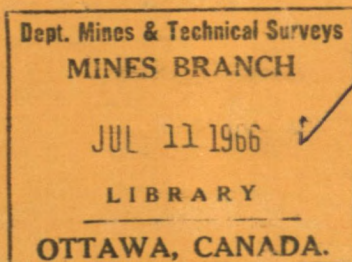




CANADA

A SURVEY OF THE TITANIUM
ALLOYS, THEIR APPLICATIONS
AND THEIR PROCESSING AND
MANUFACTURING TECHNOLOGY



H. V. KINSEY

DEPARTMENT OF MINES AND
TECHNICAL SURVEYS, OTTAWA

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A SURVEY OF THE TITANIUM ALLOYS, THEIR APPLICATIONS AND THEIR PROCESSING AND MANUFACTURING TECHNOLOGY

by

H. V. Kinsey*

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ABSTRACT

The characteristics, properties, areas of application, and processing and manufacturing techniques of the titanium alloys are all reviewed in this "state of the art" survey, which is based on information available in the open literature that appeared between 1959 and 1965. This information is nearly all related to the aeronautical field.

The only major fabrication area not covered in this report is welding. Welding has been dealt with separately in Mines Branch Technical Bulletin TB 71 (April 1965) by Dr. K. Winterton.

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Direction des mines

Bulletin technique TB 80

RELEVÉ DES ALLIAGES AU TITANE, LEURS APPLICATIONS,
ET LA TECHNOLOGIE DE LEUR TRAITEMENT ET DE LEUR
ÉLABORATION

par

H. V. Kinsey*

RÉSUMÉ

Le présent relevé qui entend faire le point sur cette spécialisation est fondé sur toutes les sources de renseignements connues et publiées entre 1959 et 1965. Il traite des caractéristiques, des propriétés, des usages, du traitement et de l'élaboration des alliages au titane. Les renseignements sont presque tous reliés au domaine de l'aéronautique.

Le seul domaine de la fabrication qui n'est compris dans le rapport est celui de la soudure. M. K. Winterton a traité séparément de la soudure dans le bulletin technique de la Direction des mines T. B. 71 (avril 1965).

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INTRODUCTION

During the past several years, the increasing use of titanium alloys in airframe and space vehicle construction has emphasized the growing industrial importance of these alloys.

Intensive work leading to the exploitation of the engineering potentials of titanium and its alloys began twenty years ago. At the present time, there are at least ten alloys available on a commercial basis in addition to commercially pure titanium, and most of these are available in all the usual mill forms.

In addition to those alloys available on a regular commercial basis, there are also about twelve titanium alloys in "semi-commercial" production, and about an equal number still in the development or experimental stage.

All of these alloys--commercial, semi-commercial, and experimental--are listed in Table 1.

Designations of commercial titanium mill products available are given in Table 2⁽¹⁾, and their typical mechanical properties in Table 3⁽¹⁾.

Typical properties of semi-commercial titanium mill products are given in Table 4⁽¹⁾.

TABLE 1
Compositions of Titanium Alloys⁽¹⁾

α Titanium Alloys

Al	Sn	Zr	Nb	Ta	V	Mo	Mn	Cr	Fe	Others	Status	Available Mill Forms
5	2.5										Commercial	All forms
6	2				1	1					Semi-comm.	
6	4				1						"	
5	5	5									"	a, b
5	5	5			1	1					"	
2 $\frac{1}{4}$	11	5				1				0.2 Si	Experimental	a, b, i
3	6	5				2				0.4 Si	"	
7		12									Semi-Comm	a, b
8		8	0.5	0.5							"	a, b, d
7			2	1							"	a, b, d
8					1	1					"	a, b, d

α - β Titanium Alloys

6	2				6						Semi-comm.	a, b, d
6	2	4			6				1	1 Cu	Experimental	a, b, d
6					4						Commercial	All Forms
2.5					16						Semi-comm.	a, b, c, d, e, g
8					10						Experimental	d
6					4					4 Co	"	a, b, d
4					1	3					Commercial	c, d, e
2 $\frac{1}{4}$	11					4					Experimental	b, i
6						2					"	
2						6					"	
7						4					Commercial	a, b, c, g, h
5						1.2		1.4	1.5		"	a, b, c
4						2		2	2		"	a, b, c, e, f
							4				"	a, b, c, g
5							8	2.8	1.2		Semi-comm.	c, d, e
												a, b, c, d

β Titanium Alloys

3					13			11			Commercial	a, b, c, d, e, g
1					8				5		Semi-comm.	Fasteners
	4					12					Experimental	
	6					12					"	
	8					12					"	

Specific product forms indicated as follows: (a) bar, (b) billet, (c) plate, (d) sheet, (e) strip, (f) tubing, (g) wire, (h) extrusions, (i) forgings.

TABLE 2
Designation of Commercial Titanium Mill Products⁽¹⁾

Alloy	Standard Designations			Available Mill Forms
	AMS	ASTM	Military	
<u>Commercially Pure Titanium</u>				
Commercial purity (99.2%)	4902	B265,gr 2	-	All Forms
Commercial purity (99.0%)	4900A	B265,gr 3	-	All Forms
Commercial purity (99.0%)	4901B,	B265,gr 4	T-7993-1	All Forms
	4921A	-	T-9047-1	(a)
	4951	-	-	(g)
<u>α Titanium Alloy</u>				
Ti-5Al-2.5Sn	4926,	B265,gr 6	-	All Forms
	4910	-	T-009046-3	(c, d, e)
	4953	-	-	(g)
	4966	-	-	(i)
<u>α-β Titanium Alloys</u>				
Ti-2Fe-2Cr-2Mo	4923	-	T-9046B-4 T-9047B-4	(a, b, d, e, f)
Ti-8Mn	4908A	B265, gr 7	T-9046B-1	(c, d, e)
Ti-4Al-4Mn	4925A	-	T-9047B-6	(a, b, c, g)
Ti-4Al-3Mo-1V	-	-	-	(c, d, e)
Ti-5Al-1.5Fe-1.4Cr-1.2Mo	4929	-	-	(a, b, c)
	4969	-	-	(i)
Ti-6Al-4V	4911	B265, gr 5	T-009046-2	All Forms
	4928	-	T-9047B-5	(a)
Ti-7Al-4Mo	-	-	-	(a, b, c, g, h)
<u>β Titanium Alloy</u>				
Ti-3Al-13V-11Cr	4917	-	-	(a, b, c, d, e, g)

Specific product forms indicated as follows: (a) bar, (b) billet, (c) plate, (d) sheet, (e) strip, (f) tubing
(g) wire (h) extrusions (i) forgings

TABLE 3
Properties of Commercial Mill Products⁽¹⁾

Alloy	Condition	Form	Room Temperature			At 600°F			Forma- bility (b) min bend radius	Weld- ability (c) min bend radius	Density, lb per cu in.
			Tensile Strength, psi	Yield Strength, psi	Elon- gation, %	Tensile Strength, psi	Yield Strength, psi	Elon- gation in 2 in., %			
Commercially Pure Titanium											
Commercial purity (99.2%)	Ann	-	59,000	40,000	28	28,000	13,000	-	1.5-2t	1-5t	0.163
Commercial purity (99.0%)	Ann	-	79,000	63,000	27	33,000	19,000	33	2-2.5t	1-5t	0.163
Commercial purity (99.0%)	Ann	-	95,000	80,000	25	43,000	27,000	28	2.5-3.5t	1-5t	0.163
α Titanium Alloys											
Ti-5Al-2.5Sn	Ann (d)	Sheet	125,000	120,000	18	82,000	65,000	17	3.5-4.5t	4-6t	0.161
α-β Titanium Alloys											
Ti-2Fe-2Cr-2Mo	Ann	Bar	137,000	125,000	18	95,000	65,000	19	3-5t	Brittle	0.171
	HT(e)	Bar	179,000	171,000	13	136,000	112,000	16	-	Brittle	
Ti-8Mn	Ann	Sheet	138,000	125,000	15	103,000	83,000	13	3-5t	Brittle	0.171
Ti-4Al-4Mn	Ann	Bar	148,000	133,000	16	110,000	90,000	17	-	Brittle	0.163
	HT(f)	Bar	162,000	140,000	9	125,000	100,000	11	-	Brittle	
Ti-4Al-3Mo-1V	HT(g)	Sheet	140,000	95,000	15	-	-	-	3-4t	-	0.163
	HT(h)	Sheet	195,000	167,000	6	152,000	113,000	7	3.5-4.5t	-	
Ti-5Al-1.5Fe-1.4Cr-1.2Mo	Ann	Bar	154,000	145,000	16	115,000	100,000	16	-	Brittle	0.163
	HT(i)	Bar	195,000	184,000	9	150,000	125,000	14	-	Brittle	
Ti-6Al-4V	Ann	Sheet	135,000	120,000	11	105,000	95,000	11	4.5-6t	9-12t	0.160
	HT(j)	Sheet	170,000	150,000	7	130,000	105,000	7	-	-	
Ti-7Al-4Mo	Ann	Bar	160,000	150,000	15	125,000	117,000	17	-	-	0.162
	HT(k)	Bar	190,000	175,000	12	155,000	120,000	15	-	-	
β Titanium Alloy											
Ti-3Al-13V-11Cr	HT(l)	Sheet	135,000	130,000	16	-	-	-	2.5-3t	3t	0.175
	HT(m)	Sheet	180,000	170,000	6	175,000	145,000	8	-	-	

(a) Property data are for general comparison; they do not represent minimum or design properties specifically, but comparative strength levels. (b) Room temperature. (c) Ductility values apply to arc-welded joints in the as-welded condition made with filler metals of the same composition as the base metal. The ductility values can be altered by the use of special filler metals or postweld annealing or heat treating operations. (d) At 1325°F for 4 hr, air cool. (e) At 1480°F for 1 hr, water quench; 900°F for 2 hr, air cool. (f) At 1400-1500°F for 2 hr, water quench; 800-1000°F for 24 hr, air cool. (g) At 1625°F for 2.5 min, water quench. (h) At 1625°F for 2.5 min, water quench; 925°F for 12 hr, air cool. (i) At 1600°F for 1 hr, water quench; 1000°F for 24 hr, air cool. (j) At 1700°F for 20 min, water quench; 975°F for 8 hr, air cool. (k) At 1650°F for 20 min, water quench; 900°F for 16 hr, air cool. (l) At 1400-1500°F for 15-30 min, air cool. (m) At 1400°F for 30 min, air cool; 900°F age, air cool.

TABLE 4

Properties of Semi-Commercial Titanium Mill Products⁽¹⁾

Alloy	Condition	Form	Room Temperature			At 600°F			Forma- bility (b) min bend radius	Weld- ability (c) min bend radius	Density, lb per cu in.
			Tensile Strength, psi	Yield Strength, psi	Elon- gation, %	Tensile Strength, psi	Yield Strength, psi	Elon- gation in 2 in., %			
<u>α Titanium Alloys</u>											
Ti-6Al-4Zr-1V	Ann (d)	Sheet	143,000	138,000	17	90,000	76,000	20	4.0t	5-6t	0.163
Ti-8Al-1Mo-1V	HT (e)	Sheet	147,000	135,000	16	112,000	88,000	16	4.5t	7-8t	0.156
Ti-8Al-2Cb-1Ta	Ann (f)	Bar	126,000	120,000	17	100,000	81,000	25	3-4t	4-6t	0.159
Ti-8Al-8Zr-1(Cb + Ta)	Ann (g)	Bar	135,000	125,000	16	110,000	90,000	17	-	-	0.160
Ti-7Al-12Zr	Ann	Bar	140,000	133,000	12	102,000	85,000	13	-	-	0.167
<u>α-β Titanium Alloys</u>											
Ti-3Al-2.5V	Ann	Strip	100,000	85,000	15	-	-	-	2-3t	-	0.162
Ti-5Al-2.75Cr-1.25Fe	Ann	Bar	160,000	154,000	15	122,000	102,000	20	-	-	0.163
	HT (h)	Bar	190,000	175,000	6	144,000	117,000	10	-	-	
Ti-2.5Al-16V	HT (i)	Sheet	110,000	55,000	16	-	-	-	4.5t	-	0.165
	HT (j)	Sheet	180,000	165,000	6	140,000	130,000	8	-	-	

(a) Property data are for general comparison; they do not represent minimum or design properties, specifically, but comparative strength levels. (b) Room temperature. (c) Ductility values apply to arc welded joints in as-welded condition made with filler metals of the same composition as the base metal. The ductility values can be altered by the use of special filler metals or postweld annealing or heat treating operations. (d) At 1325°F for 4 hr, furnace cool. (e) At 1800°F for 5 min, air cool; 1100°F for 8 hr, air cool. (f) At 1650°F for 1 hr, air cool. (g) At 1600°F for 8 hr in vacuum, furnace cool to 650°F. (h) At 1450°F for 2 hr, water quench; 900°F for 5 hr, air cool. (i) At 1380°F for 20 min, water quench. (j) At 1380°F for 20 min, water quench, 960°F for 4 hr, air cool.

