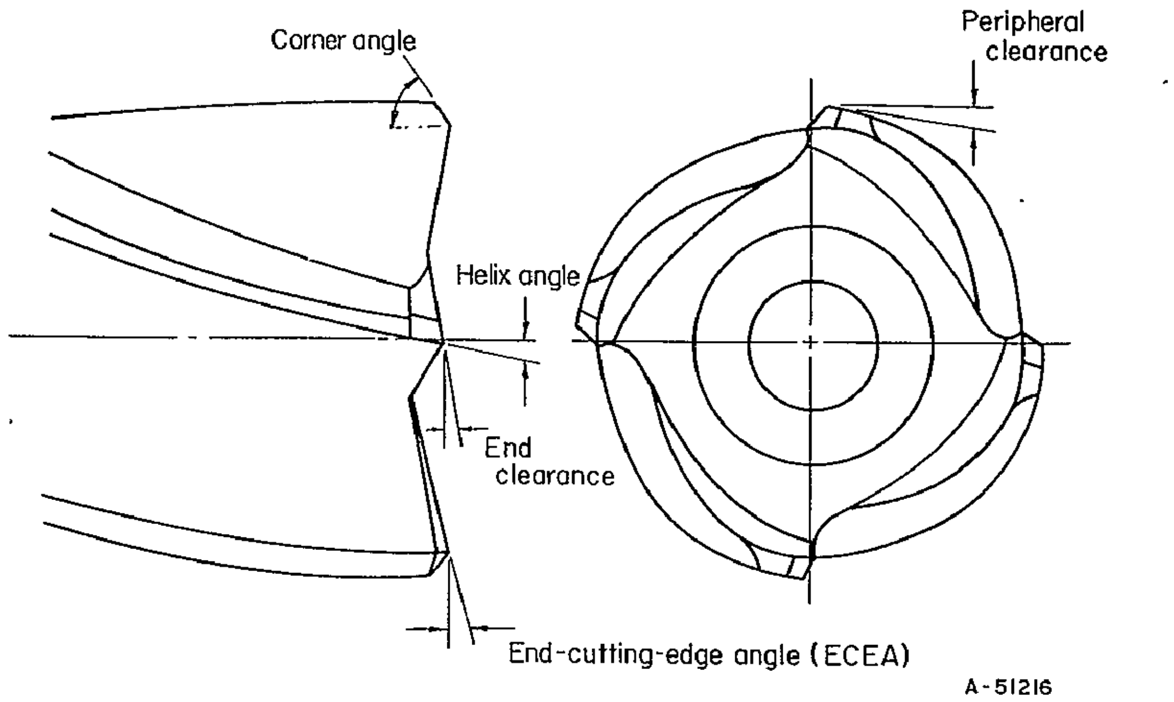
(a) From Refs. 37,40,87,88.
(b) An = annealed; HT = solution treated and aged.
(c) CISC designations for carbides; AISI designations for high-speed steels. See Figure 6 for tool angles involved.
(d) The higher speed correlates with higher feeds and lower depths of cut.
(e) Feeds shown are for 3/8- and 3/4-inch diameter end mills. Lower feeds are needed for 1/8-inch end mills, and feeds with 0.008 ipt are used for 1- to 2-inch end mills.

TABLE X. PROFILING TITANIUM ALLOYS WITH HELICAL END MILLS(a)

Depth of Cut: 0.015 to 0.005 inch

		C-2 Carbide Tools(c) (Tool Geometry - A)			M3 and M7 High-Speed Steel Tools(c) (Tool Geometry - A)		
		Cutting Speed(d), fpm	Feed(e), ipt		Cutting Speed(d), fpm	Feed(e), ipt	
Titanium Alloy	Alloy Condition(b)		3/8-In. Diameter	3/4-In. Diameter		3/8-In Diameter	3/4-In. Diameter
Commercially pure	An	300-375	to 0.002	0.003-0.004	100-140	to 0.001	0.002-0.0025
Ti-8Al-1Mo-1V	An	140-165	to 0.001	0.002-0.003	50-75	to 0.0007	0.0015-0.002
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	140-165	to 0.001	0.002-0.003	50-75	to 0.0007	0.0015-0.002
Ti-4Al-3Mo-1V	An	140-165	to 0.001	0.002-0.003	50-75	to 0.0007	0.0015-0.002
	HT	100-130	to 0.0007	0.0015-0.002	25-40	to 0.0005	0.001-0.0015
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	140-165	to 0.001	0.002-0.003	50-75	to 0.0007	0.0015-0.002
	HT	100-130	to 0.0007	0.0015-0.002	25-40	to 0.0005	0.001-0.0015
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	140-165	to 0.001	0.002-0.003	50-75	to 0.0007	0.0015-0.002
	HT	100-130	to 0.0007	0.0015-0.002	25-40	to 0.0005	0.001-0.0015
Cutting Fluids	Sulfurized oils, chlorinated oils, or sulfochlorinated oils. Thoroughly clean all titanium parts from all oil residues, especially the chlorinated and sulfochlorinated oils.						

(a) From Refs. 37,40,87,88.
(b) An = annealed; HT = solution treated and aged.
(c) CISC designations for carbide, AISI designations for high-speed steel See Figure 6 for tool angles involved.
(d) The higher speeds correlate with higher feeds and lower depths of cut.
(e) Feeds are for 3/8- and 3/4-inch end mills. Lower feeds are needed for 1/8-inch end mills, and feeds up to 0.006 are used for 1- and 2-inch mills.



Tool Angles, degrees, and Nose Radius, inch	Tool Geometry Code						
	A	B	C	D	E	F	G
Helix	30	45	30	30	15	30	30
Radial Rake	10	10	10	10	0	0 to +4	0
End Clearance	2	*	15	5	12	*	*
Peripheral Clearance	5	4 to 15	*	5	12	6	10
End-Cutting Edge	3	*	*	3	3	*	*
Corner	*	*	45 x 0.040	45 x 0.060	45 x 0.040	*	*
Nose Radius	*	*	*	*	*	*	*

*No data.

FIGURE 6. TOOL GEOMETRY DATA FOR END MILLS

be absorbed by the spindle of the machine (Ref. 35). This is accomplished by using cutters with a left-hand helix for a right-hand cut, and vice versa (Ref. 35). The effective force involved will press the cutter and arbor against the spindle, holding them in position, thus providing a more rigid setup (Ref. 35). When two milling cutters are used end to end on the arbor, both right-hand and left-hand helices should be used. This setup neutralizes the cutting forces which tend to push the cutters away from the work (Ref. 35).

Carbide cutters are preferred for spar milling because of the higher production rates attainable. Helical-style cutters are recommended since they provide wider and thinner chips than do the corresponding straight-tooth types. In slab milling, cutters with six cutting edges per inch of diameter permit heavier feeds and longer tool lives than the conventional cutter with three cutting edges per inch (Ref. 37).

Table XI gives machining data used for various slab-milling operations.

TURNING AND BORING

Introduction. Turning, facing, and boring operations on titanium are essentially the same, and no difficulty is experienced with any of them. They give less trouble than milling, especially when cutting is continuous rather than intermittent. The same speeds used for turning can be used for boring and facing cuts. However, in most cases, the depths of cut and feeds will have to be reduced for boring because of an inherent lack of rigidity of the operation (Ref. 31).

Machine-Tool Requirements. In addition to the machine-tool requirements set forth on pages 6 and 7, it is very important that the proper cutting speed for titanium is available at the machine. In general, the over-all range of spindle speeds available on many of the existing lathes is not broad enough to cover some of the lower speeds needed for titanium.

Modern lathes should have either a variable-speed drive for the spindle or the spindle gear train should have a geometric progression of 1.2 or less in order to provide speed steps of 20 per cent or less for more precise speed selections (Ref. 34).

TABLE XI. SLAB MILLING TITANIUM ALLOYS WITH HELICAL PERIPHERAL MILLS(a)

Depth of Cut: 0.05 to 0.25 inch

		C-2 Carbide Tools(c)				High-Speed Steel Tools(c)				
Titanium Alloy	Alloy Condition(b)	Tool Geometry(d)	Cutting Fluid(e)	Cutting Speed(f), fpm	Feed, ipt	Tool Material	Tool Geometry(d)	Cutting Fluid(e)	Cutting Speed(f), fpm	Feed, ipt
Commercially pure	An	--	1,3,5	300-375	0.006-0.008	T1 M1		1,3,5	130-190	0.004-0.006
Ti-8Al-1Mo-n	An	--	5	150-180	0.005-0.007	M3 T5		5	35-50	0.003-0.005
Ti-8Al-1Mo-n	An	H	1,3	230-370	0.004-0.012	--	--	--	--	--
Ti-5Al-2Sn	An	--	5	150-180	0.005-0.007	M3 T5		5	35-50	0.003-0.005
Ti-6Al-4V	An		5	150-180	0.005-0.007	M3 T15		5	35-50	0.003-0.005
Ti-6Al-4V	HT		5,6,7	100-150	0.004-0.006	T15		5,6,7	20-25	0.002-0.004

(a) Refs. 3,7,8,13,18,32,37,40,87, and 88.
(b) An = annealed; HT = solution treated and aged.
(c) CISC designations for carbides; AISI designations for high-speed steels.
(d) See Figure 5 for tool angles.
(e) See page 54 for specific type.
(f) The lower speed in each range is used for all lighter feed and the heavier depth of cut.

The trend in new lathes is toward variable-speed drives. Rigidity, dimensional accuracy, rapid indexing of tools, and flexibility are additional features which are being emphasized (Ref. 34).

The application of numerical control in turning is rapidly spreading. On lathes equipped with tracer or numerical control, variable-speed and feed features are being added so that the speed and feed can be optimized during contouring operations (Ref. 34).

Lathes with 10-horsepower ratings should be ample for most turning operations. Workpieces ranging between 1 inch and 10 inches in diameter can be turned on a standard or heavy-duty 1610 engine lathe.* These lathes have a range of spindle speeds that almost meet the requirements previously described (Ref. 34).

A modern lathe in good condition provides production rates of five to ten times the rates possible with older machines. Vibration and lack of rigidity are common problems in older equipment (Ref. 7).

Cutting Tools. Standard lathe tools are used for turning titanium. These are available in a variety of shapes, sizes, tool angles, and tool materials. High-speed steel, carbide, and cast-alloy tools can be used on titanium (Refs. 7,8). In all cases, a minimum of overhang should be used to avoid tool deflection (Ref. 2).

Tool Design. Figure 7 defines the terms used to describe the geometry of single-point cutting tools. Tool angles are important for controlling chip flow, minimum smearing or chipping, and maximum heat dissipation. The rake angles and the side-cutting-edge angle determine the angle of inclination and chip flow. Relief angles, together with the rake angles, control chipping and smearing. The side-cutting-edge angle influences the cutting temperature by controlling the tool-chip contact area. Different tool designs recommended for turning and boring titanium under various conditions are also shown in Figure 7.

Positive, zero, or negative rake angles can be used, depending on the alloy and its heat-treated condition, the tool material, and the machining operation. The side rake is the important angle (Ref. 4). Positive rakes are best for finish turning and high-speed-steel tools. Negative rakes are usually used for carbide tools at heavier feeds (0.015 ipr) (Refs. 2,4,7,8).

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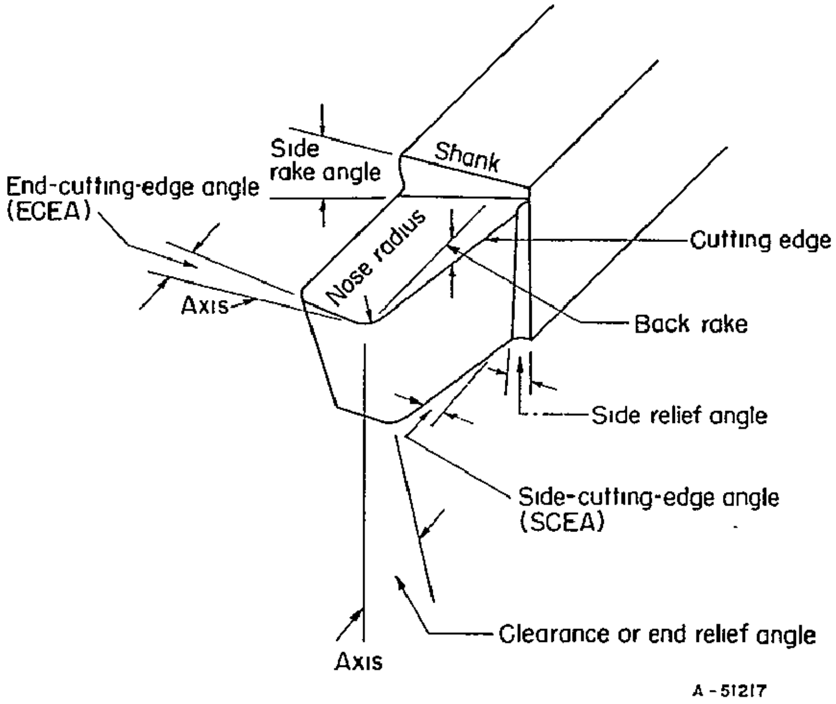
*1610 is the lathe industry designation on 16-inch swing over bed and 10-inch swing over cross slide.



Tool Angles, degrees, and Nose Radius, inch	Tool Geometry Code								
	A	B	C	D	E	F	G	H	I
Back Rake	-5	+5 to -5	+5 to -5	0	0	0 to +5	0 to +10	+6 to +10	+5 to +15
Side Rake	-5	+6 to 0 0 to -6	+5	5 or 6	15	+5 to +15	0 to 10	0 to +15	+10 to +20
End Relief	5	5 - 10	8 - 10	5	5	5 - 7	6 - 8	6 - 10	5 - 8
Side Relief	5	5 - 10	8 - 10	5	5	5 - 7	6 - 8	6 - 10	5 - 8
End-Cutting Edge	15 - 45	6 - 15	5 - 10	15 or 5	10 to 15	5 - 7	5 - 10	5 - 15	5 - 15
Side-Cutting Edge (Lead)	15 - 45	5 - 20	0 - 45	15	15 to 45	15 - 20	0 - 30	0 - 45	0 - 30
Nose Radius	1/32 - 3/64	03 - 04	03 - 04	3/64	3/64	02 - 03		03 - 04	01 - 06

FIGURE 7. TOOL GEOMETRY NOMENCLATURE AND DATA

Relief angles of between 5 and 12 degrees can be used on titanium. Angles of less than 5 degrees encourage smearing on the flank of the tool. Relief angles around 10 degrees are better in this regard, although some chipping may occur (Refs. 2,7,8).

Larger side-cutting-edge angles and their longer cutting edges reduce cutting temperatures and pressures. These reductions permit greater feeds and speeds for equivalent tool life, unless chipping occurs as the cutting load is applied and relieved (Refs. 2,7,8).

The use of a chip breaker is recommended for good chip control. The long stringy chip obtained on lathe-turning operations is difficult to remove from the machine and to keep clear of the work (Ref. 31).

Tool Quality. Cutting tools should be carefully ground and finished before use. Normally the direction of finishing on the chip-bearing surfaces should correspond to the intended direction of chip flow. A rough surface can cause a properly designed tool to deteriorate rapidly (Refs. 3,7,8). The life of a carbide tool can be extended if the sharp cutting edge is slightly relieved by honing.

Tool Materials. High-speed steel, cast alloy, and cemented carbide cutting tools are suitable for lathe-turning titanium. Ceramic tools are not recommended (Refs. 2,7,8,41). The selection of a tool material for a given job will depend on the seven factors described on page 8.

Experience indicates that high-speed-steel cutters are best suited for form cuts, heavy plunge cuts, interrupted cutting, and minimum rigid conditions. Nonferrous cast-alloy tools can be used for severe plunge cuts, machining to dead center, and cutting narrow grooves. Carbide cutting tools are recommended for continuous cuts, high-production items, extensive metal-removal operations, and scale removal (Refs. 2,7,8). Carbide cutting tools are the most sensitive to chipping and hence require "over-powered", vibration-free lathes, as well as more-rigid tool-work setups. If these conditions cannot be met, then high-speed steels must be used.

High-speed steel and cast-alloy tools should be ground on a tool grinder rather than by hand. The same is true for carbide tools; however, off-the-shelf brazed and throwaway carbide tools will fit the rake-, lead-, and relief-angle requirements conveniently (Ref. 7).

Carbide. Carbide cutters are available as brazed, clamped, and "throwaway" tooling. Brazed tools may be purchased in standard sizes and styles as shown in Table XII, or they can be made up in the shop. The performance of mechanically clamped inserts is at least as good as that of brazed tools, and they are often recommended because of their lower cost per cutting edge.

Throwaway carbide inserts are designed to be held mechanically in either positive- or negative-rake tool holders of various styles and shank sizes. Information and data on available tool holders are given in manufacturers' brochures. The general coding system for mechanical tool holders is explained in Table XIII. The tool geometries available for solid-base tool holders and suitable for titanium are shown in Table XIV.

Substantial reductions in costs are claimed by users of throwaway tooling. Factors contributing to this saving are:

- Reduced tool-grinding costs
- Reduced tool-changing costs
- Reduced scrap
- Increased use of harder carbides for longer tool life or increased metal-removal rates
- Savings through tool standardization
- Maximum carbide utilization per tool dollar.

Setup Conditions (Refs. 2,7,8). Before making a turning setup for titanium, a standard or heavy-duty lathe in good condition should be selected to perform the machining operation. The work then should be firmly chucked in the collet of the spindle and supported by the tail stock using a live center to avoid seizure. Machining should be done as closely as possible to the spindle for minimum work overhang. A steady or follow rest should be used to add rigidity to slender parts.

The cutting tool should be held firmly in a flat-base holder with minimum overhang to avoid tool deflection. It should cut on dead center.

Cutting Speeds. High speeds are not necessary for producing good finishes on titanium. Hence, relatively low cutting

TABLE XII. TOOL GEOMETRIES OF BRAZED CARBIDE TOOLS

Tool Geometry	Style of Tool A	B	C	D	E
Back rake	0	0	0	0	0
Side rake	+7	+7	0	0	0
End relief	7	7	7	7	7
Side relief	7	7	7	7	7
ECEA	8	15	--	50	60
SCEA	0	15	--	40	30

TABLE XIII. EXPLANATION OF GENERAL CODING SYSTEM FOR MECHANICAL TOOL HOLDERS

Company Identification	Shape of Insert	Lead Angle	Rake Angle	Type Cut
(a)	T	B	(b)	R or L
(a)	R	A	(b)	R or L
(a)	P	A	(b)	R or L
(a)	S	B	(b)	R or L
(a)	L	B	(b)	R or L
	T	A	T	R

Shape of Insert

T = triangle
R = round
P = parallelogram
S = square
= rectangle

Lead Angle or Tool Style

A = 0-degree turning
B = 15-degree lead
D = 30-degree lead
E = 45-degree lead
F = facing
G = 0-degree offset turning

Type Cut

R = right hand
L = left hand
N = neutral

(a) Some producers place a letter here for company identification.

(b) Some companies use the letter "T" for negative rake, "P" for positive rake, and sometimes add "S" to indicate "solid-base" holders. For example, a TATR designation denotes a tool holder for a triangular insert mounted in such a way to give a 0-degree lead angle, and a 5-degree negative rake. The "R" denotes a right-hand cut.

TABLE XIV. TOOL GEOMETRIES OF SOLID-BASE TOOL HOLDERS FOR THROWAWAY INSERTS

Negative Rake Tools				Positive Rake Tools			
Back-rake angle - 5 degrees Side-rake angle - 5 degrees End-relief angle - 5 degrees Side-relief angle - 5 degrees				Back-rake angle - 0 degrees Side-rake angle - 5 degrees End-relief angle - 5 degrees Side-relief angle - 5 degrees			
Tool Holder Style(a)	Type Insert(a)	ECEA(b), degrees	SCEA(c), degrees	Tool Holder Style(a)	Type Insert(a)	ECEA(b), degrees	SCEA(c), degrees
A	T	5	0	A	T	3	0
A	T	3	0	A	T	5	0
A	R	8	0	--	--	--	--
B	T	23	15	B	T	23	15
B	T	18	15	B	S	15	15
B	S	15	15	B	T	20	15
B	T	20	15	--	--	--	--
D	T	35	30	D	T	35	30
E	S	45	45	--	--	--	--
F	T	0	0	F	T	0	0
F	S	15	0	F	S	15	0
G	T	3	0	G	T	3	0

(a) See Table XIII for explanations..

(b) End-cutting-edge angle.

(c) Side-cutting-edge angle.

speeds are used to obtain good finishes at reasonable tool life (Refs. 3,7,8). Tables XV and XVI list cutting speeds found suitable for various machining operations on titanium and its alloys.

Feed. Turning operations for titanium require constant, positive feeds throughout machining. Dwelling, stopping, or deliberately slowing up in the cut should be avoided for reasons given on pages 5 and 6.

The metal-removal rate and surface-finish requirements will influence the amount of feed to be taken, i.e., heavy feeds for higher metal-removal rates, and light feeds for better surface finishes (Refs. 7,8). Specific recommendations on feeds are given in Tables XV and XVI.

Depth of Cut. The choice of cut depth will depend on the amount of metal to be removed and the metal-removal rate desired. In removing scale, the tool should get under the scale and cut at least 0.020 inch deeper than the tool radius (Ref. 2). For rough cuts, the nose of the tool should get below any hard skin or oxide remaining from previous processing operations (Ref. 2). In finish turning, light cuts should be used for the best finish and the closest tolerances (Refs. 2,7,8). Cut depths suggested for various operations are listed in Tables XV and XVI.

Cutting Fluids. Cutting fluids are almost always used during turning and boring operations to cool the tool, and to aid in chip disposal. Dry cutting is done in only a very few instances, usually where chip contamination is objectionable. It is not recommended for semifinishing and finishing operations.

Water-base coolants are the most satisfactory cutting fluids to use. A 5 per cent sodium nitrite solution in water gives the best results, although a 1:20 soluble oil-in-water emulsion is almost as good. Sulfurized oils may be used for low-cutting-speed applications, but precautions should be taken to avoid fires.

A full, steady flow of cutting fluid should be maintained at the cutting site for maximum effect.

General Supervision. The supervisor should be satisfied that the proper conditions have been selected before operations begin. During machining he should be assured that chips are being expelled from the cutting site as promptly as possible, particularly during

TABLE XV. FINISH TURNING OF TITANIUM ALLOYS[a]

Depth of Cut: 0.025 to 0.10 inch
Feed: 0.005 to 0.010 ipt

Titanium Alloy	Alloy Condition[b]	C-2 Carbide Tools[c] Tool Geometry[d]	C-2 Carbide Tools[c] Cutting Speed[e], fpm Brazed Tools	C-2 Carbide Tools[c] Cutting Speed[e], fpm Throwaway	High-Speed Steel Tools[c] AISI Steels	High-Speed Steel Tools[c] Tool Geometry[d]	High-Speed Steel Tools[c] Cutting Speed[e], fpm
Commercially pure	An	A, D	275-375	310-425	M1, M3, T1, T15	D	100-110
Ti-8Al-1Mo-1V	An	A, D	155-165	185-225	M3, T5, T15	D	45-60
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	A, B, D	165-215	225-250	M5 T5 T15	D	45-80
Ti-4Al-3Mo-N	An	A	165-215	225-250	M3, T5, T15	D	45-80
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	A, D, G	165-170	210-250	M3, T5, T15	D	45-70
	HT	A, D	130-145	185-200	M3, T15	D	55-65
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	A	155	185	M3, T15	D	50-60
	HT	A	120	150	T15	E	40-50
Ti-13V-11Cr-3Al	An		125	150	M3, T15	D	25-35
	HT		100	120	T15	E	25-35
Cutting Fluids	Soluble oil-water emulsions or chemical coolants can be used with carbide on high-speed steel tools. Sulfurized oils also can be used with high-speed steel tools on most titanium alloys. Highly chlorinated oils are sometimes used with high-speed steel tools on Ti-7Al-4Mo, Ti-6Al-6V-2Sn, and Ti-13V-11Cr-3Al, providing the oil residues are promptly removed by MEK.						

(a) Refs. 2,5,7,8,34,87, and 88.
(b) An = annealed; HT = solution treated and aged.
(c) CISC designations used for carbides; AISI designations for high-speed steels.
(d) See Figure 9 for tool angles involved.
(e) Higher speeds are associated with lower feeds and lower depths of cut.

TABLE XVI. ROUGH TURNING OF TITANIUM ALLOYS[a]

Depth of Cut: 0.10 to 0.25 inch
Feed 0.010 to 0.015 ipr

Titanium Alloy	Alloy Condition[b]	C-2 Carbide Tools[c]			High-Speed Steel Tools[c]		
		Tool Geometry[d]	Cutting Speed[e], fpm		Tool Material	Tool Geometry[d]	Cutting Speed[e], fpm
			Brazed Tools	Throwaway			
Commercially pure	An	A, F, G	250-310	310-375	M1, M3, T1, T15	B, E	90-125
Ti-8Al-1Mo-1V	An	A, F, G	130-140	165-200	M3, T5, T15	B, E	30-60
Ti-5Al-2.5Sn	An	A, F, G, H	140-180	200-220	M3, T5, T15	B, E, K	30-80
Ti-4Al-3Mo-1V	An	A	180	220	M3, T5, T15	B	60-80
Ti-6Al-4V	An	A, F, G, I	140-150	180-200	M3, T5, T15	B, E, L	35-70
	HT	A, F, G	100-120	150-160	M3, T5	B, E	30-55
Ti-7Al-4Mo	An	A	130	165	M3, T15	B	40-60
Ti-6Al-6V-2Sn	HT[f]	A	100	120	T15	C	30-40
Ti-13V-11Cr-3Al	An	A	100	120	M3, T15	B	20-25
	HT[f]	A	80	100	T15	D	20-25
Cutting Fluids	Soluble oil-water emulsions or chemical coolants can be used with carbide on high-speed steel tools. Sulfurized oils also can be used with high-speed steel tools on most titanium alloys. Highly chlorinated oils are sometimes used with high-speed steel tools on Ti-7Al-4Mo, Ti-6Al-6V-2Sn, and Ti-13V-11Cr-3Al, providing the oil residues are promptly removed by MEK.						

(a) Refs. 2,5,7,8,34,87, and 88.
(b) An = annealed; HT = solution treated and aged.
(c) CISC designations used for carbides; AISI designations for high-speed steels.
(d) See Figure 9 for tool angles involved.
(e) Higher speeds are associated with lower feeds and lower depths of cut.
(f) 0.010 ipr max.

boring operations. Chips lying on the surface tend to produce chatter and poor surface finishes.

The tool should be examined frequently for nicks and worn flanks. These defects promote galling, increase cutting temperature, accelerate tool wear, and increase residual stresses in the machined surface.

Arbitrary tool-changing schedules are often used to insure sharp tools. This usually means replacing carbide tools after a 0.015-inch wearland in rough turning and after a 0.010-inch wearland in finish turning. High-speed steel tools are usually replaced after a wearland of 0.030 inch has developed.

If periodic interruptions are made in a machining operation before these maximum wearlands occur, any smeared metal, nicks, or crevices found on the cutting edge should be removed by honing before machining is resumed.

Sharp edges of turned titanium surfaces are potential sources of failure. Hence, they should be "broken" with a wet file or wet emery. This operation should not be done dry or with oil because of a potential fire hazard.

After certain turning operations, parts may require stress relieving. The following treatments are suggested:

Anneal after rough machining

Stress relieve thin-wall parts after semifinish operations

Stress relieve all finished parts.

DRILLING

Introduction. The unusual chip-formation characteristics of titanium make drilling difficult (Refs. 4,43). The thin chips flowing at high velocities are likely to fold and clog in the flutes of the drill (Refs. 4,13). This tendency, plus the high thrust pressures and confined nature of drilling, produces high temperatures. Unless proper precautions are taken, the end results include rapid tool wear on the cutting lips, reduced cutting action, and poor-quality holes. The nature of the chips produced indicates the condition of the drill. A sharp drill produces tight curling chips without difficulty. As the drill progressively dulls, the cutting temperature rises, and titanium begins to smear on the lips and margins (Refs. 2,13). The appearance of feather-type chips in the flutes is a warning signal that the drill is dull and should be replaced. The appearance of irregular and discolored chips indicates that the drill has failed (Refs. 2,13, 43). Out-of-round holes, tapered holes, or smeared holes are results of poor drilling action, with subsequent reaming problems, or even tap breakage when the holes are threaded (Refs. 2,4).

Drilling difficulties can be minimized by employing five important techniques. These include designing holes as shallow as possible (Refs. 2,13); using short, sharp drills with large flutes and special points (Refs. 2,4,13); flushing the tool-chip contact site with suitable cutting fluids; employing low speeds and positive feeds in an approved manner (Refs. 2,4,13,43); and supplying solid support under the exit side of through holes where burrs otherwise would form.

Machine Tools (Refs. 7,8,44). Drilling machines must be sturdy and rigid enough to withstand the thrust and torque forces built up during the cutting. Hence, the spindle overhang should be no greater than necessary for a given operation. In addition, excessive clearances in spindle bearings cannot be tolerated. The radial and thrust bearings should be good enough to minimize runout and end play. Finally, the feed mechanism should be free of backlash in order to reduce the strain on the drill when it breaks through the workpiece.

Machines for drilling operations are made in many different types and sizes. Size or capacity is generally expressed either in terms of the largest diameter disk, the center of which is to be drilled, or in horsepower. Heavy-duty machines are exceptions. They are specified as the distance from the supporting column to the centerline of the chuck. The horsepower rating is that usually needed to drill cast iron with the maximum drill diameter. Suitable sizes of machines for drilling titanium include:

- Upright drill No. 3 or No. 4
- Upright drill, Production: 21-inch heavy-duty, 5 hp
- Upright drill, Production: 24-inch heavy-duty, 7-1/2 hp
- Upright drill, Production: 28-inch heavy-duty, 10 hp

Industry also has requirements for drilling parts at assembly locations. These needs are fulfilled by portable power-feed, air drilling machines. Modern units incorporate positive mechanical-feed mechanisms, depth control, and automatic return (Ref. 43). Some are self-supporting and self-indexing. Slow-speed, high-torque drill motors are needed. Spindle speeds between 230 and 550 rpm at 90-psi air pressure seem appropriate for high-speed drills, while speeds of up to 1600 rpm have been used for carbide drills. Thrusts between 320 and 1000 pounds are available on some portable drilling machines.

Portable drill units include the Keller K-Matic, the Keller Airfeedrill, the Winslow Spacematic, and the Quackenbush designs (Refs. 43,45,46).

The Keller K-Matic incorporates a positive, mechanical feed mechanism, a depth-control device, and an automatic return provision. Drilling tests with this design indicate that Class I hole tolerances as low as +0.002 to -0.001 can be held in a drill-ream operation (Ref. 43).

The Keller Airfeedrill utilizes a variable pneumatic feed. The air feed can be adjusted to give feeds suitable for titanium. Class I hole tolerances also can be held (Ref. 43).

The Winslow Spacematic is a self-supporting, self-indexing unit capable of drilling and countersinking in one operation. The feed rates are within those prescribed for titanium, and a ±0.002/0.001 tolerance can be held (Ref. 43).

Quackenbush portable drilling machines also can be used. One style is a 500-rpm pneumatic-powered unit with a positive mechanical feed mechanism capable of providing 0.001 ipr feed (Ref. 45).

Drills. Generally speaking, drills are made from special high-speed steels, in helical designs with large flutes, and in short lengths. Large flutes reduce the tendency for chips to clog (Refs. 2, 4,13). The length of the drill should be kept as short as feasible, not much longer than the intended hole (Refs. 33,47), to increase columnar rigidity and decrease torsional vibration which causes chatter and chipping (Refs. 2,4).

A heavy-duty stub-type screw machine drill is recommended for drilling operations on workpieces other than sheet (Ref. 2). For deep holes, oil-feeding drills, gun drills, or a sequential series of short drills of various lengths may be employed (Ref. 2). Oil-feeding drills cool, lubricate, minimize welding, and help in chip removal (Ref. 2).

The NAS 907, Type C drill should be used for drilling sheet titanium. The NAS 907, Type B drill can be used where the Type C drill might be too short because of bushing length or hole depth (Refs. 43,45).

Drill Design. The geometrical factors of drill design are indicated in Figure 10. Drills having a normal helix angle of 29 degrees and special point grinds are used for drilling titanium. The special point grinds include crankshaft, notch-type drills, and split points with positive rake notchings (Refs. 2,7,8).

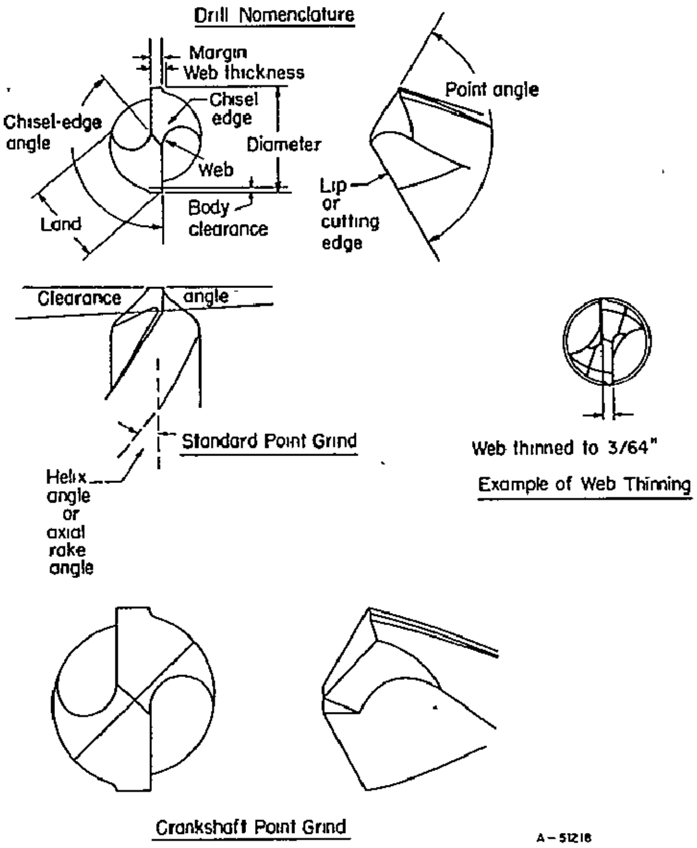
Relief angles are of extreme importance to drill life. Small angles tend to cause excessive pickup of titanium, while excessively large angles will weaken the cutting edge (Refs. 2,4). Relief angles between 7 and 12 degrees have been used by different investigators (Refs. 2,4,13,48).

Point angles have a marked effect on drill life. The choice of 90, 118, or 135 degrees will depend on the feed, drill size, and the workpiece. Hence, it is advisable to try all three angles to find which is best suited for the job. Generally, blunt points (135 or 140 degrees) are superior on small-size drills (No. 40 to No. 31) and on sheet metal, while 118 degrees, 90 degrees, or the double angle (140 degrees or 118 degrees + 90-degree chamfer) seem best on larger sizes and bar stock (Refs. 2,48).

The web is often thinned to reduce drilling pressure (Ref. 31). However, when doing so, the effective rake angle should not be altered (Refs. 2,4). Figures 8 and 9 illustrate nomenclatures and designs for standard and NAS 907-type drills.

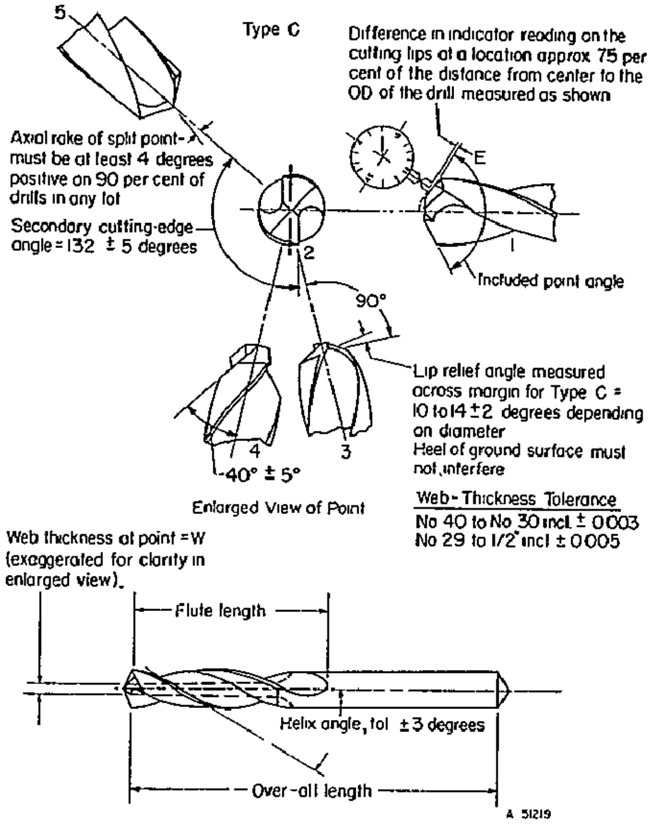
Drill Quality. The geometry of drills should be checked against recommendations before they are used. If necessary, drills should be reground accurately on a drill grinder, and the point angle, relief angle, and web thickness rechecked (Refs. 13,43). Drills should never be sharpened by hand (Ref. 48).