ALLOY METALLURGY

Titanium exists in two crystal forms. At room temperature it has a close-packed hexagonal crystal structure, called "alpha". At 900°C (1625°F), this structure transforms to a body-centred cubic structure known as "beta".

When aluminum is added to titanium, the transformation temperature is raised. In other words, aluminum is said to stabilize the alpha form of titanium. Most of the transition metals, such as vanadium, chromium, manganese, iron, cobalt, niobium, molybdenum and tantalum, lower the transition temperature, thereby stabilizing the beta form of titanium. Tin and zirconium are substantially neutral.

Generally speaking, titanium alloys containing over 5% of aluminum and only minor quantities of the beta-stabilizing alloy additions have a single-phase alpha crystal structure. These alloys are weldable and have good ductility. They are identified as the "alpha" titanium alloys.

When over about 5% of the beta-stabilizing additions are present, the resultant alloy has a two-phase structure. Both the alpha form and the beta form are present. Up to 8% aluminum may also be present. These alloys are identified as the "alpha-beta" alloys. They are heat-treatable, generally stronger and less ductile than the single phase "alpha" alloys, and not so readily weldable.

If sufficient beta-stabilizing additions are made, an alloy can be obtained that is single-phase "beta" at room temperature. The one commercial "beta" alloy is really metastable. It can be heat-treated. The strengthening mechanism is a precipitation of fine particles of alpha titanium and TiCr_2 .

For a more detailed discussion of the alloy metallurgy of titanium alloys, the reader is referred to the 8th Edition, Vol. 1, of the ASM Metals Handbook⁽¹⁾.

Alpha Titanium Alloys

The most firmly established of the alpha titanium alloys is the 5Al-2.5Sn alloy. This alloy is available in all mill forms. A significant measure of the experience with this alloy is the fact that, at least five years ago, forgings were available with guaranteed minimum mechanical properties⁽²⁾. This alloy is not heat-treatable and was developed primarily for good weldability and good elevated-temperature creep properties.

This original alpha alloy has now been joined by a group of "super-alpha" alloys, designed to retain the excellent weldability of the 5Al-2.5Sn titanium alloy with improved creep properties. The more advanced of this type of alloy are listed below:

Ti-7Al-12Zr
 Ti-5Al-5Zr-5Sn
 Ti-8Al-8Zr-1(Nb + Ta)
 Ti-7Al-2Nb-1Ta
 Ti-8Al-1Mo-1V

These alloys have been under intensive development for the past five years.

Three of these alloys, the 7Al-12Zr, 5Al-5Zr-5Sn and 8Al-1Mo-1V alloys, appear to have received the major amount of attention and to have been specifically aimed at supersonic transport applications. The 8Al-1Mo-1V sheet alloy has the highest room-temperature tensile properties^(3,4), and is also the only one of these three alloys that responds to heat treatment⁽⁴⁾. Based on the creep stress to density ratio required to produce 0.1% plastic deformation in 150 hours over the temperature

range of 370°-540°C (700°-1100°F), both the 8Al-1Mo-1V and the 5Al-5Zr-5Sn alloy are superior to the 6Al-4V titanium alloy and also the Greek Ascoloy⁽⁵⁾. It is also stated that the 7Al-12Zr alloy is the most creep-resistant of these three alloys up to 540°C (1000°F)⁽³⁾. The creep resistance of the 8Al-1Mo-1V alloy is reported to increase with stress to a maximum at around 47,500 psi in a 510°C (950°F) exposure (0.7% total deformation in 2400 hours⁽⁶⁾).

One set of properties that has been intensively studied is the residual room-temperature tensile properties after prolonged exposure to elevated temperature under stress. The specific properties of interest are tensile and notch-tensile strengths, strain-rate sensitivity, and elongation⁽⁷⁾. The 8Al-1Mo-1V alloy showed no significant deterioration of room-temperature properties after exposure at 290°C (550°F) unstressed for 14,000 hours⁽⁷⁾. In a subsequent test, this alloy was exposed to 290°C (550°F) and a stress of 67,000 psi for 22,000 hours without any significant change in room-temperature tensile properties⁽⁸⁾. However, the 5-8% Al super-alpha alloys have shown some instability when exposed to temperatures above 455°C (850°F), probably due to an ordering reaction resulting from the high aluminum content⁽⁹⁾. The 8Al-1Mo-1V alloy has also shown a loss in spot-weld strength after exposure to 290°C (550°F)⁽⁷⁾.

A further criterion of suitability of aircraft structural materials is the residual static strength in the presence of a notch. On the basis of residual static strength to density ratio, the 8Al-1Mo-1V titanium alloy was superior to the most promising alpha-beta titanium alloys, stainless steels, and a super-alloy⁽¹⁰⁾.

The formability of these three "super-alpha" alloys in sheet form is excellent. The bend radius required is comparable to that required for the alpha-beta titanium alloys⁽⁴⁾, and they are more readily weldable⁽⁴⁾.

A prototype evaluation of bulk-head fuselage frame structures made of 8Al-1Mo-1V alloy sheet was carried out⁽¹¹⁾. These components were tested under both static and repeated loading near the design ultimate strength, over the temperature range of from room temperature to 425°C (800°F), without failure.

The 7Al-2Nb-1Ta alloy has been developed more specifically for thick plate for submarine hulls. It is claimed to be available in plate thicknesses up to 1 in. with a guaranteed minimum yield strength of 105,000 psi, freedom from brittle fracture, and to be weldable by open-air welding. Progress is being made to extend the use of this alloy in plate thicknesses up to 4 in.⁽¹²⁾. A 2-1/8 in. plate 5 ft wide x 12 ft long has been cold-formed under production shop conditions into a 7 ft diameter submersible hull section⁽¹³⁾. Modified alloy compositions and improved mill processing show promise of extending the yield strength to 115,000 psi⁽¹²⁾. To compete with this alloy on the basis of equivalent hull-weight fraction performance, it would require a steel with a yield strength in excess of 200,000 psi⁽¹²⁾.

All of these "super-alpha" alloys have one rather troublesome fault. They are subject to stress corrosion attack in the presence of sea water or dry sea-water salt⁽¹⁴⁾. A nickel coating free from porosity will protect against this type of failure⁽¹⁴⁾. A further indication of the susceptibility of this type of alloy to sea water is the finding that when 7Al-2Nb-1Ta alloy test specimens containing flaws were subjected to full-reverse-bend fatigue testing, sea water accelerated the fatigue crack growth rate at all strain levels⁽¹³⁾. According to recent reports, it is probable that this defect might be eliminated, or at least minimized by a combination of better mill processing techniques and the addition of 0.5% Mo to the alloy⁽¹⁵⁾.

Alpha-Beta Titanium Alloys

A fairly complete set of data on all of the commercial alpha-beta alloys listed in Table 1 was already available by 1961^(16, 17). By 1963, all of these commercial alpha-beta alloys except the 7Al-4Mo alloy had been assigned an AMS number⁽⁴⁾. It is not surprising, therefore, to find these alloys fairly firmly established as structural alloys for aircraft and space vehicle use. These commercial alpha-beta alloys and their corresponding AMS numbers are listed in Table 5⁽⁴⁾.

TABLE 5
AMS Numbers for Commercial Alpha-Beta Titanium Alloys⁽⁴⁾

Nominal Alloy Composition, Per Cent	AMS No.
8Mn	4908A
2Fe-2Cr-2Mo	4923
4Al-4Mn	4925A
4Al-3Mo-1V	4912, 4913
5Al-1.5Fe-1.4Cr-1.2Mo	4929, 4969
6Al-4V	4911, 4928A, 4935

As a result of this situation, most of the activity in these alloys has been directed toward a more detailed study of characteristics, such as property stability, fracture toughness, etc., and the development of manufacturing techniques.

The 6Al-4V alloy would appear to be the most popular of these alpha-beta alloys. In addition to airframe components it has been, or is being, considered for U. S. Army helmets⁽¹⁴⁾, large diameter rocket motor cases⁽³⁾, deep-diving submersible hulls⁽¹³⁾, and hydrofoils⁽¹⁸⁾. On the basis of an intensive evaluation program, including notched rotating-beam fatigue testing in sea water, it has been selected as the best of 60 candidate materials for hydrofoil applications⁽¹⁹⁾. On the basis of a minimum

yield strength of 120,000 psi⁽²⁰⁾ and a fatigue limit of 55,000 psi⁽¹⁸⁾, which are both realistic values for the 6Al-4V titanium alloy, an alloy steel would have to have a minimum tensile yield strength of 213,000 psi and a fatigue limit of 100,000 psi for an equivalent strength to weight ration.

The room-temperature tensile properties of the 6Al-4V alloy are not significantly altered after 22,000 hours of exposure, unstressed, at 290°C (550°F)⁽⁷⁾. However, it did show a loss in spot-weld strength after this exposure. In another test, the same results were obtained after 500 hours exposure at 345°C (650°F) and a stress of 50,000 psi⁽³⁾. This alloy also shows excellent stability in terms of retention of room temperature tensile properties, in thermal-cycling tests, under restraint, between temperatures of 485°C and 185°C (900°F and 300°F)⁽²¹⁾.

Both the 6Al-4V and 4Al-3Mo-1V alloys are reported to show some directionality when processed to strip. The directionality of 2.5Al-16V alloy strip is insignificant⁽³⁾.

Newer developments in the alpha-beta titanium alloys are listed below:

8Al-10V

6Al-6V-2Sn

6Al-4V-4Co

6Al-6V-2Sn-4Zr-1Fe-1Cu

All of these alloys are intended primarily for sheet applications. It is reported that the first three of these alloys can be heat treated to a tensile yield strength of about 200,000 psi^(22, 23), and that the fourth of these alloys can be heat treated to a tensile yield strength of 240,000 psi⁽¹⁰⁾. However, the fracture toughness of the 8Al-10V and the 6Al-6V-2Sn alloys, when heat treated to this strength level, is reported to be poor⁽²²⁾ and experience would suggest that this is a general characteristic to be anticipated in all alpha-beta titanium alloys.

The annealed tensile yield strength of the 6Al-6V-2Sn alloy in sections 2 in. thick is 140,000 psi⁽²⁴⁾. It is suggested that the notch toughness of this alloy at this strength level is adequate for most engineering applications⁽²⁴⁾. Fracture toughness data for this alloy when heat treated to several strength levels are given in Table 6⁽¹⁹⁾. On an equivalent weight basis, this alloy, at a tensile yield strength of 140,000 psi, is equivalent to steel at a tensile yield strength of 248,000 psi.

TABLE 6
Fracture Toughness of the Ti-6Al-6V-2Sn Alloy⁽¹⁹⁾

Yield Strength, psi	Fracture Toughness, G_c , in-lb in. ²	
	Machined Notch, 0.001-Inch Root Radius	Fatigue Crack Notch ^(a)
145,400	2,400	2,144
172,400	783	711
186,900	244	194
196,600	161	93

(a) Machined notch with 0.001-inch root radius plus cracks induced by bending fatigue.