The apex of the point angle should be held accurately to the centerline of the drill, and the cutting lips should have the same



Drill Elements	Drill Geometry Code X	 Y	 Z
Drill Diameter, inch	<1/8	1/8 - 1/4	1/4 and greater
Helix Angle, degrees	29	29	29
Clearance Angle, degrees	7 to 12	7 to 12	7 to 12
Point Angle, degrees	135	118	118; 90 or double angle
Type Point	Crankshaft or Split		

FIGURE 8. DRILL NOMENCLATURE AND TOOL ANGLES USED



Drill Elements	Drill Geometry Code			
	C	D	B	E
Notch Rake Angle, degrees	4 to 7	20	4 to 7	10
Helix Angle, degrees	23 to 30	28 to 32	23 to 30	12
Clearance Angle, degrees	10 to 14	6 to 9	10 to 14	6 to 9
Point Angle, degrees	118 ± 5	135 ± 5	135 ± 5	135 ± 5
Type Point	P-5	P-1	P-3	P-2
NAS 907 Drill Types	C	D	B	E
Drilling Application	Sheet	Hand drilling sheet	Fixed feed	Fixed feed (dry)

FIGURE 9. DRILL NOMENCLATURE AND GEOMETRY FOR NAS 907 AIRCRAFT DRILLS (TYPE C ILLUSTRATED)

slope (Refs. 48,49). This combination avoids uneven chip formation, drill deflection, and oversized holes (Ref. 49).

When dull drills are reconditioned, resharpening the point alone is not always adequate. The entire drill should be reconditioned to insure conformance with recommended drill geometry (Refs. 2,47).

Machine-ground points with fine finishes give the best tool life (Refs. 2,43). A surface treatment (Ref. 31) such as chromium plating or a black oxide coating of the flutes may minimize welding of chips to the flutes.

Tool Materials (Refs. 2,4,7,8,13). High-speed steels are generally used for drilling titanium. Carbide drills can be used for deep holes when the cost is justified.

Conventional molybdenum-tungsten high-speed steel drills are usually used in production. Cobalt high-speed steels can be used and are said to give up to 50 per cent more tool life. However, their costs are 1-1/2 to 2 times higher than standard high-speed steels. Table XVII indicates the drilling applications for various AISI grades of high-speed steel.

TABLE XVII. HIGH-SPEED STEEL USED FOR DRILLS IN DRILLING TITANIUM ALLOYS

AISI Grade of High-Speed Steel[(a)]	Titanium Alloy				
	Commercially Pure	Ti-5Al-2.5Sn	Ti-8Al-1Mo-1V	Ti-6Al-4V	Ti-13V-11Cr-3Al
M1	S	S	S		G
M2					G
M3, Type 2	S	S	S		
M7	G, D	G, D	G, D		
M10	G, D, S	G, D, S	G, D, S	G, S	
M33	G, D	G, D	G, D		G
M34	G, D	G, D	G, D		
M36				S	
T4	G, D, S	G, D, S	G, D, S		
T5	G, D, S	G, D, S	G, D, S	G, S	

Note: G = general drilling; D = deep hole drilling, S = sheet drilling.

(a) See Table IV for compositions.

Setup Conditions. Setup conditions selected for drilling titanium should provide over-all setup rigidity and sufficient spindle power to maintain drill speeds during cutting.

Thin sheet metal parts must be properly supported at the point of thrust. This can be done with a backup block of AISI 1010 or 1020 steel. Where this is not possible because of part configuration, a low-melting alloy can be cast about the part.

Heavy-duty stub drills should be used instead of jobbers-length drills to prevent deflection which causes out-of-round holes (Refs. 2, 13,47). Drill jigs and bushings are used whenever added rigidity is needed (Refs. 2,13,47).

When drilling stacked sheet, the sheets should be clamped securely with clamping plates to eliminate gaps between sheets (Refs. 31,43).

Setup also involves speeds, feeds, and coolants. Successful drilling of titanium depends on being able to reduce the temperature at the cutting lips. This can be accomplished by (Ref. 43):

- Using low cutting speeds
- Reducing the feed rate
- Supplying adequate cooling at the cutting site.

Cutting Speed. Since the cutting zone is confined, drilling requires low cutting speeds for minimum cutting temperature. The choice of speed used will depend largely on the strength level of the titanium material and the nature of the workpiece. Thus, speeds up to 80 fpm may be used for commercially pure titanium, while only 15 to 20 fpm should be used on aged Ti-13V-11Cr-3Al. Table XVIII lists cutting speeds found suitable for specific operations.

Feed. The best approach in drilling titanium is to keep the drill cutting (Ref. 48). The drill should never ride in the hole without cutting since the rubbing action promotes galling of the lips and rapid dulling of the cutting edge (Refs. 33,43). The best technique is to use equipment having positive, mechanical feeds (Refs. 2, 7,8,31).

Assembly drilling of sheet should be done with portable power drills also having positive feed arrangements (Refs. 45,46). This equipment was described on page 46.

TABLE XVIII. DRILLING TITANIUM ALLOYS WITH HIGH-SPEED STEEL DRILLS[a]

Titanium Alloy	Alloy Condition[b]	Tool Material[c]	Cutting Speed, fpm	Feed, ipr, for Drill Shown[d]		
				Drill Diameter, inch	C. P. Titanium and Titanium Alloys	Ti-13V-11Cr-3Al
ommercially pure	An	M1, M2, M10	40 to 80	1/8	0.001-0.002	0.0005
i-8Al-1Mo-1V	An	Ditto	20 (40 for sheet)	1/4	0.002-0.005	0.001
i-5Al-5Sn-5Zr i-5Al-2.5Sn i-7Al-2Cb-1Ta	An	"	40	1/2	0.003-0.006	0.0015
i-4Al-3Mo-1V	An	"	40 (25 for sheet)	3/4	0.004-0.007	0.0015
	STA	M33	20 for sheet			
i-7Al-12Zr i-6Al-4V i-8Mn	An	M1, M2, M10	30 to 40	1	0.004-0.008	0.002
	STA	T15, M33	20 to 30			
i-7Al-4Mo i-6Al-6V-2Sn	An	M1, M2, M10	20	2	0.005-0.013	0.003
	STA	T15, M33	20			
i-13V-11Cr-3Al	An	M1, M2, M10	20 to 30	3	0.005-0.015	0.004
	STA	T15, M33	15 to 20			
ool Geometry:	For general drilling operations, choose drill geometry x, y, or z depending on drill size (see Figure 10). For drilling sheet, use drill geometry, C, D, or B according to application (see Figure 11).					
utting Fluids Used	A valuable oil-water emulsion, or a sulfurized oil, the latter at lower speeds and for small drills (<1/4 inch). Chlorinated oils are also used provided oil residues are promptly removed by MEK. Holes in single sheets up to 2 times the drill diameter can be drilled dry.					

) From Refs. 2,4,7,8,13,31,33,37,43,45-47,50-52,87,88.

) An = annealed, STA = solution treated and aged.

) AISI designations.

) Use the lower feeds for the stronger or aged alloys.

Hand drilling can be done, provided sufficient thrust can be applied to insure a heavy chip throughout drilling (Ref. 59). However, the high axial thrust required to keep the drill cutting, especially in heat-treated titanium alloys, can cause rapid operator fatigue. Furthermore, allowing the drill to advance rapidly on breakthrough, as is generally the case with hand feeding, will seriously shorten drill life by chipping the corners of the drill (Ref. 31).

The selection of feeds depends largely on the size of the drill being used. Generally, a feed range of 0.001 to 0.005 ipr is used for drills up to 1/4 inch in diameter. Drills 1/4 to 3/4 inch in diameter will use a heavier feed range, 0.002 to 0.007 ipr. Williams (Ref. 31) suggests the values shown in Figure 10. He believes that these values should furnish an economical balance between tool life and production rates. Some other feeds used successfully in specific operations are listed in Table XVIII.

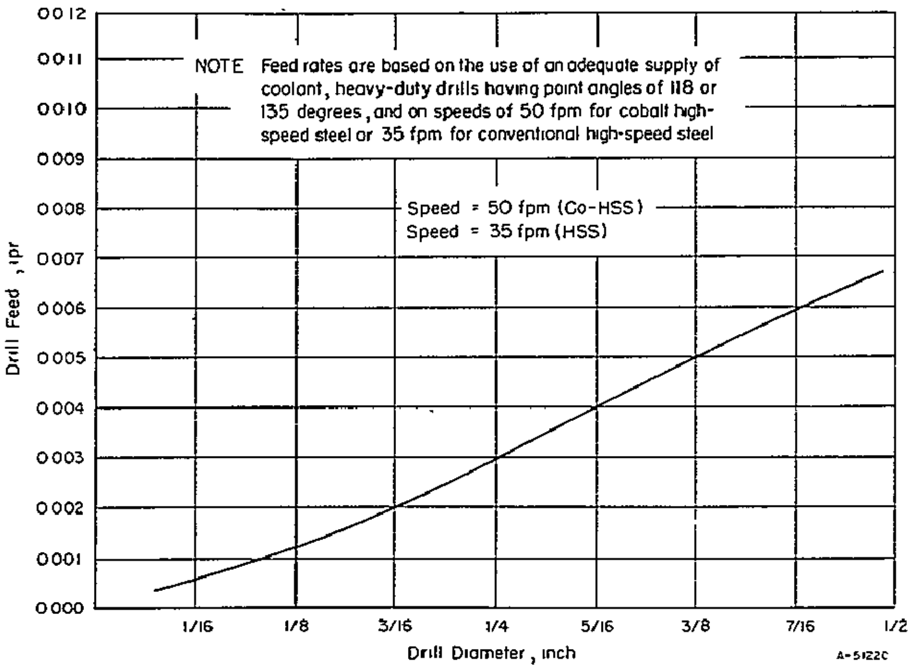


FIGURE 10. FEED RATE VERSUS DRILL DIAMETER FOR HIGH-SPEED STEEL DRILLS (REF. 31)

Cutting Fluids. Drilling titanium usually requires the use of cutting fluids, although holes in single sheets with thicknesses up to twice the drill diameter can be drilled dry (Refs. 2, 33).

Lubricating and chemically active cutting fluids like sulfurized oils or sulfurized oil/lanolin paste are recommended for low speeds, and for drills less than 1/4 inch in diameter (Ref. 4). A better coolant, like a soluble oil-water emulsion, is used for the higher speeds and larger drills. Cooling action in these instances appears to be more important than lubricity (Refs. 2,4).

A steady, full flow of fluid, externally applied, can be used (Refs. 2,7,8), but the use of a spray mist seems to give better tool life. However, a limiting hole depth of twice the diameter seems to exist for external applications of cutting fluids. Hence, oil-feeding drills work best for deep holes (Refs. 7,8).

General Supervision. The first consideration in planning a drilling setup is to select a drilling machine on the basis of the rigidity, condition, power, and feed/speed characteristics required for titanium. The next consideration would be the selection of drills, bushings, fixtures, and cutting fluids.

When starting the drilling operation, the drill should be up to speed and under positive feed as it contacts the work. The drill must be sharp (Refs. 2,13), and the proposed hole location marked with a triangular center punch (Ref. 2). A circular-type center punch must not be used since the drill will not start.

The margin of the drill should be examined periodically for smearing as well as breakdowns that might occur at the outer corner of the lips (Ref. 2). An arbitrary drill replacement point should be established to prevent work and drill spoilage (Ref. 2).

Chips should be removed at periodic intervals unless the cutting fluid successfully flushes away the chips.

When drilling holes more than one-diameter deep, retract the drill once for each half diameter of drill advance to clear the flutes. Retract simultaneously with the stop of the feed to minimize dwell. Re-engage drill quickly, but carefully, with the drill up to speed and under positive feed (Refs. 47,48).

When drilling "through holes", it is sometimes advisable not to drill all the way through on a continuous feed. Instead, retract drill before breakthrough and flush the drill and hole to remove the chips. Then return drill under positive feed and drill through carefully, avoiding any "feed surge" at breakthrough.

Drilled holes will require reaming to meet the tolerances of Class I holes, unless a bushing is used immediately adjacent to the part. Drilled holes in sheet will probably require exit-side deburring.

All assembly drilling should be done using portable, fixed-feed, jig-mounted drilling machines (Refs. 45,46). Hand drilling can be used, but the practical limit appears to be the No. 40 drill. Above this diameter, insufficient feed is the result, with consequent heat buildup and short drill life. Another problem with hand drilling is the combination of high thrust and uncontrollable feed rate to produce "feed surge" at breakthrough - and possible fractured cutting lips on the drill (Ref. 30). Hand drilling should not be used if the hole is to be tapped (Ref. 47).

TAPPING AND THREADING

Introduction. Titanium is difficult to tap. The problem of poor chip flow inherent in taps and the severe galling action of titanium can result in poor threads, improper fits, excessive tap seizures, and broken taps (Ref. 2). Titanium also tends to shrink on the tap at the completion of the cut.

As taps dull and cutting temperatures rise during tapping operations, titanium smears on the cutting edges and flanks of the tap. The immediate consequence is that the metal in excess of the normal profile is removed, resulting in oversized holes and rough threads (Refs. 13,53). This galling action increases friction between tap and hole and torque requirements. The additional torsional strain distorts the lead of the tap and increases the tapping stresses until the tap seizes and breaks (Ref. 53).

Tapping difficulties can be minimized by reducing the thread requirements to 55 to 65 per cent full thread*, and then tapping the fewest threads that the design will allow (Refs. 4,13,48). Designers should also avoid specifying blind holes or through holes of excessive lengths. In both cases, the chips are confined and can cause rough threads and broken taps. Some relaxation in class-of-fit tolerances also should be considered (Refs. 13,33).

The tapping operation, itself, requires sharp taps of modified conventional design, low tapping speeds, and an effective tapping lubricant to minimize seizure (Ref. 53).

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*Some companies have successfully tapped 75 per cent threads.

Tapping Machines. A lead-screw tapping machine is recommended to insure proper lead, a regulated torque, and a uniform hole size. Lead-screw tapping heads should be equipped with friction clutches. The clutch should prevent tap breakage when galling occurs, since a very small amount of smear may result in immediate tap breakage.

Tapping machines should be rigid, accurate, and sensitive. Machine tapping, unless done on a sensitive machine and by a competent operator, can result in excessive tap breakage and poor-quality work (Refs. 2,54).

The electropneumatic oscillating-type tapping machine, when properly set, cannot break a tap. Before any force is applied that might break a tap, the forward motion is interrupted and immediately reversed (Ref. 54). The tap is driven by balanced spiral springs, and the tension is set just under the static breaking torque of the size of the tap being used. When the tap meets excessive resistance (which would ordinarily break the tap), the machine automatically reverses one-half revolution and then goes forward again (Ref. 54).

Taps and Their Modifications. A number of different types of taps have been used successfully, including the plug, chip driving, and gun designs.

Modifications of the conventional two-flute, spiral-point, plug-style H2-pitch-diameter taps can be used. The taps are modified by grinding away the threads behind the cutting edges down to the minor diameter, but leaving full-thread lands 0.015 inch wide backing up the cutting edges (Ref. 48).

Chip-driving spiral-point taps with interrupted threads and eccentric pitch-diameter relief also have been successful (Refs. 18, 53). Taps should be precision ground and stress relieved. Two-fluted taps are usually used for 5/16-24 holes and smaller, while three-fluted taps are best for 3/8-16 holes and greater and for other tapping situations. Taps with two flutes normally do not give the support which the three-fluted taps provide (Ref. 34).

If rubbing is encountered during tapping, it may be decreased by

- Using interrupted threads with alternate teeth missing
- Grinding away the trailing edge of the tap

- Grinding axial grooves in the thread crests along the full length of the lands

- Employing either eccentric or coneccentric thread relief.

Generally speaking, spiral point taps featuring eccentric pitch-diameter relief with either full or interrupted threads have been the most successful (Refs. 18,53). However, spiral-pointed tap cannot be expected to propel chips forward in holes that are more than two diameters long (Ref. 53).

GH-3 gun taps have been used successfully by Boeing to tap the Ti-8Al-1Mo-1V titanium alloy (Ref. 37).

Tap Design. The important features of tap design are illustrated in Figure 11.

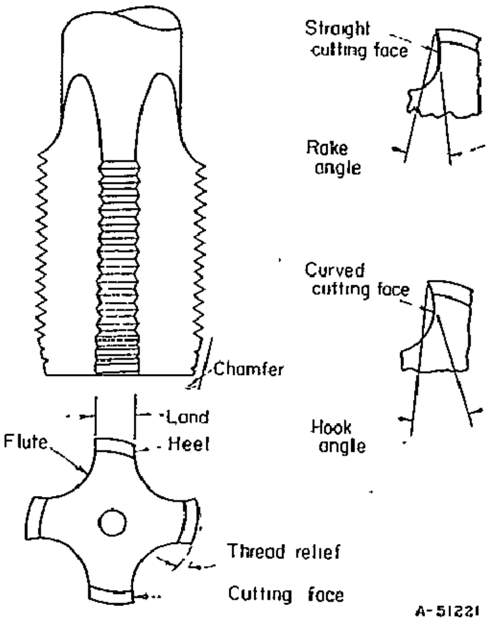

FIGURE 11. TAP NOMENCLATURE

Taps should have tool angles suitable for titanium. This usually means:

- A spiral-point angle large enough to allow chips to flow out of the hole ahead of the tap (between 10 and 17 degrees).

- A relief angle large enough to prevent seizure but not so large as to cause jamming when backing out the tap (between 2 and 4 degrees).
- Sufficient cutting rake to provide a good shearing action (between 6 and 10 degrees).
- A chamfer of around 3 or 4 threads to provide a small depth of cut. A shorter chamfer results in high torque and possible tap breakage. A long chamfer produces long, stringy chips which may jam the tap during back-out operations. However, a plug chamfer gun tap can be used for shallow holes (holes less than one tap diameter deep).
- Where bottoming holes require complete threads close to the bottom of the hole, a series of two or three taps with successive shorter chamfers may be required.

Tap Materials. Nitrided high-speed steel taps are used: AISI-M1 for tapping commercially pure titanium and AISI-M10 for titanium alloys (Refs. 2,34).

Setup Conditions. Precautions in setups for tapping parallel those recommended for drilling. Machine tools which allow maximum rigidity, accuracy, and sensitivity should be used. Lead-screw tapping is recommended since less dependence is placed on the operator. The tapping head must be set for as short a stroke as possible (Ref. 48). Hand tapping is not recommended since it lacks the required rigidity and is extremely slow and difficult (Refs. 2,4,54).

Pressing a stiff nylon brush against the top of the return stroke helps to remove chips and increases tap life by at least 50 per cent (Ref. 47).

Tapping Speed. Tapping speeds must be limited to values between 5 and 50 fpm depending on the alloy and heat-treated condition. This is important because cutting torque increases extremely rapidly beyond a certain critical threshold speed for each alloy (Refs. 2,4). Tapping speeds suggested for various titanium alloys are listed in Table XIX.

Size of Cut. The size of cut determines the incidence of tap seizure, and the size of cut is determined by the chamfer given

TABLE XIX. TAPPING DATA FOR TITANIUM AND ITS ALLOYS USING HIGH-SPEED STEEL TAPS(a)

AISI Type High-Speed Steel(b)	M1, M10 (nitrided)	
Tap Styles		
Tap Size	5/16-24 and smaller	3/8-16 and greater
Number of Flutes(c)	2 or 3	3 or 4
Tap Geometry		
Spiral Point Angle, degrees	10 to 17	
Spiral Angle, degrees	110	
Relief Angle, degrees	2 to 4	
Cutting-Rake Angle, degrees	6 to 10	
Chamfer Angle, degrees	8 to 10 or 3 to 4 threads	
Tapping Speeds, fpm		
Unalloyed Titanium	30 to 50	
Titanium Alloys(d)	10 to 30	
Ti-6Al-4V, Annealed	10 to 30	
Ti-6Al-4V, Aged	5 to 15	
Ti-8Al-1Mo-1V, Annealed	10 to 15	
Ti-13V-11Cr-3Al, Solution Treated	8 to 15	
Ti-13V-11Cr-3Al, Aged	5 to 7	
Tapping Lubricants	Lithopone paste (30% SAE 20 oil, 70% Lithopone), heavy sulfurized oil, sometimes fortified with molybdenum disulfide; barium hydroxide in water (5% by weight); highly chlorinated or sulfochlorinated oils followed by a thorough degreasing with MEK.	