The 6Al-6V-2Sn alloy would appear to give about a 20,000 psi increase in yield strength over the older 6Al-4V alloy, without any significant sacrifice in toughness. It is probably too early yet to make a complete evaluation of the newest of these alpha beta alloys, the 6Al-6V-2Sn-4Zr-1Fe-1Cu complex alloy. However, preliminary data would suggest that this alloy might continue the trend to higher tensile strengths without sacrificing toughness⁽¹⁰⁾.

A "premium" grade of most of these alloys, identified as ELI grade (extra-low interstitials), in which interstitials, such as oxygen, nitrogen, hydrogen, etc., are held to a lower minimum level than in the standard grades of alloys, has now been available for a number of years^(3, 23). This new grade was specifically designed for cryogenic applications in missiles^(3, 23). It would also appear that for thick plate (1 in. or over) applications where toughness and weldability are important, the ELI grades of alloy should be used⁽²⁵⁾.

Beta Titanium Alloys

The only beta titanium alloy that has reached the "commercial" stage is the 3Al-13V-11Cr alloy. This is identified by the AMS No. 4917⁽⁴⁾. This alloy is available in most mill forms. Its properties and behaviour have been studied as intensively as the other types of titanium alloys, and is reported quite thoroughly in the literature.

Two of the more critical properties that concern the users of titanium alloys for aircraft and space vehicles are fracture toughness and mechanical property stability after prolonged exposure to elevated temperatures. Work on these subjects has already been recognized in the discussion of the alpha and alpha-beta alloys. In the case of the 3Al-13V-11Cr alloy, it has been found that the fracture toughness of sheet specimens can, with proper heat treatment, be insensitive to strain rates over a very wide range of loading conditions⁽¹⁴⁾. The G_c fracture toughness can be improved by selected treatments. For example, for comparable strength levels, ageing at 425°C (800°F) was found to impart greater fracture toughness than ageing at 485°C (900°F)⁽²¹⁾. Strength imparted by cold work is more beneficial to fracture toughness than the same strength by ageing⁽²¹⁾. The optimum yield strength and toughness combinations are obtained in the cold-worked-plus-aged condition⁽²⁶⁾. A reduction of from 1% and 2% by high pressure shock produces about the same susceptibility to ageing as

10% reduction by conventional cold work. However, the fracture toughness of shocked and aged specimens is lower than for aged specimens not shocked⁽¹⁹⁾. Fracture toughness and notched strength decreases with increasing thickness up to 0.063 in. and remains constant between 0.063 in. and 0.130 in.⁽²⁶⁾. This alloy has good toughness in the solution-treated condition down to -80°C (-110°F) but not at -195°C (-320°F)⁽²⁶⁾.

The 3Al-13V-11Cr titanium alloy, when tested for stability in terms of deterioration of room-temperature tensile properties after prolonged exposure to elevated temperatures, in general showed more instability than alpha and alpha-beta titanium alloys as a result of exposure to 290°C (550°F). Instability was significant after 2000 hours of exposure. Total exposure time was 22,000 hours⁽⁷⁾. It has also been reported that this alloy, in the solution annealed condition, is inferior to 6Al-4V alloy in thermal cycling under restraint over a temperature range of $485-185^{\circ}\text{C}$ ($900-300^{\circ}\text{F}$). Failure is by a combination of ageing and creep⁽²¹⁾. The temperature limit for the 3Al-13V-11Cr alloy in long time creep applications is 375°C (700°F)⁽²¹⁾. It has been reported that 0.010 in. sheet of this alloy becomes embrittled as a result of exposure in air at 425°C (800°F), probably due to a combination of oxidation and ageing⁽¹¹⁾.

There is some activity in the development of new and/or improved beta-type titanium alloys. A Ti-1Al-8V-5Fe beta alloy has been developed for fasteners, such as tension and shear bolts⁽¹⁹⁾. There is also work under way on compound free beta alloys based on a nominal composition of 12Mo-4 to 8Sn⁽¹⁹⁾, and also on precipitation-hardened stable beta alloys^(11, 27).

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APPLICATIONS

More than 99% of the structural applications to date have been in aircraft and space vehicles⁽¹⁾. In these fields, the factors that have a major influence on material selection, in addition to cost, are temperature, loading, time of exposure per mission, and part configuration. Temperature is probably the most important of these factors. Aircraft and missile structures are heated by power plant and also, particularly when supersonic vehicle speeds are encountered, may be heated by the aerodynamic effect. A general discussion of the potential of titanium in aerospace applications has been prepared by the Defense Metals Information Center⁽²⁾.

As an illustration of the demands of supersonic flight on jet engine operation, the air inlet temperature of a mach 2 jet engine operating at sea level is 245°C (470°F) and the discharge air from the compressor of this engine would be 540°C (1000°F)⁽¹⁾.

The heating effect of jet engines on the structure of the aircraft must be considered. In the case of a multi-jet plane with engines carried in nacelles and jet pots, 1 to 2% of the total airframe structure may operate above the limiting temperature for aluminum alloys, simply because of engine heating. In the case of a mach 2 aircraft with two engines buried in the fuselage, up to 10% of the structure of the airframe may be too hot for aluminum. All of the primary structure of a mach 3 aircraft would be above the temperature range of aluminum alloys. Titanium alloys are available that have useful strength and resist oxidation to 480°C (900°F) for long-time service. Such alloys are potentially useful engineering materials for primary airframe structures of mach 3 aircraft⁽¹⁾.

Material selection for high-temperature aeronautical service is based on "strength properties", such as tensile, compressive, shear bearing, fatigue and creep strength, and also on density. There is, in general, no incentive to consider the use of titanium alloys for aeronautical

service at normal atmospheric temperatures. Titanium alloys will be competitive at elevated temperatures up to 540°C (1000°F).

Indices of merit range from simple ratios of strength-to-density to fairly complicated ratios based on specific failure criteria. Practical considerations of design, fabrication and assembly may influence the degree of usefulness of merit indices. The significance of these various indices are discussed in some detail, in a chapter on Titanium for High-Temperature Aeronautical Service, in Vol. 1 of the 8th Edition of the ASM Metals Handbook⁽³⁾.

Titanium alloys have also been included in material evaluation programs for missiles. The Defense Metals Information Center, in reporting on one of these studies, reports that of three candidate materials--steels, aluminum alloys, and titanium alloys--being considered for solid-propellant rocket-motor cases for the period of 1965-1970, titanium alloys have the greatest potential on the basis of usable strength-to-density ratio⁽⁴⁾. The low interstitial (ELI) grade of the 5Al-2.5Sn alloy has been developed for low-temperature (cryogenic) applications. It has outstanding properties at -250°C (-423°F), e.g. 230-kpsi ultimate strength, 205-kpsi yield strength, 15% elongation⁽⁵⁾.

Studies of potential areas of aerospace applications for titanium alloys have not always produced positive information. It has become evident that there are some types of applications where stiffness cannot readily be designed into a component, and, in these types of components, titanium's low modulus of elasticity makes it unacceptable. An example of this sort of application could be tubing for aircraft hydraulic systems. The low modulus of elasticity of titanium results in a severe whipping action in small-diameter titanium tubing when it is loaded to the same stress level as stainless steel tubing⁽⁶⁾. This condition would lead to early fatigue failure.

Titanium alloys are potentially very attractive for the hulls of very deep-diving submersibles. For this application, the availability of titanium alloys in thick plate, and the ability to design and fabricate this type of material, are both essential. It would appear, from published literature, that both aspects of this application are well in hand^(8,9,10,11). Plates at least 10 ft by 10 ft by 2 in. thick are now available. Present steel fabricating equipment appears to be adequate for the manufacture of larger titanium products required for the future, the ability to produce thick plate without sacrifice of mechanical properties has been demonstrated, and it has also been shown that these thick titanium-alloy plates can be formed and joined satisfactorily.

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GENERAL COMMENTS ON MANUFACTURING AND FABRICATION

The successful use of titanium alloys, in any one of the broad fields of application (i. e. airframes, aero-engines, missiles, and submersibles) mentioned above, requires the intelligent selection of the specific sub-assembly or component where the unique properties of titanium alloys can be used to their best advantage in order to justify the higher material cost involved. A realistic approach to the new manufacturing problems introduced is essential in order that the various manufacturing processes involved, such as forming, forging, machining, heat treating, etc., can be so modified that exorbitant unnecessary costs are avoided.

The introduction of titanium alloys into the U.S. A. aircraft industry has been, to a large extent, subsidized by government funding, and a great deal of the information gained through these experiences has been published, so that it should now at least be possible to avoid some of the more disastrous pitfalls. Before airframe components could be designed in titanium alloys, it was necessary to demonstrate that titanium alloy mill products, i. e. sheet and shapes, could be produced to meet the tight property, quality, and size specifications of the aircraft industry. The Department of Defense (U.S. A.) organized a "Titanium Sheet-Rolling Program" to accomplish this objective and to provide design properties for aeronautical design engineers to use. The bulk of the information generated by this program has been published in a series of TML reports⁽¹⁾ and DMIC reports⁽¹⁾. This work is summarized in the Final Report of the Materials Advisory Board Panel on the Department of Defense Titanium Alloy Sheet Rolling Program⁽²⁾. The bulk of this information deals with testing and evaluation techniques, the determination of engineering properties, the development of secondary fabrication operations, the effect of

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PRIMARY WORKING AND PROCESSING

General Remarks

The types of operations that fall in this category are those carried out by the producers of titanium alloy sheet and shapes. They may include the following:

- (a) Ingot break-down by forging or extrusion
- (b) Production of plate, sheet, bar stock, and shapes by rolling
- (c) Mill process anneals
- (d) Extrusion of finished shapes
- (e) Production of shaped forgings

There is little pertinent quantitative information in the open literature on items (a), (b), and (c). There are, however, some general comments that can be made that apply to any hot-working processing of titanium and its alloys.

If final hot-working operations are carried out above the beta transus, i.e. when the alloy is all beta, the finished product may be coarse-grained and have low ductility. This behaviour is called "beta embrittlement". It can be encountered in the "alpha" and "alpha-beta" alloys. Beta embrittlement may be avoided by hot working about 56°C (100°F) below the beta transus. In the case of the "beta" alloys the situation is somewhat different, since all the hot working is done in the beta condition. However, the finishing temperature of the beta alloys could be important in determining ageing response. The ageing response of these alloys is extremely sluggish. Optimum ageing times may vary from 12 hours to about fifty hours at 480°C (900°F), depending on the amount of working in the neighbourhood of 760°C (1400°F) which is below the recrystallization temperature⁽¹⁾.

The interstitial content of titanium alloys can be altered by mill process anneals. Titanium alloys show varying degrees of resistance to penetration by interstitial contaminants during hot working and heat treatment. Of a group of alloys that have been reported⁽²⁾, the alpha-beta alloys 4Al-3Mo-1V and 6Al-4V have the highest resistance. The resistance of the beta alloy 13V-11Cr-3Al is intermediate, and beta alloy 2.5Al-16V has the lowest resistance. The interstitials that seem to have received most attention are hydrogen and oxygen.

Oxygen is an alpha stabilizer. Oxygen contamination could therefore change the beta transus. This may not be too critical for some applications, as long as allowance is made for it in adjusting hot-working temperatures. For the beta alloys it is probably better to avoid oxygen contamination, if possible. Various proprietary protective coatings have been developed for this purpose⁽¹⁾.

Hydrogen contamination is likely to be more serious in alpha alloys. Hydrogen is more likely to come from chemical scale-removing operations, rather than as a direct result of heating. Hydrogen can be removed by vacuum annealing and this will very likely be necessary for alpha alloy hot-worked mill products⁽¹⁾.

There is no indication in the open literature that any of the titanium alloy producers use vacuum heat-treating furnaces for mill process anneals. Since there are several reports on techniques for the removal of mill scale from titanium mill products^(3,4), it is very likely that vacuum furnaces are only used where absolutely necessary to control hydrogen content in the final product when hydrogen content is critical and must be at a minimum level.