(a) From Refs. 18, 34, 37, 47, 48, 52-55, 87, 88.

(b) M1 high-speed steel is adequate for unalloyed titanium. M10 high-speed steel is best for titanium alloys. Nitrided taps generally give the best performance.

(c) Taps with two flutes normally do not give the support that the three or four-fluted taps provide; hence, use the latter two types for the larger sizes.

(d) Titanium alloys Ti-150A and Ti-140A at 30 fpm; Ti-4Al-4Mn at 20 fpm; annealed Ti-7Al-4Mo and Ti-6Al-6V-2Sn at 15 fpm; and aged Ti-7Al-4Mo and Ti-6Al-6V-2Sn at 10 fpm.

the tap. The normal chamfer of 3 or 4 threads should produce smaller chips and minimize jamming the tap during the backing-out phase (Ref. 4).

Tapping Lubricants. The selection of tapping lubricants is extremely important because of the susceptibility of taps to seizure (Ref. 4).

The paste type of cutting compound (Lithopone or ZnS in oil) gives the best tool life. However, if the application of paste is difficult, or not practical, the next best lubricant is a heavy, sulfurized mineral oil (Ref. 4). Mechanical separators like molybdenum disulfide may be added to relieve persistent seizures. Soluble oils are unsatisfactory for tapping titanium.

Some fabricators recommend pretreating taps with colloidal molybdenum disulfide. The tap is dipped in a suspension of MoS_2 and white spirits, and then baked for 40 minutes at 200 C (Ref. 55).

General Supervision. As a first requirement, holes for tapping should have been produced by sharp drills operating under proper drilling conditions. Dull drills produce surface-hardened holes which will magnify tapping difficulties. Sharp, clean taps must be used at low tapping speeds with recommended tapping compounds, and under rigid tool-work setups (Ref. 2).

Immediately before tapping a hole, the tap should be covered with a liberal amount of Lithopone paste (Refs. 4,48). If sulfurized oil is used, it should be forced on the tap throughout the tapping operation (Refs. 18,47).

Where holes require complete threads close to the bottom of the hole, a series of two or three taps with successively shorter chamfers may be required (Ref. 18).

Taps should be inspected carefully after use on six holes for possible smearing of lands (Ref. 47). These smears may be hard to see, but if present, they can cause premature tap breakage and oversized holes (Refs. 13,34). The workpiece also should be inspected for possible torn threads and dimensional discrepancies. It should be remembered that most tapping is done on parts which are 80 to 90 per cent finished; hence, scrap from tapping operations can be very costly (Ref. 2).

Operating data for tapping all titanium alloys are given in Table XIX.

REAMING

Introduction. With proper precautions, titanium and its alloys can be reamed successfully. Adhesion of titanium to the reamer must be prevented to avoid the production of oversized holes and poor finishes.

Types of Reamers.

Designs. Titanium can be reamed with either straight or spiral fluted reamers, but the latter seem to produce better finishes (Ref. 57). The conventional reamer has three basic tool angles; a chamfer angle, a rake angle, and a relief angle as shown in Figure 12. The first two angles do not have any pronounced effect on reaming operations. The relief angle is most influential and should exceed 5 degrees, to minimize smearing. On the other hand, relief angles in excess of 10 degrees cause vibration and chatter marks on the surface of reamed holes (Ref. 4).

Reamers with margins about 0.010 inch wide produce acceptable holes. Scoring is a problem with wider margins, and excessive chatter is likely to occur when margins are as narrow as 0.005 inch (Ref. 4).

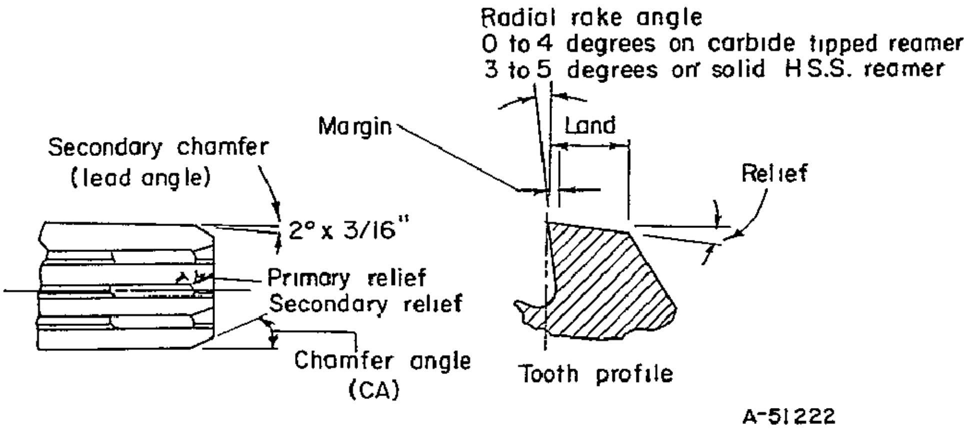

FIGURE 12. NOMENCLATURE FOR FLUTED REAMERS

Tool Materials. Both high-speed steel and carbide reamers can be used on titanium and its alloys. High-speed steel reamers, however, tend to deteriorate rapidly after tool wear starts.

Carbide-tipped reamers are much better from the standpoint of tool life (Ref. 57).

Setup Conditions. There seems to be no single set of reaming conditions which will give optimum results by all criteria (Ref. 4). Nevertheless, the basic precautions for machining titanium should be heeded. These include adequate rigidity of setup, sharp tools, and a positive feed to prevent riding without cutting. Chatter, if present, can be eliminated by altering tool design, size of cut, and cutting speed.

Cutting Speed. For high-speed-steel reamers, the recommended cutting speed for commercially pure titanium ranges between 40 and 70 fpm, while titanium alloys require lower speeds, 20 to 45 fpm. Carbide reamers may be used up to 250 fpm (Refs. 57, 88).

Feed. Small feeds are required to produce acceptable holes (Ref. 4); feeds ranging between 0.002 and 0.016 ipr are satisfactory (Refs. 57,88). Sometimes a feed as high as 0.020 ipr is used, but feeds that high may lead to excessive pickup and scarred holes (Ref. 4).

Feeds should be increased in proportion to the size of the hole. However, larger amounts of metal removal may impair concentricity (Ref. 57).

Depth of Cut. The depth of cut when varied between 0.002 and 0.016 inch (on the radius) shows no pronounced effect, except for an increase in torque with increasing depths of cut (Ref. 4).

Cutting Fluids. The most effective fluid for reaming titanium appears to be a sulfochlorinated mineral oil (Ref. 4).

Operating Data. Cutting speeds and feeds, along with the tool geometry concerned, are shown in Table XX. Undersized holes (0.01 to 0.020 undersize) should be drilled or bored for the reaming operation (Ref. 33).

TABLE XX. REAMING DATA FOR TITANIUM ALLOYS(a)

Titanium Alloy	Alloy Condition(b)	Tool Material(c) High-Speed Steel	Tool Material(c) Carbide	Cutting Speed, fpm High-Speed Steel Initial	Cutting Speed, fpm High-Speed Steel Final	Cutting Speed, fpm Carbide Tipped Initial	Cutting Speed, fpm Carbide Tipped Final	Reamer Diameter, inch	Feed, ipr, for Reamer Shown(d) Commercially Pure, Annealed	Feed, ipr, for Reamer Shown(d) Ti-13V-11Cr-3Al An	Feed, ipr, for Reamer Shown(d) Ti-13V-11Cr-3Al STA	Feed, ipr, for Reamer Shown(d) All Other Titanium Alloys(d)
Commercially pure	An	M2	C-2	40	70	65	250	1/8	0.003	0.002	0.002	0.002
Ti-8Al-1Mo-1V	An	M2	C-2	20	30	50	120	1/4	0.005	0.005	0.004	0.005
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	M2	C-2	20	45	50	175	1/2	0.008	0.007	0.006	0.007
Ti-4Al-3Mo-1V	An	M2	C-2	20	45	50	175	1	0.011	0.009	0.008	0.009
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	M2	C-2	20	35	50	150	1-1/2	0.014	0.012	0.010	0.012
	STA	M2	C-2	20	30	35	120					
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	M2	C-2	20	30	35	120	2	0.016	0.015	0.012	0.015
	STA	M2	C-2	20	25	35	100					
Ti-13V-11Cr-3Al	An	M2	C-2	20	30	50	150					
	STA	M2	C-2	20	25	35	100					

		Tool Angles, degrees						
		Helix	Radial Rake	Relief	Clearance	Chamfer	Lead	Margin, inch
Tool Geometry	High-Speed Steel	10	3 to 5	5 to 10	10 to 15	45	--	0.010-0.015
	Carbide	7	6	5 to 10	10 to 15	45	2° x 3/16"	0.010-0.015
Cutting Fluids	Sulfurized, chlorinated or sulfochlorinated cutting oils. Clean off all oil residues with MEK.							

(a) From Refs. 4,33,56,57,87,88.

(b) An = annealed; STA = solution treated and aged.

(c) AISI designations for steels, CISC designations for carbides.

(d) Feeds are the same for both annealed and heat-treated alloys.

BROACHING

Introduction. Titanium can be broached under the general setup conditions required by the other machining operations. Because of the interrupted nature of the cut, welding of the chip to the cutting edge is quite troublesome. This tendency increases as the wearland develops (Ref. 88). As the wearland increases, so does the tendency for titanium to smear on the cutter. The result is poor finish, rapid wear, and loss of tolerances (Ref. 88).

Titanium, nevertheless, can be broached successfully. In fact, a surface finish of 6 to 28 microinches, rms, can be expected for the tool designs and speeds shown herein (Ref. 4).

Type of Broaches.

Design. Tool design is a very important factor affecting broaching performance. The relief angle, rake angle, and the rise per tooth seem to be the more important elements (Ref. 4).

Figure 13 illustrates some of the elements of broach geometry. Teeth should have a positive rake so that the chips will curl freely into the gullets. The gullet size should be large enough to accommodate the chips formed during the cutting action.

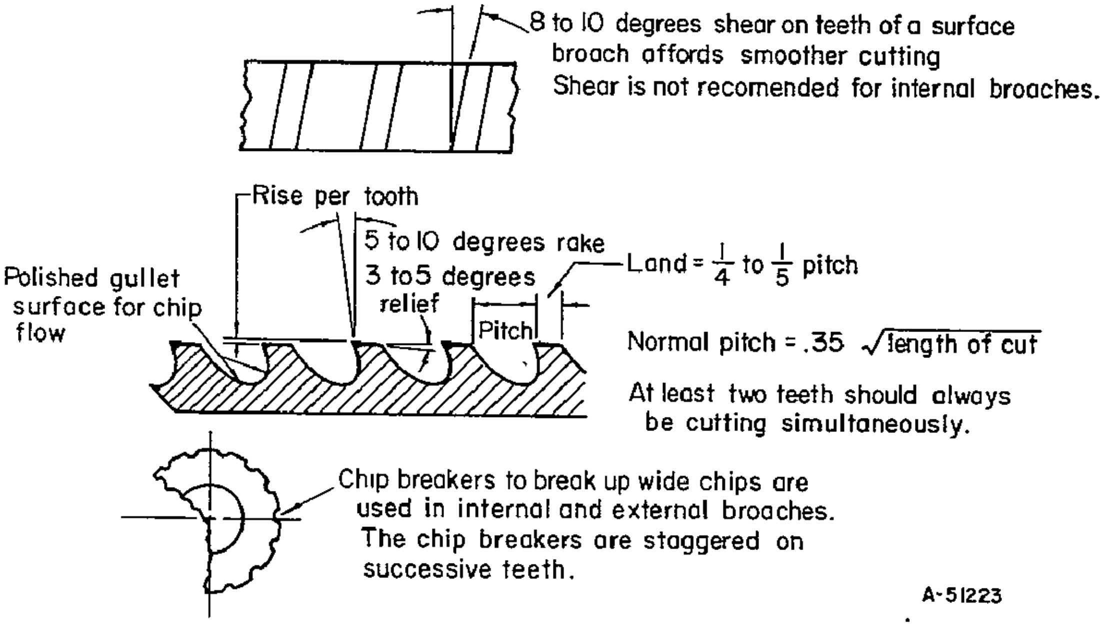

FIGURE 13. NOMENCLATURE FOR BROACHES

Solid broaches are sometimes made slightly oversize (0.0005 inch) to compensate for the slight springback which will occur when the cut is completed.

Titanium usually requires relief angles somewhat higher than the 1/2 to 2 degrees normally used in broaching other materials (Ref. 4). If the relief angle is too small, metal pickup on the land relief surface can seriously affect the quality of the broached surface. Accordingly, relief angles between 3 and 5 degrees have been adopted and used successfully.

A rake or hook angle of 20 degrees is normally recommended for broaching conventional materials. For titanium, however, a reduction to +5 degrees will improve broaching performance to a marked degree (Ref. 4). The smaller rake angle provides greater support for the cutting edge, and improves heat transfer from the cutting zone (Ref. 4). The maximum rake is about +10 degrees. An increase beyond this value invites tool failure.

The normal recommendation for the rise per tooth in broaching steel is 0.0005 to 0.003 inch. Titanium materials, however, should be broached at 0.001 to 0.006 inch per tooth, depending on the alloy and its condition and the broaching operation. The lower values of this range should provide lower cutting forces and better surface finishes (Ref. 4).

Broaches which have been wet ground may improve tool performance. Careful vapor blasting also may help tool life and finishes by reducing the tendency for smearing (Ref. 88).

Tool Materials. Any type of high-speed steel should work reasonably well as a broaching-tool material for titanium. The standard AISI Types T1, M2, and M10 should give good performance in the speed ranges recommended herein (Ref. 4).

<u>Setup Conditions</u>. Rigidity of work and tool is necessary to avoid a consecutive series of "flat surfaces" on the workpiece (Ref. 4). Surface broaching requires much greater rigidity in fixturing than does hole broaching. Hole broaching apparently provides an inherent rigidity derived from the cutter motion against the workholding device or fixture (Ref. 4).

The broach should not ride on the work without cutting.

Cutting Speed. Some titanium alloys have shown a marked sensitivity to changes in cutting speed. Thus, it appears reasonable to recommend low speeds for this type of operation (Ref. 4).

Cutting speeds should be restricted to the range of 20 to 30 fpm (Ref. 4). When broaching dovetails, the speed should be reduced to 10 to 12 fpm.

Depth of Cut. The depth of cut is governed by the "rise per tooth" of the broach. A "rise per tooth" in the range of 0.002 to 0.005 inch has been used successfully when a +5-degree relief is employed. If a 3-degree relief is used, the rise should be reduced to 0.001 ipt.

Cutting Fluid. Sulfurized mineral oil, oil-in-water emulsions, and carbon dioxide sprays have been used during the broaching of titanium. Sulfurized oils seem to give the best results since they minimize friction, improve surface finish, and reduce wear rates (Ref. 4). A prior application of an oil with a high-strength film to the surface to be broached will greatly minimize the chip-welding tendency and prolong tool life between grinds.

General Supervision. Chips should be removed from broaching tools before each succeeding pass. Any excessive wear-land development or undue smearing should be noted at that time. Tools should be kept sharp to reduce the tendency of smearing (of the land) which eventually leads to tool failure.

Operating data for broaching titanium and its alloys are listed in Table XXI.

PRECISION GRINDING

Introduction. Grinding titanium by conventional practices results in unusually high cutting temperatures and chemical reactions between the workpiece and the abrasive. This causes problems in dulling of wheels or belts from "capping" of the grains with titanium, glazing, and burnished surfaces. The troubles can be avoided by following three basic precautions:

- Choosing an abrasive wheel or belt which allows controlled, progressive, intergranular chipping as flat spots develop on the grits

TABLE XXI. BROACHING DATA FOR TITANIUM AND ITS ALLOYS[(a)]

Titanium Alloy	Alloy Condition[(b)]	Type High-Speed Steel[(c)]	Roughing Cutting Speed, fpm	Roughing Depth of Cut, inch	Finishing Cutting Speed, fpm	Finishing Depth of Cut, inch
Commercially Pure	An	T5	20	0.004-0.007	30	0.002-0.004
Ti-8Al-1Mo-1V	An	T5	10	0.003-0.006	16	0.0015-0.003
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	T5	15	0.003-0.006	22	0.0015-0.003
Ti-4Al-3Mo-1V	An	T5	15	0.003-0.006	22	0.0015-0.003
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	T5	12	0.003-0.006	18	0.0015-0.003
	STA	T15	8	0.002-0.005	12	0.001-0.002
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	T5	10	0.003-0.006	16	0.0015-0.003
	STA	T15	7	0.002-0.004	10	0.001-0.002
Ti-13V-11Cr-3Al	An	T5	11	0.003-0.006	17	0.0015-0.003
	STA	T15	6	0.002-0.004	9	0.001-0.002
		Rake Angle (Hook), degrees	Relief Angle, degrees	Rise per Tooth, inch		
Tool Geometry	Roughening	+5 to +10	3 to 4	Same as cut depth		
	Finishing	+5 to +10	2 to 3	Ditto		
Cutting Fluid	Sulfurized oil or sulfochlorinated oil, clean off all oil residues with MEK.					

(a) From Refs. 4 and 88.

(b) An = annealed; STA = solution treated and aged.

(c) AISI designations used.

- Using lower speeds to minimize grinding temperatures and welding reactions

- Utilizing a grinding fluid which will develop a low shear strength, "inhibiting" film between chip and grit.

Low grinding temperatures minimize the residual stresses which caused grinding cracks in some early fabrication studies on titanium.

Titanium and its alloys can be ground at about the same rate as hardened high-speed steels and die steels. Moderately light cuts are recommended, and periodic dressings are required to keep the wheel in proper condition. Excessive wheel loading leads to poor grinding action and causes poor surface finish, high residual tensile stresses, and low grinding ratios.

In spite of the advances made in the last few years, the aircraft and missile industries still retain a cautious attitude concerning the grinding of titanium (Ref. 34).

If a choice of finish-machining methods exists, serious considerations are usually given to turning, boring, or milling operations rather than grinding. These operations require less time than does grinding and give excellent surface finishes.

Machine-Tool Requirements (Ref. 34). There are many high-quality grinders available today. Most of the existing machines can be set for the required light downfeeds, although having no means of adjusting the spindle speed. Furthermore, not many production grinders are equipped with automatic wheel-wear compensation. These devices improve dimensional control, especially when softer wheels are used.