Extrusion

The production of finished titanium alloy structural shapes by extrusion is now a well established technique. The extrusion of Ti-7Al-4Mo alloy shapes (T's, L's, U's, Z's, and hat sections) was reported in 1962⁽⁵⁾.

Twenty-foot extruded lengths of "tee" shape were successfully straightened in terms of bow (1/4 in. in 20 feet) and elimination of camber. A previously straightened 10-foot extrusion was warm drawn from 0.130 in. down to a uniform 0.110-inch cross-section in one pass, without galling.

During 1964 the technique had been developed to the point where a minimum extrusion section 0.125-in. thick could be produced, and there appeared to be some expectation that this limiting thickness could eventually be reduced to 0.063 in. In the heat-treated condition these extrusions are available in 21-foot lengths and in 40-foot lengths in the annealed condition. The extruded surface finish is reported to be 150 RMS⁽⁶⁾.

The successful development of an extrusion process for long, thin, aircraft structural shapes in titanium alloys by a combination of hot extrusion and warm drawing has been reported^(7,8). Ceramic-coated extrusion dies were used in combination with the Ugine-Sejournet glass-lubrication process. A 3% stretch-straightening operation, combined with punch straightening, is used to remove the bow. Warm drawing at 570°C (1050°F) is used to improve dimensional tolerances and surface finish, and also to produce thinner cross-sections. At a drawing speed of 24 fpm, the cross-section of a 6Al-4V extrusion was reduced from 0.094 in. ("as extruded") to 0.08 in. although thinner sections than this are reported to be feasible, material losses are too high to make them practical.

Copper coating or canning of the titanium extrusion billet helps to control oxidation and also provides an extra barrier between the die and titanium, thereby preventing galling. The copper can be removed by pickling⁽⁹⁾. Rapid heating of the extrusion billet by electric induction will also limit the degree of oxidation and atmospheric contamination⁽⁹⁾.

An examination of the reactivity of various glasses used as lubricants in the extrusion process has shown that a glass identified as 383A is less reactive to alpha-beta titanium alloys than glass No. 85 or glass No. A-40⁽²⁾.

One of the more recent developments in the extrusion field is the use of solid zirconia (ZrO_2) die inserts⁽¹⁰⁾. Dies made of this material are reported to be superior to alloy dies for the extrusion of steels, and many other alloys requiring high extrusion temperatures and pressures.

Forging

There exist two excellent publications dealing with titanium alloy forgings. One is DMIC Report 141, Dec. 19, 1960, entitled "Titanium Alloy Forgings"⁽¹⁾. The other is called "A Manual on Fundamentals of Forging Practice"⁽¹¹⁾. In view of the existence of these publications, the author will confine himself to some rather general remarks, indicating the state of the art, limiting production parameters, shop equipment requirements., etc.

The art of designing and producing titanium alloy forgings is by now well established. Titanium is still more difficult to forge than aluminum and most steels, but as a result of careful quality control, the forging of titanium is now comparable with that of many medium alloy stainless steels.

Design Classification of Titanium Alloy Forgings

Forgings may be classified by configuration and also by tolerance. A possible configuration classification could be:

- Rib and web structural shapes,
- Forged rings,
- Disc shapes.

A suggested tolerance classification is based on a series of "Commercial Tolerances for Steel Forgings", developed by the ASM Committee on Forgings⁽¹²⁾. On this basis, titanium forgings may be classified into four distinct tolerance groups:

1. Blocker-type tolerances,
2. Conventional tolerances,
3. Close tolerances,
4. Precision tolerances.

These tolerance groups can be defined as follows:

1. Blocker Type Design

Such forgings are usually produced from one set of dies and conform to the general shape of the final part. Very little attention is paid to die wear, die shift, fillet radii, draft angles, die closure, and other tolerances described by the ASM Committee. The design should allow for adequate metal flow so that the resultant metallurgical properties are comparable with forgings of conventional design.

2. Conventional Tolerance Design

The ASM Committee's description of commercial tolerances applies to conventional design. Closer tolerances may be offered by some forging companies in order to reduce metal requirements. In such a case, the general design remains conventional but machining allowances and die closure tolerances are reduced. Typical tolerances are:

Length	± 0.05 in./ft
Thickness	$+0.06$ in./ -0.03 in.
Die wear	-0.06 in.
Draft	5-7 degrees
Machine clean-up	0.03-0.19 in.

3. Close Tolerance Design

Compared with conventional designs, closer tolerance forging designs require closer dimensional tolerance and less draft. Localized "as-forged" surfaces may be specified. Additional tooling is usually

required for forging, but the parts are forged in conventional equipment and with conventional tooling. Typical tolerances are:

Length	± 0.03 in./ft
Thickness	$+0.02$ in./ -0.01 in.
Die wear	0.03 in.
Draft	1-3 degrees
Machine clean-up	0-0.06 in.

4. Precision Tolerance Design

Precision tolerance forgings require both special tooling and forging equipment. Such forgings are characterized by very close tolerance with small fillets and radii, no draft, and little or no machining allowance. Special equipment usually consists of slow rate presses or specially developed impactors. Very complex tooling is required. Typical tolerances are:

Length	± 0.02 in./ft
Thickness	± 0.01 in.
Die wear	0.01 in.
Draft	0-0.5 degrees
Machine clean-up	0-0.03 in.

....

A general idea of the types of forging shapes commonly produced and their availability in the several categories of dimensional tolerances just discussed is provided in Table 7⁽¹⁾.

TABLE 7⁽¹⁾

Availability of Specific Tolerances for Each of Several
Forging Shapes in Titanium Alloys

Forged Shape	Blocker-type Tolerances	Conventional Tolerances	Close Tolerances	Precision Tolerances
Discs	A	A	L	U
Cones	A	A	L	U
Hemispheres	A	A	L	U
Cylinders	A	A	L	U
Blades	A	A	A	L
Airframe (fittings)	A	A	A	LS
Airframe (rib and web)	A	A	L	U
Rings	A	A	L	U

Code: A - readily available.
L - limited availability.
LS - limited availability; small parts only.
U - virtually unavailable.

It is reasonable to expect that as the dimensional tolerances are tightened, the cost of the forgings will increase. For example, the costs of precision forgings are said to be from three to five times those of conventional forgings⁽¹⁾. Therefore the use of precision forgings is likely not a practical way to reduce costs except probably for very large quantities.

Cost Factors in Forging

Titanium alloy forgings are considerably more costly than equivalent steel forgings because:⁽¹⁾

1. Material costs are high and there is little or no recoverable scrap.
2. Low production rates increase labour costs over comparable steel forgings by as much as 50%.

3. The higher forging loads needed to produce titanium alloy forgings require heavier equipment or more operations. Equipment costs can be 125% of those for comparable steel forgings.
4. Forging die cost is about the same as for steel, but die life is only about one-third.
5. There are usually more "in process" operations than for comparable steel forgings.

General Forging Characteristics

The relationship between forgeability, temperature, strain and strain rate for titanium alloys is quite different than that for alloy steels⁽¹¹⁾. For example, the forging pressure required for 6Al-4V alloy at 1090-1260°C (2000-2300°F) is about the same as that required for AISI 4340 steel but at 860°C (1600°F) the titanium alloy requires about twice the forging pressure as that needed for AISI 4340 steel. Also, forging pressure for titanium alloys increases rapidly with increasing strain rate. At 10% reduction, a ten-fold increase in strain rate can increase forging pressure by about 50%.

Because of these characteristics, more energy is required for hammer forging than for press forging at comparable temperatures. For example, to forge the all-beta 13V-11Cr-3Al titanium alloy at 790°C (1450°F) requires nearly 50% more energy at a typical hammer velocity of 200 in./sec than at a typical press velocity of 1.5 in./sec⁽¹¹⁾.

For reasons of mechanical property control, the final forging reductions for alpha and alpha-beta alloys should be made in the temperature range of 925-980°C (1700-1800°F). For beta alloys, this finishing temperature is reduced to 760-870°C (1400-1600°F). These are the direct reasons why heavier equipment is required to produce titanium forgings than for comparable steel forgings. To forge the beta titanium alloy at 760-870°C (1400-1600°F) also requires a press, rather than a hammer, to avoid cracking⁽¹¹⁾.

Typical Applications of Alpha, Alpha-Beta, and Beta Titanium Alloy Forgings

Alpha alloy forgings are used when both good weldability and good elevated-temperature-property stability are required. About the only types of forgings made from alpha alloys are jet-engine spacers, rings, and other simple forged shapes. The 5Al-2.5Sn alloy is the one most commonly used⁽¹⁾.

The alpha-beta titanium alloys are most widely used for structural components. The all-beta, 13V-11Cr-3Al, titanium alloy is used mostly for rocket-motor case components, hemisphere forgings, and ring forgings⁽¹⁾. Both the alpha-beta and beta alloys are heat-treatable.

Forgings in all these titanium alloy types are producible to a high degree of uniformity and quality and, when produced by a reputable forging company, they are guaranteed to meet specific mechanical property requirements⁽¹⁾. Accounts of experience with titanium alloy forgings are given in DMIC Report 141⁽¹⁾.

Metallurgical Control of Alpha-Beta Titanium Alloy Forgings

It has been stated previously that the microstructure, and therefore the mechanical properties, of titanium alloy forgings are controlled by the forging history. Both temperature and reduction are factors.

The critical factor influencing the mechanical properties of alpha-beta titanium alloy forgings is the amount of equiaxed alpha in the final structure. Equiaxed alpha forms when beta transforms during deformation. Reduction in area increases with increasing amounts of equiaxed alpha up to about 20%, and notch sensitivity increases with increasing amounts of equiaxed alpha. The optimum structure should contain about 20 to 30% equiaxed alpha⁽¹¹⁾.

When alpha-beta alloys are forged above the beta transus, a coarse-grained structure with attendant low ductility and widely varying strength properties results. However, optimum room-temperature properties can be obtained when initial forging is done at temperatures above the beta transus, provided that at least the last 50% of the required reduction takes place about 63°C (100°F) below the beta transus⁽¹¹⁾. If, for some reason or other, the forging operation is completed above the beta transus, if the forging is water-quenched directly from the forging press, a fine-grained, acicular structure will result and beta grain growth will be arrested. This reduces the tendency for beta embrittlement. Notched-bar impact properties can be improved by this treatment⁽¹¹⁾.

A study of high-energy-rate forging processes, using equipment, such as the "Dynapak", has shown that the beta embrittlement of the 6Al-4V titanium alloy, that usually results when it is forged above the beta transus, is not found when high-energy-rate forging is employed⁽¹²⁾.

Large, rapid reductions can raise the actual forging temperature of a billet heated in the alpha-beta region to a temperature above the beta transus, thereby causing beta embrittlement. On the other hand, die chilling effects can produce localized areas containing excessive amounts of equiaxed alpha. Hence, it is possible for a part, forged at the "ideal" forging temperature, to contain regions of varying structure ranging from completely acicular to predominantly equiaxed alpha. Accordingly, properties of such a forging could vary from an embrittled condition to a highly ductile, low strength condition. Proper design, coupled with good forging practice, will avoid such a condition. The forging operations should be scheduled to avoid overheating due to large rapid reductions. The forging should be designed to avoid extreme differences in section which could cause both localized high reduction rates and localized chilling. If very thin and very thick sections exist in the same forging, the long furnace times required to heat the thick sections can cause excessive hydrogen pick-up in the thin sections. In order to avoid these difficulties, the following design limits

are suggested for alpha-beta titanium alloy forgings that are intended to be used in the "as-forged" condition⁽¹⁾:

Maximum Section, in.	Minimum Section, in.
3 and over	0.5
2-3	0.35
1 and less	0.18

Since mechanical properties in heat-treated alpha-beta titanium alloys will be lower in thick sections than in thin sections, if the forgings are to be subsequently heat treated, the following section guide is suggested⁽¹⁾:

Maximum Section, in.	Minimum Section, in.
1.5 - 2	0.5
1 - 1.5	0.4
0.75	0.25

Sections over 2 in. thick do not respond well to heat treatment.