Several existing grinders are being modernized to provide wheel speeds suitable for titanium and other high-strength alloys. Devices for automatic gaging and sizing, wheel dressing, and wheel compensation are being added to the ultra-precision grinders. Increased rigidity in the spindle system, together with automatic wheel balancing are highly recommended features for grinding the high-strength thermal-resistant materials (Ref. 34).

Grinding Wheels (Ref. 58). Properly operated grinding wheels should wear by attrition and fracture of the bond.

Normal attrition involves, as a continuous process, a gradual smoothening of the individual abrasive grains during cutting. It is followed by intergranular fractures which are supposed to provide successively new sharp-edged cutting surfaces until the entire grain leaves the wheel.

If grains break away too slowly, the workpiece material is deposited on and in between the abrasive grains. As wheel loading continues, and the wheel becomes smoother, the grinding rate decreases. Glazing is similar, except that the tips of the grain wear smooth and become shiny through friction. Smooth wheels resulting from either cause burnish the workpiece and may result in burning, high residual stresses, and cracked surfaces (Ref. 58).

If the grains break away too rapidly, either during grinding, or by frequent wheel dressing, wheel wear is excessive.

Grinding wheels are available in various combinations of grit sizes, wheel hardnesses, and bond materials. These attributes influence metal-removal rates and wear for specific grinding conditions. Table XXII shows the wide choices available and indicates the characteristics of a typical wheel used for grinding titanium.

Abrasives. The choice of a silicon carbide or aluminum oxide wheel depends on the grinding application.

Silicon carbide wheels usually produce a better surface finish. On the other hand, aluminum oxide wheel may give lower residual stresses in the workpiece because they are used at lower speeds. Silicon carbide wheels, unfortunately, need grinding oils. This and the higher grinding speeds involved produce a definite fire hazard.

Wheels made with black or regular silicon carbide abrasive like 37C* seem to be inferior to those with aluminum oxide abrasives made by the same manufacturer from the standpoint of wheel wear when each is run at its optimum speed with the same grinding fluid (Refs. 13,58). The optimum speed for silicon carbide wheels is much higher than that of an aluminum oxide wheel (Refs. 13,58). In fact, if a wheel must be operated in the vicinity of 6000 fpm, because of equipment limitations, silicon carbide wheels give better results than aluminum oxide wheels (Refs. 13,58).

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*Norton Company designation.

TABLE XXII. CHART OF MARKINGS ON GRINDING WHEELS

Abrasive Symbols(a)		Grit Size					Wheel Grade			Structure				
Silicon Carbide	Aluminum Oxide	Coarse	Med.	Fine	Very Fine	Grain Combination	Soft	Med.	Hard	Dense	Med.	Open	Bond Form	Bond Type and Manufacturer's Symbols
5C	A	10					A			0			V = vitrified	Modification bond(b)
6C	2A	12	36	90	240	1 Coarse	B			1	5	9	R = rubber	
CA	97A	14	46	100	280	2	C			2	6	10	B = resinoid	
C2A	4A	16	54	120	320	3	D	I		3	7	11	E = shellac	See manufacturer's brochures
C4A	9A	20	60	150	400	4	E	J		4	8	12	M = metal	
7C		24	70	180	500	5	F	K				13	S = silicate	
		30	80	220	600	6	G	L	Q			14		
						7 Fine	H	M	R			15		
								N	S			16		
								O	T					
								P	U					
									V					
									W					
									X					
									Y					
									Z					
A typical(c) marking sequence	4A		60			1 - K				5 - VL				

Description of Various Grades of Silicon Carbide and Aluminum Oxide Abrasives(a)

C - Silicon Carbide	A - Aluminum Oxide
5C - Green silicon carbide	A - Tough aluminum oxide
6C - Black silicon carbide	2A - Semifriable
CA - Mixed aluminum	97A - Friable mixture
C2A - Oxide and	4A - Special friable
C4A - Silicon carbide	9A - Very friable (white)
7C - Mixed silicon carbide	

(a) Cincinnati Milling Machine Company nomenclature.

(c) Most suitable for titanium.

(b) Some manufacturers also add a number designating whether the wheel grade is either exact or 1/3 softer or 1/3 harder than the better grade indicated (K in the example shown).

Aluminum oxide wheels with special friable abrasives like 32A* or its equivalent have been found to be the most satisfactory for titanium. However, white aluminum oxides like Grade 38A* can be substituted at a sacrifice of about 20 per cent in wear rate (Ref. 59).

Table XXIII shows some abrasive-grain classifications, listed by manufacturers, which may be comparable. However, grinding wheels from different suppliers are not necessarily identical.

TABLE XXIII. TYPES OF ALUMINUM OXIDE AND SILICON CARBIDE ABRASIVES USED FOR GRINDING TITANIUM

Abrasive Manufacturer	Type of Abrasive Special Friable Aluminum Oxide	 White Aluminum Oxide	 Black or Regular Silicon Carbide
		Abrasive Designation	
Norton	32A	38A	37C
Cincinnati	4A	9A	6C
Carborundum	--	AA	C
Bay State	3A-8A	9A	2C
Chicago	52A	53A	49C
Desanno	7A	9A	C
Macklin	26A	48A	C
Simonds	7A	8A	C
Sterling	HA	WA	C

Grit Size. The size of the abrasive grains influences the efficiency of grinding by affecting the rate of intergranular fracturing, and the supply of fresh cutting edges. Smaller grains tend to leave the wheel prematurely, resulting in faster wear. Larger grains are usually difficult to penetrate and dull excessively before leaving the wheel.

The optimum grit size for aluminum oxide wheels is between 60 and 80. The optimum grit size for silicon carbide wheels is between 80 and 100 (Refs. 13,58,59).

Wheel Hardness. The material used to bond the abrasive grits determines the wheel hardness. It is usually desirable to use the hardest wheel that will not result in burning or smearing of hard alloys, or produce chatter on softer alloys.

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*Norton Company designation.

For this reason, the medium grades J to M, seem to be the most suitable for titanium (Refs. 13,59). For example, the "M" grade in aluminum oxide wheels exhibits between 30 to 50 per cent higher grinding ratios than the softer "K" grade, depending on the cutting fluid used (Ref. 13). The softer wheels, however, perform better at higher speeds; the harder wheels at somewhat slower speeds (Ref. 13).

Type of Bond. Vitrified bonds seem to give the best performance, possibly because they are more porous. As such, they permit better swarf clearances, and result in lower grinding temperatures (Refs. 58,59).

Setup Conditions. The following recommendations are made in order to provide the good grinding environment needed for titanium.

- High-quality grinders with variable-speed spindles
- Rigid setup of work and wheel to avoid vibrations which cause surface damage
- Rigid, mechanical, holding fixtures
- Arbors for external grinding
- Oxidized machine centers to prevent galling of small parts.

Troubles originating from resonant vibrations can usually be corrected by improved jigs or by backing up thin, slender sections to prevent deflection.

Adjustments in wheel speed, work speed and feed, truing conditions, and the grinding fluid will usually compensate for the selection of a wheel with less than optimum characteristics.

Wheel Speeds. For a given grinding wheel and coolant an optimum grinding-speed range can produce much higher grinding ratios (G-ratios) than a speed a few hundred feet per minute faster or slower (Ref. 13). For the aluminum oxide wheel 32A60VBE, these optimum speeds appear to be between 1500 and 2800 fpm for both grinding oils and rust-inhibitor coolants (Refs. 13,58,59).

For silicon carbide wheels, the optimum speed seems to be in the range from 4000 to 4500 fpm when using a grinding oil (Ref. 13).

Where it is necessary to use the conventional speed of about 6000 fpm, silicon carbide wheels give the best wheel life, but surface damage can be significant.

Wheel speeds of 4000 fpm can be used with silicon carbide wheels and sulfochlorinated oils to produce a good combination of surface finish and dimensional tolerance with relatively low residual stresses (Ref. 60). Lower residual stresses are produced at low wheel speeds (1800 fpm) using aluminum oxide grinding wheels and rust-inhibitor-type fluids (Ref. 60).

A word should be added about table speed. The G-ratio for the 32A60VBE wheel running at 1600 fpm peaks at 200 ipm table speed. This speed, however, is too low for practical grinding. Hence, the recommended table speeds are in the somewhat higher range of 300 to 500 ipm (Refs. 13,59).

Feeds. Two types of feeds are involved in grinding: the downfeed and the cross feed. The former is similar to the depth of cut in machining while the latter corresponds to the feed.

The lightest downfeeds (0.0005 ipp) seem to give the highest G-ratios over a wide range of cross feeds (between 0.025 and 0.25 ipp). However, as the downfeed is successively increased from 0.0005 to 0.0015 ipp the grinding ratio falls and does so more rapidly as the unit cross feed is increased (Ref. 13). Hence, a cross feed of around 0.050 ipp is normally used, together with downfeeds of between 0.0005 and 0.001 ipp. Heavier downfeeds can cause burning and excessive wheel wear (Ref. 59). The cross feed, however, may be increased to 0.10 ipp provided the downfeed is decreased to 0.0005 ipp (Refs. 13,58,59).

Grinding Fluids. It is important to use a grinding fluid which will cool efficiently and inhibit the chemical reaction between titanium and the abrasive wheel. Titanium and its alloys should never be ground dry. Dry grinding results in excessive residual stresses and smeared surfaces, in addition to the creation of a fire hazard from dry titanium metal dust (Ref. 13).

Water alone is not suitable, and ordinary soluble oils do not produce good grinding ratios although they do reduce the fire hazard of grinding (Refs. 13,58).

The highly chlorinated oils give some of the highest G-ratios, especially with silicon carbide wheels. Some of the conventional sulfurized and chlorinated grinding oils also have proved quite satisfactory. Some of the nitrite-amine type rust inhibitors give good results, especially with aluminum oxide wheels (Refs. 13,61).

The degree of concentration or dilution of a grinding fluid plays an important part in the grinding action. Maximum G-ratios are obtained with undiluted oils. When grinding oils are diluted with plain mineral oil, most of their advantages are lost (Ref. 13).

The rust inhibitors should be used at about 10 per cent concentration. This gives a reasonable grinding ratio without the practical difficulties caused by higher concentrations (Ref. 13).

All fluids should be filtered to remove grit, and to prevent "fish tail" marks on finished surfaces. Fluids should be changed more often than is customary in grinding steel.

General Supervision. Grinding operations should be supervised and controlled very carefully. When the grinding procedure used is questionable, quick checks to indicate possible surface cracking can be made by dye and fluorescent penetrants or etching to indicate surface cracking. However, none of these tests will indicate surface damage which does not involve cracking. Care must be exercised in using a 1-minute etch with 10 per cent HF to reveal cracks. Improper etching treatments and etching solutions can cause cracks, since surfaces already may be damaged by residual tensile stresses too small to cause cracks initially.

Wheels used to grind titanium and its alloys must be dressed more frequently than those used to grind steels because of the tendency of titanium to load the wheel.

Some ground parts must be stress relieved by heat treatment prior to final inspection. A common stress relief is to heat the part at 1000 F for 1 hour in a neutral atmosphere to avoid contamination.

Data on speeds and feeds found suitable for silicon carbide and aluminum oxide grinding wheels are given in Table XXIV.

TABLE XXIV. PRECISION GRINDING OF TITANIUM AND ITS ALLOYS(a)

Abrasive Material(b)	Silicon carbide		Aluminum oxide		
Abrasive Types	Regular, green		Special friable, white		
Grit Size	Medium (60-80)		Medium (60-80)		
Wheel Grade (Hardness)	Medium (J-K-L-M)		Medium (K-L-M)		
Structure	Medium (8)		Medium (8)		
Bond(c)	Vitrified (V)		Vitrified (V)		
Operation(d)	Roughing	Finishing	Roughing		Finishing
Feed					
Down, ipp	0.001	0.0005(e)	0.001	0.0005	0.0005(f)
Cross, inch	0.062 0.050(g)	0.05 0.025(g)	0.05	0.10	0.05
Speeds					
Table, ipm	300-500	300-500	300-500		300-500
Wheel, sfpm	2500-5000	2500-5000	1800-2500		1800-2500
Grinding Fluids	Highly chlorinated oils or sulfochlorinated oils (do not dilute); possible fire hazard; hence, flood the work; completely remove all chlorinated oils from the workpiece with MEK		Rust-inhibitor types(h) present no fire hazard; oils used for silicon carbide wheels also have been used with very little fire hazard since the low speeds involved generate very little sparking and oil mist		

(a) From Refs. 2, 7, 8, 13, 34, 52, 58, 59.

(b) Equipment considerations are primary in abrasive selection. If only conventional speeds are available then generally aluminum oxide is not recommended; if low speeds are available then aluminum oxide is superior.

(c) Particular modification of vitrified bond does not seem to matter with titanium.

(d) Type wheels which have been used include 37C80-28V and 32A60-L8VBE.

(e) For surface finishes better than 25 microinches rms, the down feed should be less than 0.002 ipp on the last pass.

(f) The last 0.003 inch should be removed in steps not to exceed 0.0005 ipp. The final two passes should be at zero depth.

(g) Recommended for B120VCA using green silicon-carbide wheels.

(h) 10:1 and 20:1 concentrations of potassium nitrite have been used. The operating advantages of the latter appear to offset the slight increase of grinding efficiency of the former.

BELT GRINDING

Introduction (Refs. 7,8,13,62-64). Titanium sheet can be belt ground to close dimensional tolerances. Belt grinders have produced flat surfaces with only 0.004-inch maximum deviation over areas up to 36 x 36 inches.

Machine-Tool Requirements. The carrier-type machine is usually used in the abrasive belt grinding of sheet. The work is held on a table that oscillates back and forth under grinding belt. A Billy roll directly under the contact roll maintains the pressure between the work and the belt.

Machine rigidity is important for achieving close dimensional tolerances.

Abrasive Belt-Contact Wheel Systems. Paper-backed belts, used dry or with a grinding oil, are suitable for flat sheet work. Cloth backed belts are used when a more rugged backing is needed. Cloth belts are generally available in two types: drills (X-weight) which are the heavier and stiffer of the two, and jeans (J-weight) (Refs. 65,66). The flexible J-weight backing is used for contour polishing; the X-weight provides the best belt life and fastest cutting (Ref. 66). Fully waterproof, cloth-backed belts are necessary when water-base grinding fluids are used. All belts are usually manufactured to close thickness tolerances to permit grinding to precise dimensions.

Contact Wheels. The contact wheel, which supports the belt at the pressure point, regulates the cutting rate and controls the grain breakdown (Refs. 65,66).

Plain-faced contact wheels are normally used for titanium when unit pressures are high enough to promote the necessary breakdown of abrasive material for best grinding action. They usually produce a better surface finish than do most serrated wheels. They minimize extreme shelling*. They also permit off-hand grinding and polishing of curved and contoured parts.

The contact wheel should be small in diameter and as hard as practicable. This combination provides almost a line contact and, hence, a high unit pressure between the abrasive grits and the work.

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*Shelling is the tendency for the abrasive grains on the abrasive belt to loosen and flake off.

Suitable contact-wheel materials for titanium include rubber, plastic, or metal. Rubber is usually recommended because metal contact wheels show little significant increase in stock removal and grinding rate at the price of considerable noise, vibration, poorer surfaces, and higher power consumption (Ref. 13).

Rubber contact wheels are available in various degrees of hardness, measured in terms of Durometer units. These values may range from 10 (sponge rubber) to about 100 (rock hard). The softest rubber (other than sponge) has a value of 20. The harder the contact wheel, the faster an abrasive belt will cut and the coarser the surface finish becomes. Softer wheels produce better surface finishes. However, even soft wheels become effectively harder as spindle speeds increase, and they present more support to the belt. Softer rubber wheels can be used for blending and for spotting operations to remove isolated defects.

The best contact wheel is one which is firm enough to give restricted contact and good penetration by the grit but resilient enough to eliminate shelling failure of the belt at the high loads (Refs. 65, 66,68).

Abrasive Belts. Coatings of silicon carbide give the best results under normal feeds. These belts must possess a dense texture (closed coat). Aluminum oxide abrasive belts are usually recommended when very heavy feeds are used (Ref. 13).

Roughing and spotting operations are normally carried out on belts coated with medium- or fine-grain abrasives. The fine grit size 80 is slightly superior to the medium grit size 40 and 60. Extra-fine grain abrasives (grits 120 to 220) are used for finish belt-grinding operations (Ref. 67).

Synthetic resin bonds provide maximum durability for belts used on titanium. They are available in a waterproof or nonwaterproof backing.

Setup Conditions.

Belt Speeds. Cutting speed affects the rate of metal removal, belt life, and surface finish. Lower belt speeds reduce cutting temperatures as well as the tendency toward burning or marring of the surface by incandescent chips.

Although the optimum speed varies with the contact wheel, grit size, and work thickness, a speed of 1500 fpm generally gives good results (Ref. 13).

Feeds. Feeds in belt grinding are controlled indirectly by adjusting the pressure (Ref. 13). The correct feed permits an economical rate of metal removal and avoids loading of the belt with chips. Feeds should be controlled to give the best dimensional tolerances. If feed pressures must be increased, it may be advisable to use a softer contact wheel.

A definite correlation exists between optimum grinding pressure and belt speed. Higher speeds require less pressure and vice versa. Feed pressures between 80 and 120 psi have been used, depending on the belt speed (Ref. 13).

Grinding Fluids (Refs. 13,62,67). Lubrication is a most significant factor in abrasive belt grinding. Dry grinding, except for certain intermittent operations (blending, spotting, etc.), is not recommended because of the fire hazard (Ref. 13).

A grinding fluid should be used when taking continuous cuts over fairly large areas. It reduces grinding temperatures and quenches the intense sparking that occurs when titanium is ground. Because of the extremely hot sparks formed by titanium, only sulfochlorinated grinding oils possessing high flash points (above 325 F) should be used. They should be applied close to the grinding point for rapid spark quenching.

Chemically active organic lubricants may prove superior in finishing operations, provided the fire hazard can be minimized.

Soluble oil emulsions in water are normally poor grinding fluids for titanium but can be used where the alternative is to grind dry at speeds greater than 1500 fpm.

With waterproof belts, water-base fluids containing certain inorganic compounds and rust inhibitors give good results. They reduce the fire hazard of titanium dust. Aqueous-solution lubricants seem to give the best performance in grinding setups where high loads are used (stock-removal operations). The following water-base fluids have been used:

- Sodium nitrite (5 per cent solution)
- Potassium nitrite (5 per cent solution)
- Sodium phosphate (up to 12 per cent solution)
- Potassium phosphate (up to 30 per cent solution).

The phosphate solutions are caustic enough to remove paint. The more concentrated solutions, however, are not much worse than the 5 per cent solutions in this respect and are considerably more effective as grinding lubricants.

Care must be exercised when potassium nitrite is used as a fluid because the dry salt may become a fire hazard. Grinding fluids can be applied by spraying or by immersing the belt.

Operating Data. Sometimes a roughing operation is first made, using a 50-grit belt to remove gross surface imperfections. An intermediate grind (80 grit) is then used to reduce the grind marks, followed by a finishing operation using a 120-grit belt (Ref. 67).