Since the beta transus of a given alpha-beta titanium alloy can vary by as much as 25°C (40°F) from heat to heat, the beta transus of each heat should be determined and the forging temperature adjusted accordingly⁽¹⁾.

A structure containing an unfavourably high proportion of equiaxed alpha can be corrected by heating to about 56°C (100°F) below the beta transus and either air cooling or water quenching. This treatment improves notch sensitivity with little or no loss of room-temperature ductility⁽¹¹⁾.

For parts receiving small total reductions (less than 50%), it is desirable to begin with a billet that has a structure that contains at least 10 to 15% of equiaxed alpha. This is especially true of parts that are

upset-forged from billets having length-diameter ratios over 1:2. Such parts contain large "dead-metal" zones which receive little or no work.

Metallurgical Control of Beta Titanium Alloy Forgings

The only beta titanium alloy currently available on a commercial basis is the 13V-11Cr-3Al. This is essentially a metastable single-phase alloy. As is characteristic of all single-phase alloys, ductility decreases with increasing grain size and strength increases with increasing cold work. The recrystallization range for this alloy is 760-870°C (1400-1600°F)⁽¹¹⁾.

This alloy can also be strengthened by precipitation of alpha from metastable beta. This can be a very sluggish process, requiring as long as four days in the recrystallized condition. Also, in the recrystallized alloy the alpha precipitate concentrates at the grain boundaries, causing low ductility. However, when cold work is retained, ageing can be completed in from 12 to 14 hours without concentration of the precipitate at the grain boundaries^(1, 11). It is therefore apparent that, in order to obtain optimum properties in beta titanium alloy forgings, the final reduction should be made in the temperature range of 760-870°C (1400-1600°F) in order to retain cold work in the finished forging. The amount of cold work retained controls the ageing response. This means that beta titanium alloy forgings should be designed so that there is uniform distribution of cold work throughout the finished forging^(1, 11).

Metallurgical Control of Alpha Titanium Alloy Forgings

The influence of forging temperatures on the mechanical properties of alpha alloy forgings is similar in many respects to that for alpha-beta alloys. The strength level is not influenced greatly by forging temperature, but the ductility decreases sharply when the forging temperature exceeds the beta transus^(1, 11). Best ductility at room temperature is obtained by forging near the alpha transus⁽¹⁾.

In designing alpha alloy forgings, a minimum section of 1/2 in. is preferred and adequate machine clean-up should be allowed (e. g., 0.05 in. for small forgings, more for large forgings)⁽¹⁾.

Composition Sensitivity and Control in Forging⁽¹¹⁾

Both forging behaviour and mechanical properties are influenced significantly by variations in interstitial elements (e. g., oxygen, nitrogen, carbon, and hydrogen). An increase of from 0.1 to 0.2% oxygen will raise the beta transus of 6Al-4V alloy by about 47°C (75°F) and increase the strength level by as much as 15%. The influence of increasing carbon or nitrogen content is similar but much milder.

When titanium alloys are heated above about 540°C (1000°F), they react with oxygen and nitrogen, forming an adherent surface scale and a hard, alpha-rich, sub-surface layer. This sub-surface layer is brittle even at forging temperatures and can cause rupture during forging. Alpha alloys are particularly sensitive to this and may require frequent in-process grinding operations. When the beta alloy is forged above about 980°C (1800°F), it exhibits the same characteristics. Oxygen contamination of beta alloys is usually avoided by applying a protective surface coating. These coatings are usually of a proprietary nature and therefore there is little information on them in the open literature.

When hydrogen is absorbed at forging temperatures, it diffuses inward, raising the hydrogen content of the entire forging. This can lead to hydrogen embrittlement. If conventional oil or gas-fired heating furnaces are used, an oxidizing atmosphere is preferred, to minimize hydrogen pick-up. Inert atmospheres are recommended only for parts containing extremely thin sections that require multiple heating operations.

The oxygen-rich layer may be from 0.005 to 0.025 in. thick. It may be removed by pickling in an aqueous solution of 2 to 4% hydrofluoric acid, 30% nitric acid. The removal rate of this solution is about 0.005 in.

per minute. The nitric acid is added to minimize hydrogen contamination. Hydrogen can be removed from titanium alloy forgings only by vacuum annealing.

Equipment Cleanliness in Forging⁽¹¹⁾

While forging titanium, care should be taken to prevent contact with steel scale. A "thermite" type reaction can be set off by pressure and high temperature and this can ruin a forging die.

Straightening of Titanium Alloy Forgings⁽¹¹⁾

The straightening of titanium alloy forgings is difficult by cold coining or cold reverse bending. Straightening should be done at temperatures between 370-540°C (700-1000°F). Surface contamination should be removed before straightening, or cracking may result.

Operator Technique⁽¹¹⁾

Operator skill is an important factor in the successful production of titanium alloy forgings. The operator can cause beta embrittlement by forging too rapidly. The risk of this happening can be minimized by avoiding the use of larger forging hammers than really necessary. For initial breakdown, an under-capacity hammer is sometimes preferred.

Titanium Alloy Castings

The main field of application of titanium alloy castings is in chemical plants and food processing, where the corrosion resistance of titanium can justify the cost⁽¹³⁾. However, as experience in the production of titanium alloy castings grows, their use for critical load-carrying application, such as airframe components, is beginning to be considered.

Titanium castings are produced by melting and casting, either in vacuum or in an inert atmosphere of argon or helium. The melting

operation is usually a combination of consumable electrode and fixed electrode melting in a water-cooled, copper tilting crucible. A "skull" of solid titanium alloy is always kept at the crucible-melt interface⁽¹⁴⁾.

Various types of moulds and mould materials have been used. The major moulding problem has been to minimize contamination of the casting surface. Both machined graphite moulds and expendable moulds rammed in a graphite mix are used^(13, 14, 15). Castings produced in moulds machined from solid graphite generally have a lower degree of surface contamination than those produced in rammed graphite-composition moulds⁽¹⁴⁾. A typical ramming mix is:⁽¹⁵⁾

Grade BB5 graphite powder	-	70 %
Black foundry pitch	-	10 %
Carbonaceous cement	-	8 %
Water	-	7 %
Laundry starch	-	5 %
		<hr/>
		100 %

A suitable "shell" core mix for titanium castings is:⁽¹⁵⁾

Graphite powder	-	72-80%
Phenol formaldehyde resin	-	10-20%
Pitch	-	8%

Castings produced in rammed moulds of this type have a surface finish of about 200 microinches rms⁽¹⁵⁾.

The problem of surface contamination has been receiving some attention. Research is in progress to develop a mould coating which will be inert to molten titanium. A salt flux is being developed for this purpose⁽¹⁶⁾.

Size limitations for titanium alloy castings made in expendable rammed graphite moulds are stated to be 6 ft x 3 ft x 2 ft^(13, 17). Minimum

section thickness is $3/32$ of an inch⁽¹⁷⁾. Dimensional tolerances are ± 0.002 in. for the first three inches, increased by 0.005 in. for each additional inch⁽¹³⁾. A patternmaker's shrinkage of $3/8$ in. per foot is used. This is made up of $1/8$ in. for mould shrinkage and $1/4$ in. for metal shrinkage.

Gating and risering of these moulds follows normal practice. Experience has shown that bottom gating is preferable, and also that turbulence should be minimized. Centrifuging is sometimes helpful in order to get good mould filling and soundness. From one-third to one-half of the metal melted ends up in finished castings^(14, 15).

Melting and casting environment has been demonstrated to have an influence on the properties of the resulting castings. Test bars cut from castings produced by melting and casting in vacuum gave elongation values of from 10.6-12%, as compared with wrought properties of 11% for the same alloy. Test bars cut from identical castings produced by melting and casting in an argon-helium atmosphere gave an elongation value of 6.4%⁽¹⁴⁾.

A proprietary process, known as the "Impel" process, using a mild steel mould, can produce titanium alloy castings having over-all dimensions of 5 in. x 11 in. x 24 in. and less. The maximum section thickness is $1/2$ in. The minimum section thickness is not stated⁽¹⁷⁾. Just recently, a proprietary investment precision casting process has been announced⁽¹⁸⁾. However, no details are available.

As an indication of the degree of acceptance that titanium alloy castings have achieved, it is interesting to note that the ASTM has developed a tentative specification (B367-61T) for titanium and titanium alloy castings. The designations, compositions, and some property data for current commercial titanium cast products are given in Table 8⁽¹⁷⁾.

TABLE 8
Titanium Cast Products ⁽¹⁷⁾

Brinell Hardness, (3000 kg Load)	RT Tensile Properties				RT Charpy ft-lb	Producers' Nomenclature		Nominal Composition (Balance Ti), per cent
	E, 10 ⁶ psi	US, kpsi	YS, kpsi	Elong., %		Oregon Metallurgical	Titanium Metals	
201	15.5	80	60	13	3	-	TMCA, IMPEL Unalloyed	99.0 Ti
217	15.5	90	70	10	-	-	-	98.9 Ti
217	15.5	90	70	10	-	OMC 103	-	0.15-0.20 Pd
235*	-	65-105	55-95	12	-	OMC 105**	-	98.64 Ti Min
321	16.0	140	130	11	8	OMC 166-A Aircraft		5Al-2.5Sn
321	17.0	145	130	8	15	OMC 165-A Non-aircraft	TMCA, IMPEL	6Al-4V
311	17.0	147	130	10	17	OMC 164-B Aircraft	6Al-4V	6Al-4V (low O)

* Maximum

**Certified test results available on request.

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SECONDARY FABRICATION

Machining of Titanium Alloys - General Remarks

The use of titanium alloys in the manufacture of airframe components, while desirable, and often necessary, from a design point of view, has introduced some rather severe machining problems. Problems of this nature would have arisen, however, whether or not titanium had appeared on the scene, since the introduction of titanium alloys is just an extension of an already existing trend. Between 1920 and 1960 the strength of airframe materials had increased by a factor of four⁽¹⁾, and during the latter part of this period titanium alloys were just one of the candidate materials. Other contending materials were high-strength steels, stainless steels, and nickel alloys. All of these alloys represent a radical decrease in producibility rating in machining operations, as compared with aluminum alloys.

R. L. Vaughn and N. Zlatin have reported on a technique whereby they establish information on maximum productivity for comparison purposes, by running standard tests in the shop on machines that will eventually do the job⁽²⁾. By this technique, producibility ratings, and not machinability ratings, can be determined accurately. These producibility ratings are based on comparison with standard materials. The standards chosen for this study were aluminum alloy 7075-T6 and AISI 4340 steel at 300 BHN. Producibility ratings for a wide range of materials were reported by Vaughn and Zlatin. Some ratings for titanium alloys are reported in Table 9⁽²⁾.

It will be noted from this table that the machining time for titanium alloys can vary between 167 and 7 times the time for aluminum alloy 7075-T6, depending on the hardness of the titanium alloy, the machining operation being performed, and the type of tool used. The end milling time for alloy C120AV, when using a 3/4-in. -diameter high-speed steel cutter, can be increased by a factor of from four to five by an increase in hardness from

TABLE 9
Producibility Rating of Titanium Alloys⁽²⁾

Machining Operation	Compared to Aluminum Alloy 7075-T6			Compared to AISI 4340 Steel at 300 BHN		
	A110-AT Stress Relieved 300 BHN	C-120AV Annealed 310 BHN	C-120AV Sol. Tr. and Aged 365 BHN	A110-AT Stress Relieved 300 BHN	C-120AV Annealed 310 BHN	C-120AV Sol. Tr. and Aged 365 BHN
Turning (high speed steel)	0.06:1	0.05:1	0.03:1	0.6:1	0.5:1	0.3:1
Turning (carbide)	0.15:1	0.15:1	0.15:1	0.5:1	0.5:1	0.4:1
Face Milling (high speed steel)	0.04:1	0.04:1	0.02:1	0.4:1	0.4:1	0.2:1
Face Milling (carbide)	0.05:1	0.05:1	0.03:1	0.3:1	0.3:1	0.2:1
End Milling ($\frac{3}{4}$ in. dia HSS)	0.03:1	0.03:1	0.006:1	0.5:1	0.4:1	0.1:1
End Milling ($\frac{3}{4}$ in. dia carbide)				0.6:1	0.5:1	0.3:1
Drilling (high speed steel)	0.05:1	0.05:1	0.03:1	0.5:1	0.5:1	0.3:1

310-365 BHN, while for the same size of carbide cutter an increase in hardness from 310-365 BHN would only increase the machining time by a factor of about 1.5.