The correct treatment of belt troubles requires an understanding of glazing and loading. Glazing occurs on abrasive belts when the grinding pressure is insufficient to break down the abrasive particles properly. A loaded belt contains smeared metal welded to the grains, a condition which impairs cutting ability. Proper lubrication is one way to prevent loading (Ref. 66).

The same inspection procedures recommended in the precision grinding section also apply to belt grinding.

Table XXV summarizes the pertinent data required for the belt grinding of titanium.

ABRASIVE SAWING

Introduction. Titanium is difficult to cut with abrasive wheels. In fact, it is practically impossible to plunge straight through a large piece of titanium (Ref. 1). Wheel loading causes high residual stresses on the cut surfaces (Refs. 1,2). Stress-relief treatments may be necessary to prevent delayed cracking of cut surfaces.

TABLE XXV. GRINDING OF TITANIUM AND ITS ALLOYS USING SILICON CARBIDE ABRASIVE BELTS(a)

	Grinding Operation		
	Spotting and Roughing		Finishing
Belt Characteristics			
Abrasive Grit Size	40 to 80 (1-1/2 to 1/8)		120 to 220 (3/0 to 6/0)
Belt Backing	E (paper) X (cloth)		E (paper) X (cloth)
Coating Texture	Closed		Closed
Bond	Resin		Resin
	Spotting	Roughing	Finishing (b)
Grinding Variables			
Grit Size(c)	40 to 80 (1-1/2 to 1/8)	80	120 to 220 (3/0 to 6/0)
Speed (fpm)	1000 to 1500	1500(a) to 2200	1500(a) to 2200
Feed (psi) (d)	--	120 to 80	120 to 80
Depth of Cut		0.002	0.002
Table Speed (fpm)	--	10	10
Grinding Fluids	No	Yes	Yes
Type Grinding Fluids			
For Paper Belts	Heavily sulfurized chlorinated oils (flash point 325 F or higher)		
For Cloth Belts	A 10 per cent nitrite amine rust inhibitor - water solution or a 5 per cent potassium nitrite solution (e) (Fifteen per cent solutions of trisodium or potassium phosphate also have been used.)		

(a) From Refs. 7, 8, 13, 64, 67, 68.

(b) In finishing operations with fine grits, a light pressure is required to prevent shelling. A dull belt (but cutting well) often produces a finer finish than a new, sharp belt of the same grit.

(c) Fine grits tend to fail by shelling at pressures which coarser grits will easily withstand.

(d) Feed pressure is inversely proportional to speed.

(e) When using potassium nitride, follow safety precautions described previously.

When proper techniques are used, however, the cut surfaces are bright, smooth, and square. Surface finish between 10 and 14 microinch rms can be obtained (Ref. 13).

Machine-Tool Requirements. Rigid setups and abrasive cutoff machines having wheel heads capable of oscillating and plunging motions are recommended (Refs. 1,3). It is also advisable that the cutoff machine be equipped with hydraulic feed mechanisms which can be set to produce any desired cutting rate (Ref. 13).

Cutoff Wheels. The choice of the right combination of abrasive grit, wheel hardness, and type of bond will do much to alleviate difficulties. These characteristics are identified for cutoff wheels in much the same way as shown in Table XXII.

Silicon carbide cutoff wheels are generally used on titanium; aluminum oxide wheels do not seem to be satisfactory (Ref. 13). Rubber-bonded, silicon carbide Type 37C and its equivalent seem to give the best results. The medium grit sizes of 46 and 60 are usually used.

Wheel grade "L", which is the hardest grade in the soft range, and the "M" grade, which lies in the medium hardness range, are the most applicable.

Conditions of Setup. The choice of speeds and feeds depend on the diameter of the work and the mode of cutting (oscillating, nonoscillating, work rotation). Some combinations which have given satisfactory results are presented in Table XXVI.

Speed. Speeds from 6800 to 12,000 fpm have been used successfully in abrasive cutoff operations (Refs. 3,13).

Feeds. Successive overlapping shallow cuts should be taken in order to keep the work-wheel contact area as small as possible at all times (Ref. 3). Feeds between 2 and 6 square inches per minute are used, depending on setup conditions and wheel speed.

Cutting Fluids. A rust-inhibitor type of coolant should be supplied at the rate of about 20 gallons per minute to the work-wheel contact area in order to reduce cutting temperatures enough to avoid heat cracking of the cut surfaces.

TABLE XXVI. ABRASIVE SAWING TITANIUM AND TITANIUM ALLOYS(a)

Workpiece Cross Section, sq in.	Typical Wheels Used(b)	Wheel Diameter, inch	Cutting Rate, sq.in./min	Wheel Speed, fpm	Cutting Fluid
Up to 3	37C90-NOR-30 37C60-POR-30	10	2 to 3	9,500	Water-base or cambelline solution (1:50)
3 to 5	37C46-MOR-30	16	2 to 3	9,500	
Up to 5	37C601-L6R-50 37C601-L4R-50	16	3 to 4	12,000	10 per cent nitrite amine solution at 20 gal/min
Up to 7	C60-NRW-3 C60-NRL	20	2.5 to 3	7,300	Water-base or cambelline solution (1:50)
7 to 80	C60-NRW-3 C60-NRL	26	5 to 6	6,800	Water-base or cambelline solution (1:50)

(a) From Refs. 13, 57, 69, 70, 71.

(b) The "37C" wheels are Norton designations; the "C" wheels are Allison designations.

The coolant should penetrate to the wheel-work contact area. It should be applied equally to both sides of the wheel to avoid cracked cuts and wheel breakage.

Soluble oil coolants can be used, but they have a tendency toward foaming (Ref. 1). Soluble-oil coolants are available which minimize the objectionable rubber-wheel odor.

The size of the workpiece influences the choice of cutting techniques. Small stock can be cut without an oscillating head or rotation of work. Bars from 1 to 3 inches in diameter may require either an oscillating or a nonoscillating wheel. Both should be tried in order to determine which is better for the given situation (Refs. 13,57).

Bars larger than 3 inches in diameter usually require rotation of the work as well as an oscillating wheel. The work should be rotated slowly, or indexed, so that the wheel can cut toward the center without cutting too far beyond center (Refs. 13,57).

It may be desirable to stress relieve the workpiece by heat treatment for 1 hour at 1000 F after cutting. Whether the treatment is necessary or not can be checked by inspecting the cut surfaces with dye or fluorescent penetrants when cracks are suspected.

BAND SAWING

Introduction. Difficulties in band sawing titanium and its alloys can be minimized by selecting a saw band with the proper saw pitch, and by using a feeding pressure suited to the work thickness involved. The combination of band velocity and feed also influences the economic tool life (Ref. 72).

The roughness on the cut surface usually ranges from 60 to 200 microinch. Finishes better than 125 microinch rms are obtained by using higher speeds, lighter feeds, and a fine saw pitch (Ref. 72).

Machine-Tool Requirements. Rigid high-quality band saw equipment powered with motors providing at least 2 horsepower should be used (Refs. 4,72). The machines should possess automatic positive feeding and band-tensioning features (Refs. 4,72). In addition, they should have a positive-flow, recirculating-type coolant system.

Saw Bands. Precision and claw-tooth saw bands are used for cutting titanium (Ref. 72). The widest and thickest band which can produce the smallest radius desired on the part should be selected (Ref. 72). The following band widths will cut the minimum radii indicated:

Saw Width, inch	Minimum Radii Cut, inch
1/16	Square
3/32	1/16
1/8	1/8
3/16	5/16
1/4	5/8
3/8	1-7/16
1/2	2-1/2
5/8	3-3/4
3/4	5-7/16
1.0	7-1/4

Wider saw bands provide greater stability when the saw is pretensioned.

Figure 14 illustrates some of the common terms used in describing sawing operations.

Saw Band Design. Two important design features of a saw band are the "pitch" or the number of teeth per inch, and the "set" of the teeth. The selection of the saw pitch for a saw band cutting titanium depends mainly on the cutting-contact area. If the pitch is too coarse, the feeding force on each tooth will be excessive. On the other hand, if the pitch is too fine, the chips will crowd or fill the gullets. In general, the coarsest pitch consistent with desired finish should be selected; however, at least two teeth should always contact the cut (Ref. 72).

The saw set creates clearance to prevent the trailing surfaces of the band from binding. It determines the kerf and hence the amount of metal removed. A fine-pitch saw band with a light set usually gives the best finish, particularly when used with higher band velocities and low feed rates. This combination also produces a slot (or kerf) which approaches the over-all saw set dimension (Ref. 72).

The following tabulation gives some data for raker set, precision-type band saws used for power band sawing titanium.

Pitch Teeth per Inch	Width, inch	Gage, inch	Nominal Set, inch
4	1	0.035	0.060
6	1	0.035	0.045; 0.058
8	1	0.035	0.045; 0.058
10	1	0.035	0.045; 0.058

A right-left raker set combined with the coarsest pitch consistent with the work thickness and the desired finish is usually adequate for most applications (Ref. 72). For some of the stronger alloys of titanium, better results can be expected from the modified design shown in Figure 15. First, the extreme tips of the teeth are ground flat, and then a 4 to 6-degree clearance angle is added to the stubs. Next, a 90-degree face-cutting angle is ground on each tooth (Ref. 72). A band of this design can be reground three or four times, provided it is removed from production before failure occurs (Ref. 72).

Tool Materials. Saw bands made from high-speed steel are recommended for sawing titanium. An appropriate heat treatment produces a microstructure which remains strong at elevated temperatures in a reasonably flexible band (Ref. 72).

Setup Conditions. Hand or gravity-type feeds do not produce satisfactory results when sawing titanium. Vibration-free machines with positive mechanical feeds are necessary to prevent premature band failure (Refs. 4,72).

Maximum rigidity is favored by using the widest and thickest band permitted by the band wheel and the radii to be cut. The band should be pretensioned to approximately 12,000 psi to minimize unnecessary bending of the saw band in the cut (Refs. 4,72). Guide inserts should be adjusted to a snug fit to insure accurate cuts and minimum "lead" (Figure 16). For the same reasons, the band support arms should be close to the work (Ref. 73).

Cutting Speeds. Band velocity is a critical variable in sawing titanium. Excessive cutting speeds cause high cutting temperatures and unwanted vibrations (Ref. 72).

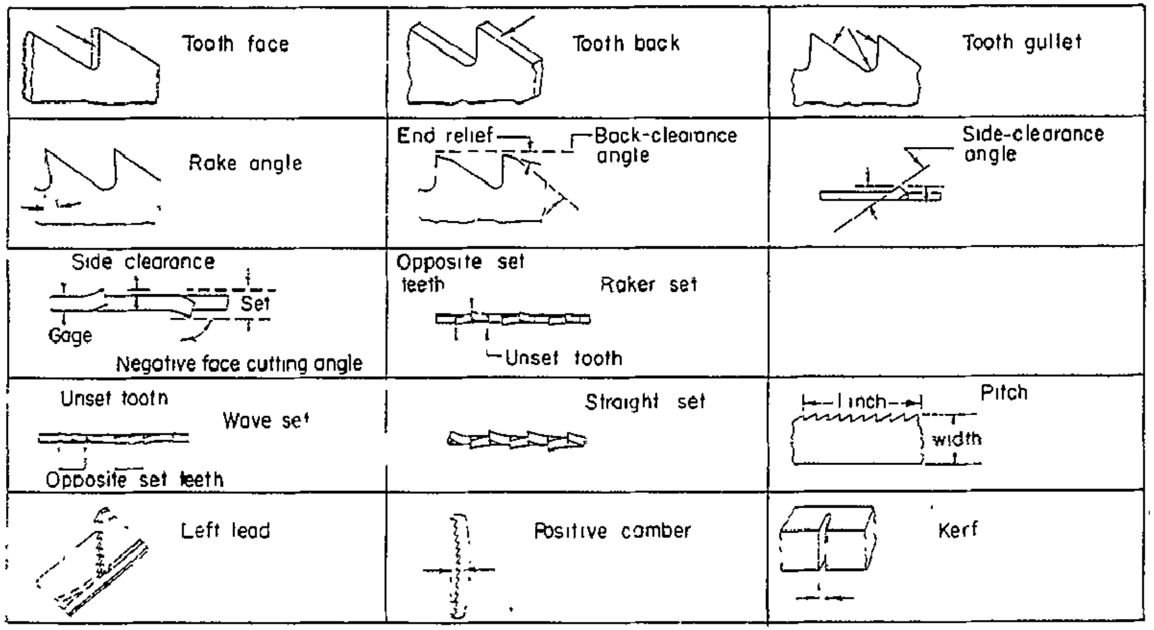


FIGURE 14. ILLUSTRATIONS OF SOME COMMON TERMS USED IN ALLOYS (REF. 72)

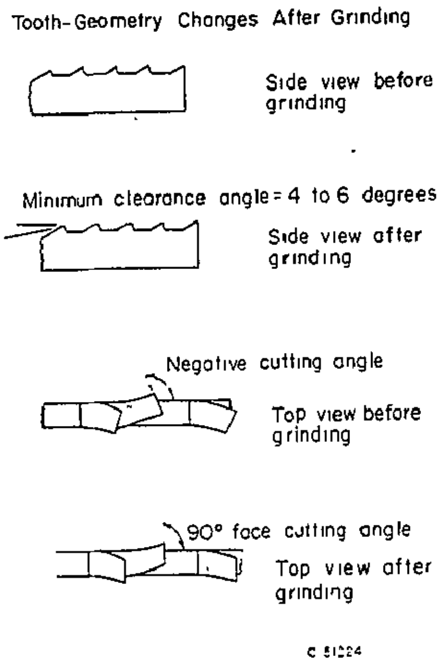


FIGURE 15. A MODIFIED DESIGN SUGGESTED FOR SAWING HARD TITANIUM ALLOYS (REF. 72)

Band velocities used for sawing titanium and its alloys usually range from 50 to 120 fpm, depending on the alloy, surface finish, cutting rate, and tool life desired (Refs. 4,72). The following tabulation subdivides this range according to alloy (Ref. 4):

Titanium Material	Cutting Speeds, fpm
Commercially pure	85 to 100
Ti-8Mn	60 to 70
Ti-4Al-4Mn	35 to 45

Feeds. Feeds in the range of 0.00002 to 0.00012-inch per tooth can be used successfully (Refs. 4,72). The smaller feeds give the best tool life, but the heavier feeds increase productivity and may be more economical (Refs. 4,72). Excessive feeds clog the teeth with chips before they emerge from the kerf, and reduce cutting rates.

Feeding forces must be reduced as the saw pitch decreases to prevent overloading individual teeth. On the other hand, feeding pressures so light that the teeth do not penetrate the work cause excessive abrasion and rapid dulling (Ref. 72).

Cutting Rate. The maximum cutting rate in band sawing is affected mainly by the thickness of the workpiece, the factor controlling the feeds and saw designs which can be employed. Faster cutting rates are achieved in sawing solid bars 1 inch or greater in thickness (or diameter) since more teeth can be loaded uniformly at the same time. For thinner sections, the limited number of engaged teeth requires a reduction in cutting rate to reduce the feed per tooth. Cutting rates, ordinarily, should not exceed 1 square inch per minute. Higher rates may cause inaccurate cutting and can damage the saw set (Ref. 72). In general, cutting rates are smaller for band sawing tubing and structural mill shapes than for bars and plates.

Cutting Fluids. Cutting fluids used in band sawing titanium include soluble oils, sulfurized oils, and chlorinated oils (Refs. 4,72,73). Fluids flowing forcefully from shroud-like nozzles will penetrate the kerf and prevent chips from adhering to the tooth faces and gullets. An atomized spray of soluble oil under 40 psi of air pressure also has been used with good results (Ref. 72). Boston suggests that the latter technique might be preferable if the rubber tires on the band-saw wheels are subject to reaction with oil-base fluids (Ref. 4).

Heavy oxide films will cause problems in band sawing titanium. In fact, an oxide coating as thin as 0.001 inch will reduce the life of new saws drastically (Ref. 72). This trouble can be solved by breaking this surface at the line of cut with a used saw blade.

During the sawing operations, the saw band must not skew in the cut. If the cutting time starts to increase rapidly, the saw band should be replaced.

Operating conditions for band sawing titanium sheet, plate, bars, and tubing are suggested in Tables XXVII to XXXI, inclusive.

TABLE XXVII. RECOMMENDED(a) SPEEDS, FEEDS, AND CUTTING RATES FOR BAND SAWING TITANIUM AND ITS ALLOYS(b)

Line	Titanium Material	Brinell Hardness Number	Band Speed, fpm	Unit Feed, inch/tooth	Cutting Rate, sq in./min
1	Commercially pure	190-240	50-90	0.00002 to 0.00012	0.25 to 0.75
2	Titanium alloys	285-340	50-110	0.00002 to 0.00012	0.50 to 1.0

(a) Based on 5-inch rounds and a 6-pitch saw.

(b) Cutting fluids include soluble oils, sulfurized oils, and chlorinated oils.

TABLE XXVIII. PITCHES OF BAND SAWS RECOMMENDED FOR SAWING DIFFERENT WORK THICKNESSES

Line	Work Thickness, inch	A/L Ratio(a), inch	Appropriate Pitch, teeth per inch
1	7/64 to 5/32	0.10 to 0.15	18
2	5/32 to 3/16	0.15 to 0.28	14
3	3/16 to 3/8	0.28 to 0.375	10
4	3/8 to 1.0	0.375 to 1.0	6
5	1.0 and greater	1.0 and greater	6

(a) A/L represents the ratio "area of cut" to the "length of the cut". In circular sections, A/L equals 1/4 π of the diameter. In square or rectangular sections it equals the cut thickness.

TABLE XXIX. RECOMMENDED MODIFICATIONS OF CUTTING RATES FOR PIPE, TUBING, AND STRUCTURAL SHAPES

Line	Minimum Wall Thickness to be Sawed, inch	Fraction of Minimum Cutting Rates
1	Up to 3/16	0.40
2	3/16 to 3/8	0.50
3	3/8 to 5/8	0.60
4	5/8 to 1.0	0.70
5	1.0 inch and over	1.00

TABLE XXX. LINEAR FEEDS WHEN BAND SAWING TITANIUM SHEET OR WIRE

Unit Feed, inch/tooth	Linear Feeds, inches/minute, for the Band Velocities Indicated							
	50 fpm	60 fpm	70 fpm	80 fpm	90 fpm	100 fpm	110 fpm	120 fpm
			Saw Pitch	18 teeth/in.				
			Sheet					
			Thickness	7/64-5/32 in.				
			A/L Ratio	0.10-0.15				
			Wire A/L Ratio	0.10-0.15				
0.00002	0.22	0.26	0.30	0.35	0.39	0.43	0.47	0.52
0.00003	0.32	0.39	0.45	0.52	0.58	0.65	0.71	0.78
0.00004	0.43	0.52	0.60	0.69	0.78	0.86	0.95	1.04
0.00006	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.55
0.00008	0.86	1.04	1.21	1.38	1.55	1.73	1.90	2.07
0.00010	1.08	1.30	1.51	1.73	1.94	2.16	2.38	2.59
0.00012	1.3	1.55	1.81	2.08	2.33	2.59	2.85	3.11
			Saw Pitch	14 teeth/in.				
			Sheet					
			Thickness	5/32-2/16 in.				
			A/L Ratio	0.10-0.28				
			Wire A/L Ratio	0.10-0.15				
0.00002	0.17	0.20	0.24	0.27	0.30	0.34	0.37	0.40
0.00003	0.25	0.30	0.35	0.40	0.45	0.50	0.56	0.61
0.00004	0.34	0.40	0.47	0.54	0.60	0.67	0.74	0.81
0.00006	0.50	0.61	0.71	0.81	0.91	1.01	1.11	1.31
0.00008	0.67	0.81	0.94	1.08	1.21	1.34	1.48	1.62
0.00010	0.84	1.01	1.18	1.35	1.51	1.68	1.85	2.02
0.00012	1.01	1.21	1.41	1.61	1.81	2.02	2.22	2.42

TABLE XXXI. LINEAR FEEDS WHEN BAND SAWING TITANIUM BARS, PLATE, AND ROUNDS

	Linear Feeds, inches/minute, for the Band Velocities Indicated							
Unit Feed, inch/tooth	50 fpm	60 fpm	70 fpm	80 fpm	90 fpm	100 fpm	110 fpm	120 fpm
			Saw Pitch	10 teeth/in.				
			Bar and Plate					
			Thickness	3/16-3/8 in.				
			A/L Ratio	0.28-0.375				
			Rounds A/L Ratio	0.28-0.375				
0.00002	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29
0.00003	0.18	0.22	0.25	0.29	0.32	0.36	0.40	0.43
0.00004	0.24	0.29	0.34	0.38	0.43	0.48	0.53	0.58
0.00006	0.36	0.43	0.50	0.58	0.64	0.72	0.79	0.86
0.00008	0.48	0.58	0.67	0.77	0.86	0.96	1.06	1.15
0.00010	0.60	0.72	0.84	0.96	1.08	1.20	1.32	1.44
0.00012	0.72	0.86	1.01	1.15	1.30	1.44	1.58	1.73
			Saw Pitch	6 teeth/in.				
			Bar and Plate					
			Thickness	3/8 in. and greater				
			A/L Ratio	0.375 and greater				
			Rounds A/L Ratio	0.375 and greater				
0.00002	0.07	0.09	0.10	0.12	0.13	0.14	0.16	0.17
0.00003	0.11	0.13	0.15	0.17	0.20	0.22	0.24	0.26
0.00004	0.14	0.17	0.20	0.23	0.26	0.29	0.32	0.35
0.00006	0.22	0.26	0.30	0.35	0.39	0.43	0.48	0.52
0.00008	0.29	0.35	0.40	0.46	0.52	0.58	0.63	0.69
0.00010	0.36	0.43	0.50	0.58	0.65	0.72	0.79	0.86
0.00012	0.43	0.52	0.60	0.69	0.78	0.86	0.45	1.04

ELECTROCHEMICAL MACHINING (ECM) OF TITANIUM ALLOYS

INTRODUCTION

The need for fabricating or shaping parts from hardened high-strength and thermal-resistant metals and alloys has created difficult metal-removal problems and necessitated the development of new or improved machining methods.

Among some of the novel nonmechanical methods developed for machining the tough alloys frequently used in rockets, missiles, and aircraft, etc., are electrochemical machining or shaping (ECM), electric discharge machining (EDM), chemical milling, electron-beam machining, and others. This section of the report will deal with electrochemical machining, a process which is already being widely used in industry, with special emphasis on machining or shaping of titanium alloys.

THE ECM PROCESS

General. Metal removal in ECM is by dissolution of the workpiece by means of an electrical current passing between the workpiece (anode) and a shaped tool or tools (cathode) through a suitable electrolyte. The rate of metal removal is proportional to the applied current and is in accordance with Faraday's law.

The high velocities of electrolyte solution flow used in ECM, together with the close spacing (e.g., 0.002 to 0.035 inch) of the electrodes, allow the passage of high currents at relatively low voltages (e.g., 3 to 30 volts), thus permitting high rates of metal removal. For example, current densities of 50 to 1500 amperes per square inch or more are common for ECM, whereas current densities of 0.1 to 2.0 amperes per square inch are typical for many electroplating operations. Electrolyte pumping pressures for ECM operations range from about 10 to 400 psi.

A schematic representation of a drilling operation, which will illustrate the workings of the ECM process, is shown in Figure 16. At the start, the drilling tool is brought to the desired gap distance (e.g., 0.002 to 0.020 inch) from the titanium-alloy workpiece surface and then the voltage is applied. As the drilling operation proceeds, the workpiece dissolves and the drilling tool is advanced to maintain a constant machining gap. In the example shown, the electrolyte flows down through the tool and out through the space between the tool and the workpiece. The tool shown is insulated on the outside to minimize side cutting and to produce a hole with straight sides.

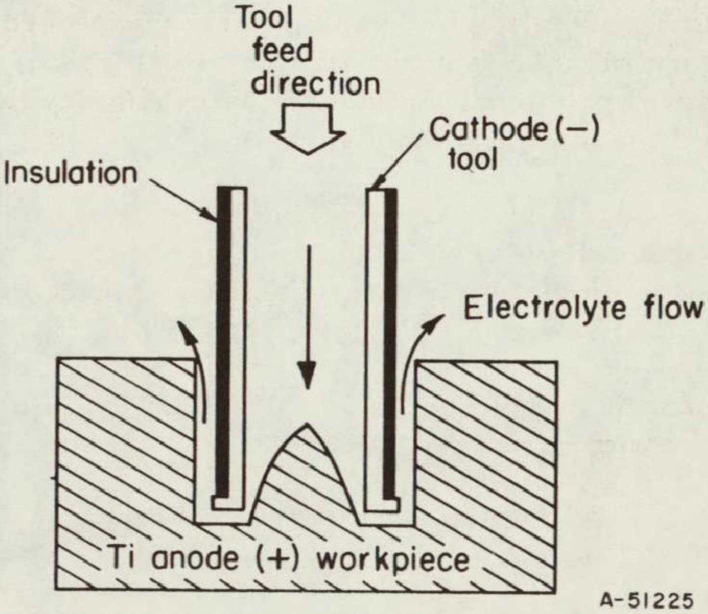


FIGURE 16. ECM-DRILLING OPERATION

The general procedure, described above, can be used for trepanning, die-cavity sinking, and other shaping or contouring operations. For example, three-dimensional cavities can be produced by ECM using a single-axis movement of the tool electrode which closely resembles the reverse image of the desired cavity form. Multiple-hole and irregular-shaped-hole drilling can be accomplished readily by ECM.

Equipment. A typical general-purpose ECM installation that can be used for cavity sinking, trepanning, drilling, broaching, contouring, etc., is shown in Figure 17. The power pack is at the right, while the electrolyte handling and circulating system is at the left.

ECM units with power capacities ranging from about 100 amperes to 10,000 amperes are available commercially. ECM units having 10,000-ampere capacities are already in operation in industry, and larger units are being planned.

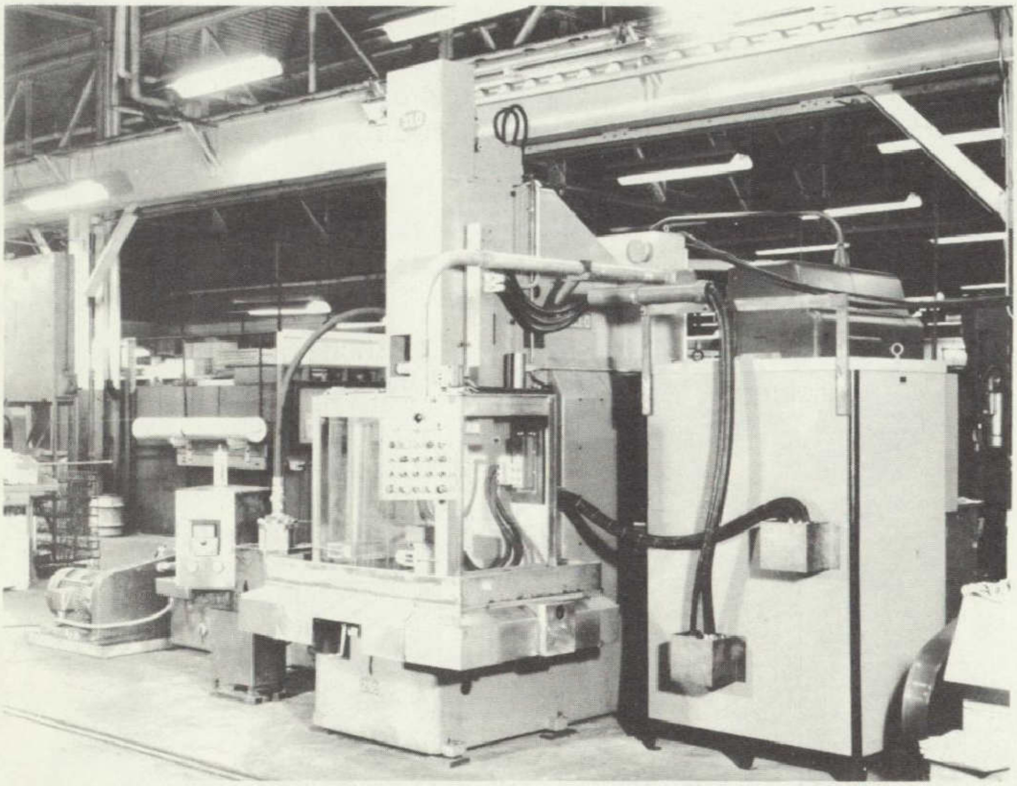


FIGURE 17. GENERAL PURPOSE ECM INSTALLATION

Courtesy of the Ex-Cell-O Corporation

Metal-Removal Rates and Tolerances. Typical metal-removal rates based on feeds or rate of tool travel for cavity-sinking or blade-contouring operations are from about 0.005 inch to 0.200 inch or more per minute. Penetration rates for drilling operations are usually higher and range from about 0.030 to 0.500 inch or more per minute. Planing or broaching operations can be carried out at rates of 1 to 4 inches or more per minute with removal of about 0.010 to 0.050 inch of metal (depth of cut) from the surface.

Penetration rates for titanium and other metals at various current densities are shown in Figure 18. These are theoretical rates based on anodic dissolution efficiencies of 100 per cent. In general, for most ECM operations, the dissolution efficiencies for most metals are high and range from about 90 to 100 per cent.

Tolerances in ECM depend upon the type of operation being performed. Hole diameters can be machined to within ±0.001 inch. Tolerances for other shapes can run from about ±0.002 to about

±0.030 inch, depending on configuration and the particular type of ECM operation involved.

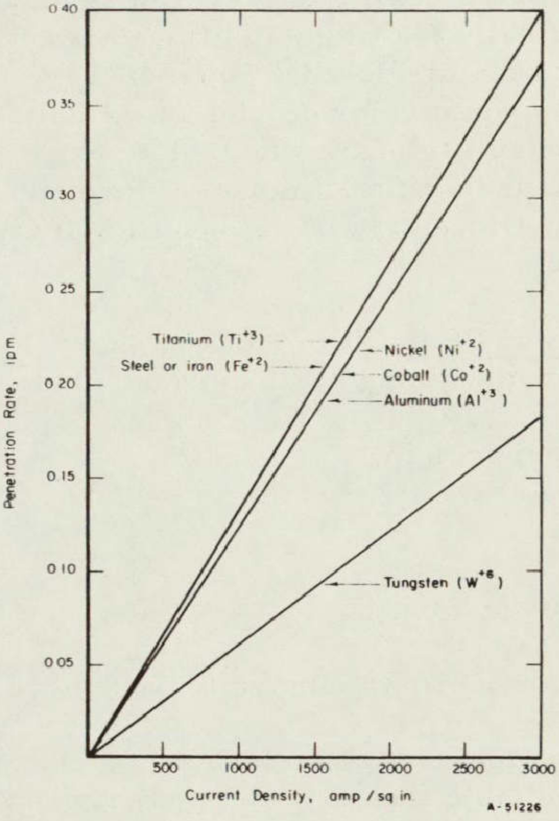


FIGURE 18. PENETRATION RATES FOR TITANIUM AND OTHER METALS

Rates shown are theoretical for dissolution in the valence state indicated.

<u>ECM Tooling and Fixturing</u>. The ECM electrode tool(s) are generally shaped very closely to the reverse image of the shape to be produced. Detailed information on design of cathode tools is proprietary and has not been generally disclosed. ECM electrodes are usually made of stainless steel, copper, brass, or other conductive and corrosion-resistant materials. Special fixturing is usually needed to provide good controlled electrolyte flow to the electrodes and for efficient and accurate ECM operation. Tooling costs for certain types of ECM operations may be fairly expensive. For that reason, ECM is generally better suited to production-type work than to single- or small-lot jobs, unless, of course, the unique capabilities of ECM justify the cost of using the process for machining small lots of parts of hard-to-machine metals or shapes.

Electrolytes. The choice of the electrolyte and the chemistry and microstructure of the particular titanium alloy being machined are especially important in determining how effectively ECM will machine and also the quality of the ECM surfaces. Electrolyte compositions specifically for titanium alloys are of a proprietary nature and have not been disclosed. Some of these formulations are based on the use of sodium chloride plus other salts or materials added to enhance the ability of the electrolyte to give good ECM cutting performance and surface finishes. Proprietary formulations for ECM of titanium alloys as well as specific other metals and alloys are marketed.

Advantages of ECM. Some unique characteristics or advantages of ECM for machining or shaping titanium alloys are:

(1) Stress-free machining

(2) No tool wear

(3) Burr-free machining

(4) No burning or thermal damage to workpieces.

The fact that the tool does not wear, erode, or change during ECM, means that once a suitable tool is developed, it can be used or reused indefinitely to produce replicate parts, without any need to compensate for tool wear.

ECM Operating Conditions for Titanium Alloys. As indicated earlier many of the specific data and information on ECM electrolyte compositions and operating conditions are of a proprietary nature and have not been publicly disclosed. However, some useful data and information that are available on electrolyte compositions and ECM operating conditions for titanium alloys are given below.

Operating data, from work by Bayer et al. (Ref. 74), on trepanning of exemplary parts in Ti-8Al-1Mo-1V alloy are given in Table XXXII. Figure 19 shows the blade-like projections trepanned from rectangular bars of Ti-8Al-1Mo-1V alloy and M-252 alloy. Production of the exemplary parts was carried out to demonstrate over-all capabilities (tolerances, feed rates, surface roughnesses, etc.) of the ECM process. The relatively high roughness values in certain areas of the Ti-8Al-1Mo-1V parts were attributed to machining at low current densities. It should be kept in mind that the

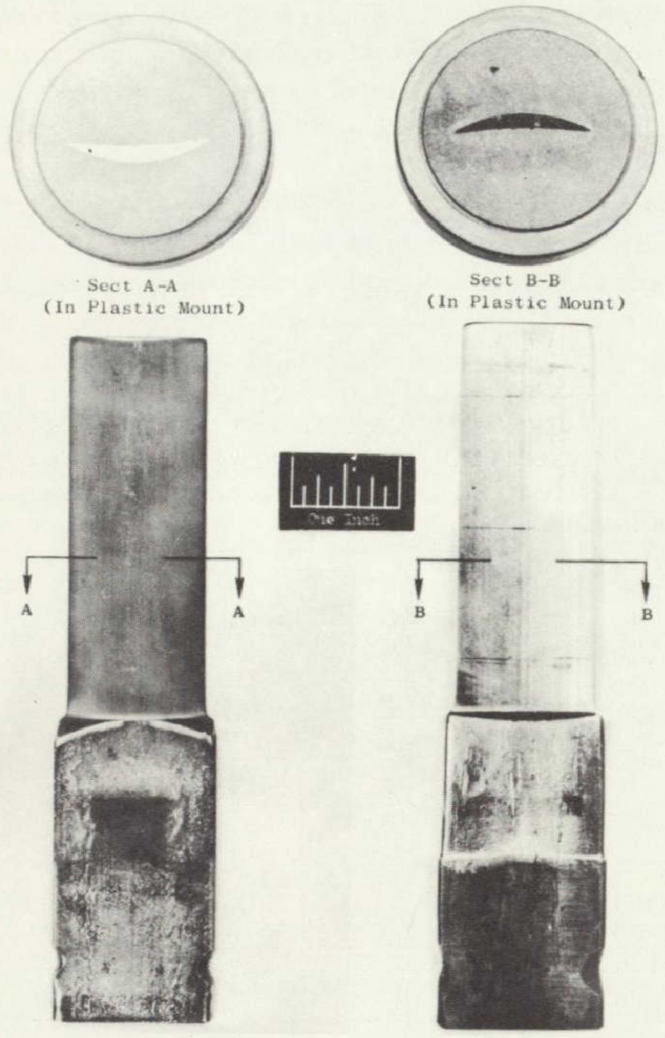
TABLE XXXII. REPRESENTATIVE OPERATING CONDITIONS FOR ECM TREPANNING OF EXEMPLARY PARTS OF Ti-8Al-1Mo-1V ALLOY(a, b)

Operating Parameter	Value
Electrolyte Composition	Sodium chloride (NaCl)
Electrolyte Concentration, lb/gal	0.8
Electrolyte Tank Temperature, F	103
Feed Rate, ipm	0.200
Depth of Ram Travel, in.	4.0
Applied Voltage, volts	20.0
Current, Start, amp	100
Current, Max, amp	500
Current, End, amp	460
Electrolyte Inlet Pressure, Start(c), psig	205
Electrolyte Inlet Pressure, End(c), psig	265
Electrolyte Exit Pressure, Start(c), psig	50
Electrolyte Exit Pressure, End(c), psig	0

(a) Data are from work by Bayer, Cummings, and Jollis (Ref. 74) of General Electric Company, Cincinnati, Ohio, done under Contract No. AF 33(657)-8794.

(b) Rectangular bars of Ti-7Al-1Mo-1V served as workpieces for the ECM work. The bars had a Rockwell C hardness value of 32 to 36.

(c) The electrolyte pressures leveled off after the initial 0.100 inch of travel at the values shown at the end of the ram stroke.



Material: Titanium 8-1-1

Location	Surface Roughness, microinches(AA)
Concave, top section	220-280
Concave, root section	220-240
Concave, length	220-260

Material: M-252

Location	Surface Roughness, microinches(A A)
Concave, top section	100-120
Concave, root section	26-32

FIGURE 19. EXEMPLARY PARTS TREPANNED IN TITANIUM AND M-252 ALLOYS

(See Table 32 for trepanning operating conditions for the Ti-8Al-1Mo-1V part)

[Courtesy of General Electric Company (Ref. 74)] surface roughnesses shown in Figure 19 are for exemplary parts machined with a particular set of operating conditions. They do not necessarily reflect the best surfaces that might be obtained under different operating conditions.

Compressor blades of Ti-6Al-4V alloys in the as-forged and ECM-processed conditions are shown in Figure 20 (Ref. 75). Both sides of the blade were machined simultaneously by ECM with a metal-removal rate of about 0.040 inch per minute from each side using a salt-type (NaCl) electrolyte. The ECM surface roughnesses were 8 to 12 microinches rms.