The above data is somewhat at variance with that reported by the Defense Metals Information Center. In their survey of the comparative costs of fabricating airframes from aluminum and from titanium, they report the following:⁽³⁾

Process	Cost of Machining Titanium vs Aluminum
Turning	1-3:1
End Milling	2:1
Straight Milling	1.2-4:1
Drilling	2.5:1
Routing and Sawing	4-6:1

It could be that this variance might be due, at least in part, to the different time periods covered by these two papers. Vaugh and Zlatin's data are probably based on techniques and experience developed up to 1960, whereas the DMIC report is dated 1964. Advances in tool design, equipment, and techniques have been extremely rapid and the apparent discrepancy could just be a measure of these advances.

It is quite clear that there has been no dramatic "break-through" in machining techniques for titanium or any other of the high-strength alloys. Improvements are simply the result of continued effort on tool materials, design, coolants, machine tools, etc. As a result, tools and techniques are now available for the efficient machining of titanium alloys. Good surface finishes, in the order of 20-30 microinches rms, are easier to attain on titanium alloys than on steel.

The machining characteristics and source of machining problems

for titanium and its alloys are discussed at some length by G. T. Olofson, A. F. Gerds, F. W. Boulger, and J. A. Gurklis⁽⁴⁾. The sources of these problems are:

- (a) Excessive cutting temperature,
- (b) Chemical reactivity with tools,
- (c) Low modulus of elasticity,
- (d) Chip characteristics.

Machining Requirements

High-quality machine tools, vibration-free rigid set-ups, and appropriate machining conditions should be used. Machine tools for various machining operations should exhibit the following characteristics:⁽⁴⁾

		<u>Mill</u>	<u>Turn</u>	<u>Drill</u>	<u>Tap</u>
True running spindle	-	x	x	x	x
Excellent spindle bearings	-	x	x	x	x
Dynamic balance	-	x	x		
Flywheel-assisted speed drives	-	x			
Snug table gibs	-	x			
Backlash elimination	-	x	x	x	
Rigid frames	-	x	x	x	
Wide speed/feed ranges	-	x	x	x	x
Ample power to maintain speed	-	x	x	x	x
Easy accessibility for maintenance	-	x	x	x	x

Appropriate machining set-ups for titanium alloys should meet the following requirements:

- (a) Strong, sharp-cutting tools that are rigidly held, with cutting edges free of feather burrs.
- (b) Positive, uniform mechanical feed.
- (c) Cutting tools should never dwell or ride in the cut without removing metal.

- (d) Low cutting speeds.
- (e) Adequate cooling at the cutting site.
- (f) Proper cutting fluids.

The compositions of tool materials commonly employed in machining operations on titanium are listed in Table 10⁽⁴⁾. Some competitive grades of carbides are identified in Table 11⁽⁴⁾.

The machining operations most commonly encountered in airframe fabrication are milling and drilling. Milling may be used in the production of airframe components, such as spars, panels, and other structural members. Drilling is commonly used to prepare holes for fasteners.

Milling Operations

Milling machines used for milling titanium should be driven by at least a ten to fifteen horsepower motor⁽⁴⁾. If more power is available this could be advantageous. Numerically controlled or tracer controlled milling machines are used for profile and pocket-milling operations.

Details of tool design, tool material selection, operating parameters such as feed, cutting speed, depth of cut, cutting fluids have been reported in detail in many publications^(2,4,5). Some of these details are summarized in Tables 12⁽⁴⁾, 13⁽⁴⁾ and 14⁽⁴⁾.

When selecting tool materials for milling titanium, it should be borne in mind that tool life is low by ordinary standards. The choice of the proper tool material is not a simple matter. The correct selection depends on the following factors:

- (a) The milling machine and its condition
- (b) The type of cut and rigidity of set-up
- (c) The composition and hardness of the work piece
- (d) The shape and size of the part

TABLE 10
Compositions of High-Speed Tool Steels (a, b)⁽⁴⁾

AISI Code (c)	Alloy Content, Weight Per Cent				
	W	Cr	V	Co	Mo
T1	18	4	1	-	-
T4	18	4	1	5	-
T5	18 $\frac{1}{2}$	4	1 $\frac{3}{4}$	8	-
T6	20	4	2	12	-
T8	14	4	2	5	-
T15	14	4	5	5	-
M1	1 $\frac{1}{2}$	4	1	-	8
M2	6	4	2	-	5
M10	-	4	2	-	8
M3	6	4	2.75	-	5
M4	5.50	4	4	-	4.50
M6	4	4	1.5	12	5
M7	1.75	3.75	2.0	-	8.75
M30	2	4	1.25	5	8
M33	1.75	3.75	1.0	8.25	9.25
M34	2	4	2	8	8
M15	6.5	4	5	5	3.5
M35	6	4	2	5	5
M36	6	4	2	8	5
M41	6.75	4.25	2.00	5.00	3.75
M42	1.50	3.75	1.15	8.00	9.50
M43	1.75	3.75	2.00	8.25	8.75
M44	5.25	4.25	2.25	12.00	6.25

- (a) Table taken from ASM Metals Handbook, Supplement 2, 1954.
- (b) For commercial listings, reference can be made to "A Guide to Tool Steels and Carbides", Steel, April 21, 1958.
- (c) T1, M1 and M10 perform similarly for ordinary applications. When greater than average red hardness is needed, cobalt-containing grades are recommended. All grades in the molybdenum and tungsten groups are not necessarily comparable. Special-purpose steels such as T6, T8, T15, M6, M35, and M36 seem to have no close counterparts in the other groups. The unique compositions and properties of these steels suit them to certain applications without competition.

TABLE 11
Tool-Material Guide for Carbides⁽⁴⁾

CISC (a) Grade	Partial List of Carbides (b) Made by Various Manufacturers													
	Adamas	Carmet	Carboloy	Firclomet	Firthite	Kenna-Metal	Newcomer	Sandvik Coromant	Talide	Tungsten Alloy	Valenite	Vascoloy Ramet	Wesson	Willey
C-1	B	CA3	44A	FA5	H	K1	NC4	H1	C89	9	VC1	2A68 VR54	GS	E8, E13
C-2	A	CA4	883, 860	FA6	HA	K6	NC3	H1	C91	9H	VC2	2A5, VR54	G1	E6
C-3	AA	CA7	905	FA7	HE	K8	NC2	H3	C93	9C	VC3	2A7	GA	E5
C-4	AAA	CA8	999	FA8	HF	K11	NC2	H5	C95	9B	VC4	2A7	GF	E3
C-5	DD	CA51	78C	FT3	TQ4	KM	NS65, NS4	S6,S4	S88	11T	VC5	EE, VR77	WS	945
C-5A	434	CA610	370	FT41, FT5	TXH	K21	-	S1P	S88X	9S	VC125	VR77, VR75	26	8A
C-6	D	CA609	78B	FT4	FXH, TA	K2S	NS3	S2	S90	10T	VC6	VR75	WM	710
C-7	C	CA608	78	FT6	TXL	K5H	NS2, NS17	S1	S92	8T	VC7	E, VR73	WH	606
C-7A	548	CA606	350	FT61	T16, TXL	K4H	-	-	S92X	5S	-	VR73	WH	6A
C-8	CC	CA605	330	F17	T31, WF	K7H	NS15	F1	S94	5S	VC8	EH	WH	509, 4A

(a) Carbide Industry Standardization Committee.

(b) 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.

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 non-ferrous materials
C-2 General Purpose - cast iron and non-ferrous materials
C-3 Light Finishing - cast iron and non-ferrous materials
C-4 Precision Boring - cast iron and non-ferrous 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 - fine 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.

TABLE 12

Milling Titanium Alloys with Helical Face Mills⁽⁴⁾

Cutter Material: Titanium Alloy Machined	Carbide				High-Speed Steel			
	Ti-5Al-2.5Sn Ti-4Al-3Mo-1V	Ti-8Al-1Mo-1V	Ti-6Al-4V Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ti-13V-11Cr-3Al	Ti-5Al-2.5Sn Ti-4Al-3Mo-1V	Ti-8Al-1Mo-1V	Ti-6Al-4V Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ti-13V-11Cr-3Al
Tool Material Type	C-1 or C-2	C-1 or C-2	C-2	C-2	T15 or M15	M3	M3 or T15	T15
Tool Angles, degrees								
Axial Rake	0	+6 to -6	0	0 to +10	0 to +10	+6 to -6	0	10
Radial Rake	0 to -10	0 to -14	0	0 to +10	0 to +10	0 to -14	0	0 to +10
Corner	45 to 60	0	45	45	30 to 45	0	45	45
End-Cutting Edge	6 to 10	0	10	5 to 10	6 to 10	0	10	5 to 10
Relief	10 to 12	6	10	10	10 to 12	6	10	10
Tool Nose Radius, inch	0.04-0.125	0.04	0.04	0.04	0.04-0.125	0.04	0.04	0.04
Feed, ipt	0.002-0.012	0.005	0.004-0.006	0.003-0.006	0.002-0.008	0.005	0.004-0.006	0.004-0.006
Depth of Cut, inch	0.05-0.25	0.25-0.050	0.05-0.10	0.05-0.10	0.05-0.25	0.025-0.05	0.05-0.10	0.05-0.10
Speed, fpm								
Annealed Alloys	80-200	160-170	125-150	100-125	15-75	80	60	45
Aged Alloys	55-95	-	80-100	70-100	30-50	-	50	30
Cutting Fluids	Soluble oil- water emulsions	Soluble oil- water emulsions	Sulphurized mineral oil	Sulphurized mineral oil	Soluble oil- water emulsions	Soluble oil- water emulsions	Soluble oil- water emulsions	Soluble oil- water emulsions
Types	Water-soluble waxes	Chemical coolants	-	-	Water-soluble waxes	Chemical coolants	-	-
Application	Spray mist or flood	Spray mist	Flood	Flood	Spray mist or flood	Spray mist	Flood	Flood

TABLE 13

Milling Titanium Alloys with Helical End Mills⁽⁴⁾

Type of Operation	End Milling			Profile or Pocket Milling				
Cutter Material	High Speed Steel			High Speed Steel			Solid Carbide	
Titanium Alloy Machined	Ti-5Al-2.5Sn	Ti-6Al-4V Ti-7Al-4Mo Ti-6Al-6V-2Sn	Ti-13V-11Cr-3Mo	Ti-5Al-2.5Sn	Ti-8Al-1Mo-1V		Ti-8Al-1Mo-1V	
Operation Performed				Profiling	Slotting	Corner Milling	Slotting	Corner Milling
Tool Material Type	M3, Type 2	M2	M2	M3, Type 2	T5	T5	C-1 or C-2	C-1 or C-2
Tool Angles, degrees								
Helix	30	30	30	45	30	30	30	30
Radial Rake	0	0	0	10	0 to +4	0 to +4	0 to +4	0 to +4
Corner	-	-	-	-	-	-	-	-
End-Cutting Edge	-	-	-	-	-	-	-	-
Relief	10	10	10	4 to 15	6	6	12	12
Tool Nose Radius, inch	-	-	-	-	-	-	-	-
Feed, ipt	0.003-0.005	0.003-0.005	0.003-0.005	0.0015-0.003	0.002-0.004	0.004	0.002-0.004	0.004
Depth of Cut, inch	1/3 cutter diameter	1/3 cutter diameter	1/3 cutter diameter	-	-	-	-	-
Speed, fpm								
Annealed Alloys	60-70	50-60	30-40	10-30	50	70-90	200	200
Aged Alloys	-	30-40	20-25	-	-	-	-	-
Cutting Fluids	Heavy-duty water-soluble oil			Soluble oil-water emulsions or rust inhibitor coolant, mist applied	Soluble oil-water (1:30 dilution) or barium hydroxide (5% solution) applied as a spray mist			

TABLE 14
Spar- or Slab-Milling Titanium Alloys ⁽⁴⁾

Cutter Material Titanium Alloy Machined	Carbide	
	Ti-8Al-1Mo-1V	Ti-6Al-4V Ti-7Al-4Mo Ti-6Al-6V-2Sn
Tool Material Type	C-2	C-2
<u>Tool Angles, degrees</u>		
Axial Rake	15	15
Radial Rake	0	0
Corner	-	-
End-Cutting Edge	-	-
Relief	12	12
Tool Nose Radius, inch	-	-
Feed, ipm (a)	90-150	90-150
Depth of Cut, inch (b)	0.025-0.075	0.025-0.075
<u>Speed, fpm</u>		
Annealed Alloys	230-370	230-370
Aged Alloys	-	-
Cutting Fluids	Soluble oil-water emulsions (1:30 dilution) or barium hydroxide (5% solution) as a spray mist	

- (a) The unit feeds resulting from the linear feeds shown range between 0.004 to 0.12, ipt, depending on the finish desired. However, too light a feed can produce red-hot chips which can cause a fire hazard.
- (b) When cleaning up extrusions, only about 0.05 inch depth of cut can be taken in order to reduce material costs. Hence, for long parts, use the feed/speed combination which gives the most economical metal removal based on machines available and cutting-tool inventory.