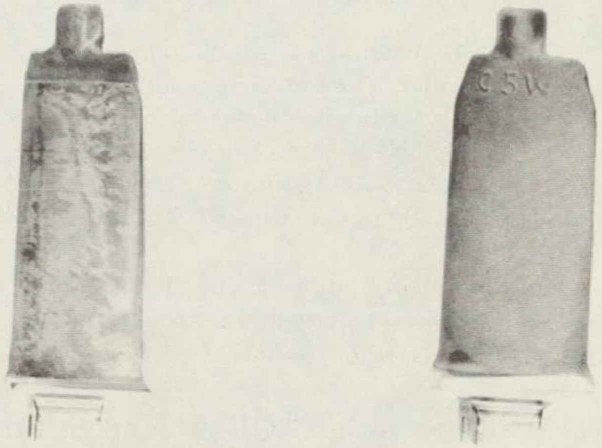


FIGURE 20. ECM-PROCESSED EXPERIMENTAL COMPRESSOR BLADES (Ti-6Al-4V)

Top: As-forged blade
Bottom: ECM-processed blade

[Courtesy of the Ex-Cell-O Corporation (Ref. 75)]

Electrolytic Grinding of Titanium Alloys. Operating data from a study on the effects of electrolytic grinding (mechanically assisted) of Ti-6Al-4V alloys are given in Table XXXIII (Ref. 76). Metallographic examination showed that the electrolytically ground surfaces were satisfactory (i.e., uniform in appearance, free of pits, intergranular attack, etc.).

TABLE XXXIII. DATA AND RESULTS OF ELECTROLYTIC GRINDING OF Ti-6Al-4V ALLOY[a,b]

Operating Parameter	Value
Depth of Cut, inch	0.010
Feed Rate, inch/min	2.0
Applied Voltage, volts	9.0
Current, amp	150
Return Pass[c]	Yes
Surface Produced	Satisfactory

(a) Data are from Jacobus (Ref. 76), McDonnell Aircraft Corporation.

(b) The Ti-6Al-4V material was ground in the mill-annealed condition. Grooves were made in test plates using an electrolytic grinder equipped with an A3HC-60-1/2 metal-bonded aluminum oxide wheel. Full-strength solution of Anocut No. 90 (Anocut Engineering Co., Chicago, Illinois), electrolytic salts were used.

(c) A return pass means feed in one direction and rapid traverse (14 in./min) return to the starting point with current and electrolyte flow.

The term electrolytic grinding (EG) as used in this report refers to metal removal by a combination of electrochemical action and mechanical abrasion. Electrolytic grinding might be considered as a specialized form of electrochemical machining. In EG, a conductive wheel (cathode) impregnated with abrasive particles is rotated against the workpiece (anode). Generally about 85 to 95 per cent or more of the metal removal is by electrochemical action, with abrasion accounting for the remainder. Because of this, the wheel pressures in EG are generally much lighter and also electrolytic wheels generally last 5 to 10 times, or more, longer than conventional wheels. Electrolytes for electrolytic grinding are usually aqueous solutions of salts such as sodium nitrite, sodium nitrate, etc., plus addition agents. Electrolyte formulations aim at providing good conductivity, good grinding performance, and also at being nontoxic and noncorrosive to personnel, machines, and surroundings. Special proprietary formulations are marketed for electrolytic grinding of titanium and most other metals and their alloys.

The favorable results reported in Table XXXIII indicate that EG would be especially suitable for grinding titanium-alloy parts, where there might be a danger of surface cracks or heat checks being produced by conventional mechanical grinding. In addition, the production of burr-free surfaces, together with the ability to machine fragile or delicate workpieces like honeycombs are favorable features of electrolytic grinding.

COMMENTS ON MECHANICAL PROPERTIES OF ECM-PROCESSED TITANIUM PARTS

Published data on the mechanical properties of ECM-processed titanium alloys are scarce. However, a recent DMIC report (Ref. 77) indicated that ECM generally had a neutral effect on mechanical properties such as yield strength, ultimate tensile strength, sustained-load strength, ductility, hardness, etc., for most metals and alloys, including titanium alloys.

Because metal removal in ECM is by anodic dissolution, the titanium-alloy workpieces are not subjected to hydrogen discharge, which occurs at the cathode tool. Thus, there is no danger, in a properly conducted ECM operation, of loss of ductility or delayed-fracture of the titanium alloys from hydrogen embrittlement.

This same DMIC report (Ref. 77) further indicated that metals (including titanium alloys) for which mechanical surface treatments or cold working increase fatigue strength will appear to be weakened about 10 to 20 per cent by ECM or electropolishing. The mechanical-finishing methods often impart compressive stresses to the metal surface; this raises fatigue strength. In contrast, ECM or electropolishing, by removing stressed layers, leave a stress-free surface that allows measuring the true fatigue strength of the metal. The conclusion is that ECM and electropolishing are safe methods to use for processing metals. Where maximum fatigue strength is important, use of a post-ECM or postelectropolishing treatment, such as vapor honing or shot peening, is indicated. These subsequent mechanical treatments can restore or impart compressive stresses to the surface, so that ECM or electropolished parts, thus treated, will exhibit comparable or better fatigue properties than mechanically finished parts.

Summation Comments. ECM as well as EG, appear to be promising methods for machining titanium alloys. This is especially true for operations such as: production of complex shapes or cavities, blade contouring, multiple-hole drilling, trepanning of round- or-irregular shaped holes, deburring, broaching, etc. It is expected that ECM soon will be used more extensively for machining titanium-alloy parts used on advanced aircraft or missiles, especially since the ECM process is readily adaptable for production work and automation, and does not require highly skilled personnel for routine production operations.

CHEMICAL MILLING

INTRODUCTION

Chemical milling generally refers to the shaping, machining, fabricating, or blanking of metal parts by controlled chemical dissolution with suitable chemical reagents or etchants. The process is somewhat similar to the etching procedures that have been used for decades by photoengravers, except that the rates and depths of metal removal are usually much greater for chemical milling.

Much of the earlier work was carried out on aluminum parts for the aircraft industry. It was found that chemical milling could save labor, time, and materials and also provide increased design capability and flexibility in fabricating parts for advanced aircraft and space missiles and vehicles. During the last 3 or 4 years there has been an increased amount of interest in utilization of chemical milling for the production of parts of titanium, and of high-strength, high-temperature metals and alloys. Some of the technical information on procedures, solutions, and techniques are of a proprietary nature, and have not been disclosed.[*],[**],[***]

Chemical milling is particularly useful for removing metal from the surface of formed or complex shaped parts, from thin sections, and from large areas to shallow depths; the weight saving is especially important in aircraft and space vehicle design. Metal can be removed from an entire part, or else selective metal removal can be

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[*] CHEM-MILL is the registered trademark of North American Aviation, Inc., which has granted Turco Products, Inc., Wilmington, California, the exclusive right to sublicense other firms to use the CHEM-MILL process.

[**] "Chem-Size" refers to a proprietary chemical dissolution process developed by Anadite, Inc., South Gate, California, for improving the tolerances of as-rolled sheet and plate, and of parts after forming.

[***] "Chem-Tol" refers to the proprietary chemical dissolution process developed by the United States Chemical Milling Corporation, Manhattan Beach, California, for production of sheet material and parts to close tolerances.

achieved by etching the desired areas while the other areas are protected by a mask from chemical attack. Tapering, step etching, and sizing of sheets or plates can be done readily by chemical milling. The amount of metal removed or depth of etch is determined by the time of immersion in the etching solutions.

Processing Procedures. The chemical-milling processing procedure consists of four general operations or steps, namely: (1) cleaning (or surface preparation), (2) masking, (3) chemical etching or dissolution, (4) rinsing and stripping or removal of the mask. The masking and etching operations are probably the most critical for successful chemical-milling work.

Cleaning. Cleaning of titanium-alloy surfaces is usually done by conventional methods, such as wiping with a solvent-dipped cloth, vapor degreasing, and alkaline cleaning to remove all dirt and grease. Where scale, oxidation products, or other foreign material are firmly attached to the surfaces, acid pickling or abrasive cleaning might be needed to produce a clean surface. Thorough rinsing followed by drying completes the cleaning operation. Failure to properly clean titanium surfaces will cause masking difficulties and uneven attack of the metal by the etchant solution.

Masking. Masking for titanium alloys involves the application of an acid-resistant coating to protect those part areas where no metal removal is desired. The mask is usually applied by either dip, spray, or flow-coating techniques. The particular method employed depends on part size and configuration. Vinyl polymers (Ref. 78) are frequently used because of their ability to hold up well against the oxidizing acids, generally used in the titanium etchant solutions. Multiple coats (three or more) are used to get sufficient mask thickness and good coverage. The mask coating is usually cured by baking at about 250 to 300 F for about 1 to 2 hours to improve its adhesion, tensile, and chemical-resistance properties.

Other desirable characteristics of a good mask material are as follows:

(1) Suitable for accurate pattern transfer on contours and complex configurations, i.e., it must maintain straight lines in the etched design, regardless of its complexity.

(2) Good scribing qualities.

(3) Easy removal after scribing to present clean surfaces for etching, and also good stripping after etching to yield clean surfaces for possible subsequent processing.

The patterns on the masked workpiece are usually applied by means of templates, followed by scribing and then manual peeling of the mask from the areas to be etched. Mask patterns can also be applied to metallic workpieces by silk-screen techniques and by use of photosensitive resists. These procedures are generally utilized on jobs where fine detail and shallow cuts are required.

Etching. A good chemical-milling solution should be capable of removing metal at a predetermined and uniform rate, without adversely affecting dimensional tolerances and the mechanical properties of the workpiece. Pitting, uneven attack of the workpiece surface, or production of rough surface finishes, are all detrimental features of an etchant system.

The more commonly used etchants for chemical milling of titanium alloys are aqueous solutions containing (1) hydrofluoric acid; (2) hydrofluoric acid-nitric acid mixtures; and (3) hydrofluoric acid-chromic acid mixtures. The exact solution compositions used are proprietary. In addition to the main components given above, the solutions usually contain special additives to enhance their etching characteristics. The presence of dissolved titanium in etchant solutions also helps performance.

Etchant solutions are usually circulated over the workpiece surface in order to promote uniform dissolution. Parts also are periodically moved, turned, or rotated to achieve uniform metal over the entire surface. Careful solution-composition control and temperature control must be maintained in order to obtain uniform and predictable rates of metal removal.

Typical production tolerances for chemical milling are ±0.002 inches (Ref. 79). To this must be added the actual raw-stock tolerance prior to chemical milling. The following figures can be used as a guide to depth-of-cut limitations for chemical milling (Ref. 79):

Sheet and plate	0.500-inch maximum depth/surface
Extrusion	0.150-inch maximum depth/surface
Forging	0.250-inch maximum depth/surface.

Because chemical etching proceeds sideways at about the same rate as downwards, the minimum widths that can be machined are about three times the etch depths.

Etching rates for titanium alloys range from about 0.5 to 5.0 mils per minute. Typical industrial production rates are about 1.0 to 1.5 mils per minute. A comparison of the performance characteristic of etching systems for milling titanium, aluminum, and steel alloys is given in Table XXXIV (Ref. 80). Typical surface finishes currently being produced on titanium alloys by chemical milling range from about 15 to 50 microinches rms.

TABLE XXXIV. COMPARISON OF DATA AND CHARACTERISTICS OF SYSTEMS FOR CHEMICAL MILLING ALLOYS, TITANIUM, ALUMINUM, AND STEEL[a]

Item	Titanium Alloys	Steels	Aluminum Alloys
Principal Reactants	Hydrofluoric acid	Hydrochloric acid-nitric acid	Sodium hydroxide
Etch Rate, mils/min	0.6 to 1.2	0.6 to 1.2	0.8 to 1.2
Optimum Etch Depth, inch	0.125	0.125	0.125
Etchant Temperature, F	115 ± 5	145 ± 5	195 ± 5
Exothermic Heat, Btu/(ft^2)(mil)	160	130	95
Average Surface Finish, microinches rms	40 to 100	60 to 120	80 to 120

(a) Data are from Sanz and Shepherd (Ref. 80).

Rinsing and Stripping. After the parts are completely etched, they are thoroughly rinsed with water. The mask is then either stripped by hand or immersed in a solvent tank to soften the mask and facilitate its removal.

Effects on Mechanical Properties. The general feeling is that chemical milling (providing good uniform metal dissolution is achieved; i.e., no intergranular attack, selective etching, or pitting) does not adversely affect the mechanical properties of metals. Published data on those effects are rather scarce and more such data are needed.

Published results from tensile, compressive, and shear tests showed that chemical milling had no significant effect on these mechanical properties for the Ti-6Al-4V alloy (Ref. 80). Chemical milling also had no significant effect on the tensile properties of 5Al-2.5Sn titanium alloys (Ref. 80).

Hiner (Ref. 81) showed that chemical milling did not affect the tensile properties of heat-treated Ti-7Al-4Mo alloy (see Table XXXV).

TABLE XXXV. TENSILE PROPERTIES OF CHEMICALLY MILLED Ti-7Al-4Mo ALLOY[a, b]

Amount Removed From Diameter, inch	Yield Strength, psi	Ultimate Tensile Strength, psi	Reduction in Area, per cent	Elongation, per cent in 4 D
Controls	182,000	192,750	30.0	10
0.005	180,750	191,000	31.9	10
0.014	181,500	191,500	34.9	10
0.040	180,500	190,500	31.9	10

(a) Data are from Hiner (Ref. 81).

(b) Longitudinal blanks were cut from Ti-7Al-4Mo forged stock and heat treated to 190,000 psi ultimate tensile strength. The blanks were then machined into standard 1/4-inch-diameter tensile specimens. Allowance was made for removal of various amounts of material by chemical milling to permit uniform specimens at time of testing.

A Ryan Aeronautical Company report (Ref. 82) gives results of fatigue tests on 6Al-4V and A-110AT (5Al-2.5Sn) titanium alloys. Chemically milled specimens, on the average, showed slightly better fatigue life than the as-received material. On the other hand, Sanz and Shepherd (Ref. 80) cite fatigue-test (reversed-cantilever bending) results on 5Al-2.5Sn alloy (A-110AT) sheet indicating that chemical milling increased the hydrogen content of this alloy and reduced the fatigue strength slightly. Subsequent vacuum annealing of these parts reduced the hydrogen to a low level and increased fatigue strength significantly.

Hydrogen Pickup During Chemical Milling. Titanium alloys are susceptible to hydrogen pickup during chemical milling. The more important factors governing the amount of hydrogen absorbed are: composition and metallurgical structure of the titanium alloy, etchant composition, etchant temperature, and etching time. The amount of hydrogen absorption is related to the amount of beta phase present in the alloy. Results of various studies on hydrogen pickup are discussed below.

The susceptibility of various titanium alloys to hydrogen embrittlement during chemical milling in an HF-H_2O chromic acid bath was investigated by Jones (Ref. 83). Bath composition was as follows:

Hydrofluoric acid (HF)	23 per cent by volume
Water (H_2O)	77 per cent by volume
Chromic acid	125 grams/liter

Bath temperature was 140 F, and etch rate was 1.0 mil per minute. Of the three titanium alloys studied, the beta alloy (Ti-13V-11Cr-3Al) was most severely embrittled. The alpha-beta alloy (Ti-6Al-4V) showed some minor embrittlement, whereas the alpha alloy (Ti-5Al-2.5Sn) was not embrittled. Elevated-temperature vacuum treatments were necessary to restore ductility to the Ti-13V-11Cr-3Al alloy. Because of the minor embrittlement, as shown by bend ductility, no embrittlement-relief treatments were evaluated or deemed necessary for the chemically milled Ti-6Al-4V alloy.

Guerin, Slowiak, and Schneider (Ref. 84) reported that considerable hydrogen pickup was observed in experimental Ti-8Al-1Mo-1V parts chemical milled at an etching rate of 1 mil per side per minute at a temperature of 180 F. The solution contained hydrofluoric acid, chromic acid, titanium powder, and dodecyl sulfonic acid. The hydrogen contents before and after are tabulated below.

Material	Hydrogen Content, ppm
As-received sheet	40
Chemically milled from 0.040 to 0.030 inch thickness	360
Chemically milled from 0.040 to 0.010 inch thickness	635

The authors indicated that MIL specifications for Ti-8Al-1Mo-1V alloy allow a maximum 150 ppm, so they would automatically reject these sheets. The large hydrogen pickup was attributed to operation at the high (180 F) temperature. However, low etching rates of 0.1 to 0.2 mil per side per minute were obtained when operating at 115 F.

Further studies to cope with the hydrogen-pickup problem were in progress at the time the report was written.

Boyd (Ref. 85) has reported the finding of various studies on hydrogen embrittlement of titanium alloys chemically milled in hydrofluoric acid-nitric acid solutions. The hydrogen pickup was closely related to the HNO_3-HF ratio in the bath. One study showed that by maintaining the HNO_3 concentration above 20 per cent with 2 per cent HF present, the hydrogen pickup could be held to less than 50 ppm for many of the commonly used titanium alloys. However, other investigators reported contrary or different results.

The CHEM-MILL Design Manual (Ref. 79) reports that hydrogen embrittlement is not a serious problem when chemically milling the Ti-8Mn alloy so long as the initial content is kept below 80 ppm and the part is milled from one side only to a depth not to exceed one-half of the original thickness. It also indicates that with the exception of the all beta alloy, Ti-13V-11Cr-3Al, none of the other alloys of titanium pick up enough hydrogen during chemical milling to be a problem.

Stearns (Ref. 86) states that with the exception of such beta alloys as Ti-13V-11Cr-3Al, a properly controlled titanium etchant has no adverse effects upon the physical properties of the alloy being milled. Surface finishes are consistently good, falling in the 30 to 40 microinches rms range.

The work discussed above indicates that hydrogen pickup can be a problem in the chemical milling of certain titanium alloys (especially all-beta alloys) under certain operating conditions. Additional research or development work is needed to (1) define and understand the hydrogen pickup problem; (2) minimize hydrogen pickup by development of better etchant solutions and operating conditions; and (3) develop suitable baking or vacuum outgassing procedures for embrittlement relief.

Estimated Processing Costs. On the basis of a survey made by the Defense Metals Information Center for the Air Force in late 1963, the total costs of chemical milling titanium alloys were estimated to be three to four times as high as costs for chemical milling aluminum alloys (Ref. 30). This survey reflects information and comments obtained from engineers and managers in the major aerospace companies and also vendors of chemical-milling services. The above ratio was based on the removal of an equal volume of metal in each case. The ratio would be about 2 to 1 on the basis of equal weight of metal removed.

Specific costs of chemical milling depend on factors such as size, depth of metal removed, complexity of part, etc., but examples of the costs of chemical milling are \$5.35 per pound of aluminum removed (actual cost) and \$11.25 per pound of titanium removed (estimated cost). The higher costs for titanium are due primarily to more expensive etchant solutions, equipment, maintenance, process control, and inspection.

On the basis of probable development of improved formulas for etching solutions and better over-all operating procedures for milling titanium, it was estimated that, within 2 to 3 years, the relative cost for milling titanium versus aluminum would drop from about 3-4 to 1 to about 2-3 to 1.

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