- (e) The finish required
- (f) The dimensional accuracy needed
- (g) The skill of the operator.

Conventional high-speed steel cutters can be used in the following instances:

- (a) Low production volume of small parts
- (b) Slots and form cuts
- (c) Milling under conditions of insufficient rigidity
- (d) End mills, form mills, narrow side-cutting slitting saws, and large radius cutters.

Carbide milling cutters are especially useful for high production or extensive metal removal operations, particularly in face milling and slab milling operations. They are to be recommended wherever possible, because of the higher production rates attainable.

Carbide cutting tools require heavy-duty, vibration-free machines, and rigid fixturing. The success of carbide milling depends largely on supervision, and control by well-qualified personnel.

Cutters should be ground and mounted to run absolutely true, in order to make the best use of the light feeds used in milling titanium and to make certain that all teeth are cutting the same amount of material. Cutting speed and coolant are very critical factors because of the large amount of heat generated when cutting titanium. Both mist and flood application of coolants are being used. One aircraft firm has reported that, by refrigerating the coolant with dry ice to a temperature of from -55 to -70°C (-68 to -98°F), speeds can be significantly increased⁽⁶⁾. Proprietary coolants and chemical coolants such as barium hydroxide are also receiving much attention.

Drilling

J. L. Phillips reports that hole preparation can make up an appreciable portion of the cost of airframe fabrication, particularly with respect to the type of airframe encountered in supersonic aircraft where major amounts of titanium alloys are used as structural members⁽⁷⁾. According to the data given in Table 9⁽²⁾ and reference 3, it will cost about twice as much in the actual operating time to drill holes in titanium as in aluminum alloys. However, drilling equipment, particularly portable, will be much more expensive.

In metal-cutting operations used for hole preparation, the considerations are often more severe or restricting than in other types of metal cutting. Metal removal is less efficient. For example, it takes approximately $1\frac{1}{2}$ horsepower to remove one cubic inch of steel per minute by milling and approximately $3\frac{1}{2}$ horsepower to remove the same amount by drilling⁽⁷⁾. This characteristic renders the drilling of titanium difficult by techniques considered conventional for other materials. Rapid tool wear results in out-of-round holes, tapered holes or smeared holes, with subsequent tap breakage if the holes are to be threaded⁽⁴⁾. These problems can be minimized by paying attention to the following details:⁽⁴⁾

- (a) Using short, sharp drills
- (b) Employing low speeds and positive feeds
- (c) Supplying cutting fluid to the cutting zone
- (d) Supplying solid support to the work-piece, especially on the exit side of the drilled hole.

General information on drilling for titanium alloys is listed in Table 15⁽⁴⁾.

Tool failure is very rapid and usually difficult to detect before it occurs. For reasons outlined by Phillips⁽⁷⁾, it is desirable to prevent tool failure while drilling. Also, when drilling holes for expansion-type rivets,

TABLE 15
Drilling Data for Titanium Alloys⁽⁴⁾

Type of Drilling	General Drilling and Deep Holes	Sheet Drilling
Machine tool	Radial drilling machine Upright drilling machine	Air-feed drill units Air-feed-oil check drill units
Type high-speed steel drills	M7, M10, M33, M34 T4, T5	M1, M3 Type 2, M10, M36 T4, T5
Drill types	Standard twist drills	NAS 907 aircraft drills (a)
<u>Drill Geometry:</u>		
Helix angle, degrees	29	25-28
Clearance angle, degrees	7-12	10-18
Point angle, degrees	118 or 135	135
Web	?	Thin web one-half
Type point	Crankshaft or split point	Split point
<u>Drilling Data - Feed, ipr</u>		
Drilling Diameter, inch		
< 1/8	0.0015	x
1/8-1/4	0.002-0.005	0.002-0.005
1/4-1/2	0.004-0.009	0.002-0.009
<u>Drilling Data - Speed, fpm (b)</u>		
Alloy and Condition		
Unalloyed Titanium	40-80	40
Ti-8Al-1Mo-1V, annealed	x	40
Ti-6Al-4V, annealed	30-40	30
Ti-6Al-4V, aged	20-30	25
Ti-4Al-3Mo-1V, annealed	x	25
Ti-4Al-3Mo-1V, aged	x	20
Ti-13V-11Cr-3Al, annealed	20-30	x
Ti-13V-11Cr-3Al, aged	15-20	x
Cutting Fluids: (c)	Sulphurized oils (flood applied) Sulphurized lanolin paste Water-soluble types (spray mist)	Sulphurized oils (flood applied) Water-soluble types Dry (single sheets only)

- (a) For hand drilling - NAS 907 Type D with p-3 point and lip rate reduced to zero. For fixed-feed drilling - NAS 907 Type B with p-3 point and lip rate reduced to zero. For fixed-feed drilling - NAS 907 Type E with p-2 point (dry).
- (b) Use reduced speeds for deep holes.
- (c) Sulphurized oils or sulphurized lanolin paste are recommended for low speeds and for drills less than 1/4 inch in diameter; water-soluble coolants can be used for higher speeds. Holes in single sheets up to two times the drill diameter can be drilled dry. Oil-feeding drills for deep holes.

there are rather close tolerances on hole diameter and out-of-roundness. These tolerances cannot be held if drilling is continued after the drill starts to lose its sharpness. The recommended technique, therefore, is to so standardize drilling conditions that drills can be removed from service after drilling a pre-established number of holes. For example, when, with a cutting fluid, speeds of 40 sfm are possible, a speed of 25 sfm has been found to be essential for reliable, repeatable operation⁽⁷⁾. Performance reliability of drills is very sensitive to grinding accuracy. Thus, while an optimum configuration drill, ground with absolute accuracy, should have a 150-hole tool life at 40 sfm and 0.0045 ipr, the actual life expectancy is only 85 holes because of unpredictable life due to minor deviations from optimum configuration⁽⁷⁾.

Titanium has a greater tendency to make an unguided drill generate a three-cornered hole than many other materials. Variation of drill geometry, speeds, feeds, or use of different cutting fluids will not correct this tendency. A short, precise drill and freon-butyl cellosolve cutting fluid will minimize it and produce holes within the normally acceptable tolerance for expansion-type rivets. A drill bushing must be used in order to obtain a truly round hole.

Prescribed thrust forces must be maintained during drilling, in order to maintain positive feed at a predetermined rate. This is essential for controlled drilling and predictable tool life. Portable drilling with hand-fed drilling tools or with air feed tools presents feed problems, and for this reason drilling units having positive feed are essential in most cases. There are, however, some important exceptions to this. A trade-off between process selection and tooling requirements should be considered. For example, for very short production runs the low and inconsistent drill life encountered with hand drilling may be cheaper than the provision of designed tooling to hold positive feed drill motors. Some other exceptions where free-hand drilling could offer a cost advantage are:

- (a) Holes approximately 0.1 in. diameter. These would be pilot holes. No. 40 drills at speeds up to 40 sfm without a cutting fluid can achieve consistent results.
- (b) Multi-step drilling with several drills.
- (c) Drilling in thin materials which allows penetration of the point prior to engaging of the full drill diameter.

Phillips discusses in some detail the influence of tool drill geometry, drill material, special drill designs and the selection of proper operating parameters⁽⁷⁾. The selection of the most economical speeds and feeds will depend on an appropriate economic analysis. Usually, slower speeds and feeds are the best choice. Feed rate per revolution of the drill is critical for maximum tool life. For example, this is about 0.005 ipr at 40 sfm. A standard HSS drill with a 135° split point used with a cutting fluid at a speed and feed of 25 sfm and 0.05 ipr will produce the most economical reliable operation. Research in exotic drill techniques does not appear to offer the potential returns that might be achieved by developing new drill units.

In the assembly of critically loaded tension structures, fasteners with tapered shanks may be used to improve fatigue resistance. The taper used is usually 1/4 in. included taper per foot for both the shank and the hole. Typical hole specifications are:⁽⁷⁾

Finish less than 125 rhr

Hole roundness within 0.001 in. tir

Hole taper - 0.250 ± 0.004 in. per foot

Diameter within 0.0015 in. total tolerance

Depth control ± 0.003 in.

These holes are produced with portable tools having a self-clamping index foot. Drilling jigs cannot be used. The range of diameters likely to be encountered is 5/16-1/2 in.

Depth control is one of the more critical problems. When drilling on flat panels the tool can be calibrated by drilling at least ten test holes on a flat test panel. However, this type of calibration is not too satisfactory when subsequent drilling is to be done on curved panels. The cure is probably to provide contoured test panels for calibration.

Drills used to make tapered holes in aluminum alloys will not work on titanium alloys. A special cobalt high-speed drill, having two flutes in the drilling section and four flutes in the reaming section, is recommended. All flutes should have very narrow (0.005 in.) margins. The countersink section should have a heavy web and cutting fluid feed holes.

Cutting speeds of 20-25 sfm with a feed rate of 0.005 ipm are recommended. A probable drill life of 400 holes before resharpening would be reasonable. The tapered reamer portion, which cannot be resharpened, should have a life of from 800-1200 holes. The diameters of the holes produced are usually about 0.002 in. smaller than the diameter of the drill used.

Reaming, Broaching, and Countersinking

Reaming, broaching, and countersinking with portable tools present no unusual problems. Phillips discusses these operations in detail in his paper⁽⁷⁾.

Standard high-speed steel reamers with straight flutes and a five-degree positive radial rake are recommended. These will produce a hole from 0.0002-0.0004 in. larger in diameter than the reamer. With a maximum reaming speed of 25 sfm and a feed rate of 0.001-0.002 in. per flute per revolution, a minimum tool life of 100 through holes 1/4 in. diameter by 1/4 in. deep can be expected. Reaming cannot remove exit or interface burrs.

Normal drilling speeds and feeds with standard high-speed steel countersink tools are adequate. If a radius is required at the juncture of the hole and the countersink, positive feed drilling equipment and an integral drill and countersink tool are essential. Otherwise, manual countersinking is satisfactory.

Broaches designed for use with aluminum are not adequate for reliable broaching of titanium. Clearance angles should be increased to 2° on the finishing section and $2\frac{1}{2}^\circ$ on the roughing section, to prevent galling. Nitriding will reduce galling tendencies. Existing broach pullers are adequate.

Cold working has been considered as a means of enhancing the fatigue characteristics of a component containing a hole. In the case of supersonic aircraft structures which can be exposed to elevated temperatures in service, the permanence of any such improvement is questionable. Further property evaluation will be necessary before this type of hole preparation can be justified⁽⁷⁾.

Tapping Operations⁽⁴⁾

The limited 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. Titanium tends to shrink on the tap at the completion of the cut. These difficulties can be minimized by:

- (a) Reducing thread requirements to 55-57 per cent full thread
- (b) Tapping fewest threads the design will permit
- (c) Avoiding the use of blind holes
- (d) Avoiding through holes of excessive length
- (e) Relaxing class-of-fit tolerances wherever possible.

The tapping operation itself requires sharp taps of modified conventional design, low tapping speeds, and an effective tapping lubricant.

Tapping should be done with a lead screw tapping machine equipped with a friction clutch. The machine should be rigid, accurate, and sensitive. Hand tapping is not recommended.

Gun taps and chip-driving spiral point taps with interrupted threads and full eccentric relief have both been used successfully to tap titanium alloys. They 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 larger. If rubbing is encountered during tapping, it may be decreased by:

- (a) using interrupted threads with alternate teeth missing,
- (b) grinding away the trailing edge of the tap,
- (c) grinding axial grooves in the thread crests along the full length of the lands, or
- (d) employing either eccentric or concentric thread relief.

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

- (a) A spiral point angle large enough to allow chip flow out of the hole ahead of the tap.
- (b) A relief angle large enough to prevent seizure but not so large as to cause jamming when backing out of the tap.
- (c) Sufficient cutting rake to provide a good shearing action.
- (d) A chamfer of about three threads to provide a small depth of cut. A shorter chamfer results in high torque and possible tap breakage. A longer chamfer produces long stringy chips.

Surface treatments, such as nitriding, oxide coating, or chromium plating, have contributed to successful tapping by reducing galling and increasing resistance to abrasion.

High-speed steel taps of AISI-T1 steel, for commercially pure titanium and AISI-M10 steel for titanium alloys, are recommended. Tapping speeds and requirements are summarized in Table 16⁽⁴⁾.

TABLE 16
Tapping Data for Titanium Alloys⁽⁴⁾

Type High-Speed Steel: Type Hole Tapped:	AISI-T1, AISI-M1, or AISI-M10			
	Through		Blind	
Hole Depth, tap diameters	One or less	> 1	One or less	> 1
Type Tap Used	GH-3 gun	Spiral	Plug or bottom	Plug and bottom (a)
<u>Number Flutes</u>				
For 5/16-24 tap and smaller	2	3	4	4
For 3/8-16 tap and greater	3 or 4	4	4	4
Chamfer, number of threads	Plug	2-1/2-3	-	-
<u>Tool Angles, degrees</u>				
Spiral point angle	-	10-17	-	-
Spiral angle	-	110	-	-
Relief angle	-	2-4	-	-
Cutting rake angle	Standard	6-10	-	-
<u>Tapping Speeds, fpm</u>				
Unalloyed titanium	-	40-50	-	-
Titanium alloys	-	10-30	-	-
Ti-6Al-4V, annealed	-	10-20	-	-
Ti-6Al-4V, aged	-	5-10	-	-
Ti-8Al-1Mo-1V, annealed	10-12	10-12	-	-
Ti-13V-11Cr-3Mo, annealed	-	8-10	-	-
Ti-13V-11Cr-3Mo, aged	-	5-7	-	-

(a) Where no clearance exists, use plug tap first to start threads, and then use bottom tap to chase threads.

The selection of proper cutting oils and compounds for tapping is extremely important. Paste-type cutting compounds usually give the best results.

Turning and Boring Operations

Turning and boring operations on titanium with single point tools are not particularly difficult when proper cutting conditions as outlined under "general machining requirements" are followed. A modern lathe in good condition should make it possible to achieve production rates of five to ten times the rates attained with older machines. Standard lathe tools, which are available in a variety of shapes, sizes, tool angles, and tool materials, may be used. Recommendations on tool geometry, tool material, operating parameters and cutting fluids are given in Tables 17⁽⁴⁾ and 18⁽⁴⁾.

Grinding

(a) Precision Wheel Grinding

If a choice of finish machining methods exists, serious consideration should be given to turning, boring, or milling operations, rather than grinding. These operations require less time than does grinding and give an excellent surface finish⁽⁴⁾.

Titanium can crack when ground under conditions normally used for steels. However, when grinding conditions specifically adapted for titanium alloys are used, cracking is not a major problem. The proper type of wheel, used in conjunction with a high-quality variable speed grinder, a rigid set-up, low wheel speeds and feeds, and flooding of the grinding area with inhibitor or purging type cutting fluid, will minimize grinding difficulties. Details for the precision grinding of titanium and its alloys are given in Table 19⁽⁴⁾.

TABLE 17
Turning Titanium Alloys with Carbide Tools⁽⁴⁾

Titanium Alloy Machined	Rough Machining			Finish Machining	
	Ti-5Al-2.5Sn	Ti-6Al-4V	Ti-13V-11Cr-3Al	Ti-5Al-2.5Sn	Ti-6Al-4V
Tool Material Type	C-1 Throwaway Type <u>SBT</u>	C-2 Brazed Type A; Throwaway Type <u>TAP</u>	C-2 Throwaway Type <u>SET</u>	C-2 Brazed Type B; Throwaway Type <u>SBP</u>	C-2 Brazed Type A or B; Throwaway's <u>TGP</u> , <u>SBP</u> , <u>TAP</u>
<u>Tool Angles, degrees</u>					
Back Rake	+5 to -5	+5 to -5	-5	+5 to -5	0 to +10
Side Rake	0 to -6	+5	-5	+6 to -6	0 to +10
End Relief	5 to 10	8 to 10	5	5 to 10	6 to 8
Side Relief	5 to 10	8 to 10	5	5 to 10	6 to 8
End-Cutting Edge	6 to 10	5 to 10	45	6 to 15	5 to 10
Side-Cutting Edge	5 to 20	0 to 45	45	5 to 20	0 to 30
Tool Nose Radius, inch	0.03-0.045	0.03-0.04	1/32	0.03-0.045	0.06-0.10
Feed, ipr	0.015	0.003-0.015	0.0075	0.006-0.015	0.002-0.006
Depth of Cut, inch	0.10-0.25	0.060-0.20	0.10	0.03-0.10	0.001-0.030
<u>Speed, fpm</u>					
Annealed Alloys	100-120	70-150	-	130-200	150-350
Aged Alloys	-	-	100	-	-
Cutting Fluids	Barium hydroxide (5% solution)				

TABLE 18
Turning Titanium With High-Speed Steel Tools⁽⁴⁾

Titanium Alloy Machined:	Rough Machining		Finish Machining		
	Ti-5Al-2.5Sn	Ti-6Al-4V	Ti-5Al-2.5Sn	Ti-6Al-4V	Ti-13V-11Cr-3Al
Tool Material, AISI Type	T5, T15	T5	T5, T15	T5	T15
<u>Tool Angles, degrees</u>					
Back Rake	0 to +5	+6 to +10	0 to +5	+5 to +15	0
Side Rake	+5 to +15	0 to +15	+5 to +15	+10 to +20	+5
End Relief	5 to 7	6 to 10	5 to 7	5 to 8	5
Side Relief	5 to 7	6 to 10	5 to 7	5 to 8	5
End-Cutting Edge	5 to 7	5 to 15	5 to 6	5 to 15	15
Side-Cutting Edge	+15 to +20	0 to 45	10 to 20	0 to 30	15
Tool Nose Radius, inch	0.02-0.03	0.03-0.04	0.02-0.03	0.01-0.06	0.03
Feed, ipr	0.015-0.050	0.003-0.015	0.008	0.002-0.006	0.008-0.010
Depth of Cut, inch	0.10-0.25	0.06-0.20	0.060	0.001-0.030	0.015-0.10
<u>Speed, fpm</u>					
Annealed Alloys	30	35-70	30-60	50-100	30-40
Aged Alloys	-	-	-	-	20-25
Cutting Fluids	Barium hydroxide (5% solution)				

TABLE 19
Precision Grinding of Titanium and Its Alloys⁽⁴⁾

Abrasive Material: (a)	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: (b)	Vitrified (V)		Vitrified (V)		
Operation: (c)	Roughing	Finishing	Roughing		Finishing
Down Feed, ipp:	0.001	0.0005(d)	0.001	0.0005	0.0005(e)
Cross Feed, inch	0.062-0.50(f)	0.005-0.025(f)	0.05	0.10	0.05
Table Speed, ipm	300-500	300-500	300-500		300-500
Wheel Speed, sfpm	2500-4000	2500-4000	1800-2000		1800-2000
Grinding Fluids:	Highly chlorinated oils or sulphochlorinated oils (do not dilute); possible fire hazard; hence flood the work		Rust-inhibitor types (g) 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) 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.

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

(c) Type wheels which have been used include 37C80-L8V and 32A60-L8VBE.

(d) For surface finishes better than 25 microinches rms, the down-feed should be less than 0.0002 ipp on the last pass.

(e) 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.

(f) Recommended for B-120VCA using green silicon-carbide wheels.

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

The possibilities of applying ultrasonic vibrations to a grinding-wheel-and-spindle system have been examined using 6Al-4V titanium alloy as well as various steels^(8,9). It was reported that ultrasonic grinding benefits were decreased surface burn, decreased power to grind, and improved grinding ratios. Fatigue and tensile properties were not diminished, even though much harder wheels were used ultrasonically in comparison to conventional grinding.

(b) Abrasive Belt Grinding

Abrasive belt grinding is used to grind titanium sheet to close tolerances. Belt grinders have produced flat surfaces with only 0.004 in. maximum deviation over areas up to thirty-six inches square. The cost of belt grinding titanium is estimated to be six to ten times that for stainless steel.

The chemical and physical properties of titanium combine to make belt grinding of titanium particularly difficult. The strong tendency to overheat on grinding must be recognized and adequate measures, such as generous use of cooling fluids and the proper choice of abrasives, must be taken to minimize this tendency. If the work overheats, excessive oxygen and nitrogen pick-up will result, causing an unacceptable increase in surface hardness.

Belt grinding is usually done on a carrier-type machine. The work is held on a table that oscillates back and forth under the belt. Data on abrasive-belt grinding is given in Table 20⁽⁴⁾.

The proper choice of contact wheels, which support the belt and hence govern the grinding action, is important. The wheels may be plane-faced or serrated. Plane-faced wheels usually produce a better surface finish. The harder the contact wheel, the faster the abrasive belt will cut and the coarser the surface finish will become. The best contact wheel is one which is firm enough to give restricted contact and good penetration

TABLE 20
Abrasive Belt Grinding of Titanium and Its Alloys⁽⁴⁾

Belt Characteristics	Grinding Operation		
	Spotting and Roughing	Finishing	
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 (a)	Closed (a)	
Bond	Resin	Resin	
Grinding Variables	Spotting	Roughing	Finishing (b)
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, inch	-	0.002	0.002
Table Speed, fpm	-	10	10
Grinding Fluids	No	Yes	Yes
<u>Type Grinding Fluids:</u> For Paper Belts Heavily sulphurized chlorinated oils (flash point: 325°F or higher). For Cloth Belts A 10 per cent nitride 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) Preferred.

(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 nitrite, follow safety precautions described previously.

but resilient enough to eliminate the failure of the belt by loss of abrasive grains at the highest feasible load.

Chemically active organic grinding fluids may prove superior, provided the fire hazard from grinding sparks can be minimized. Water-proof belts and water-base fluids containing certain inorganic compounds and rust inhibitors give good results. Soluble oil emulsions in water are poor grinding fluids for titanium.

Health and Safety

No physiological reaction from titanium on the human body has been reported. A potential explosion hazard may exist if very finely divided titanium is present in the air in proper proportions.

The fine chips and turnings can present a fire hazard, particularly if the metal is cut at high speeds without adequate use of coolants. Chip accumulation from poor housekeeping habits and improper storage can produce likely sites for titanium fires.

Non-Mechanical Metal Removal Processes

There are three types of non-mechanical metal removal processes that may be used to "machine" titanium alloys. These are chemical milling, electrochemical metal removal (ECMR), and electrical discharge machining (EDM). All of these processes remove metal without the use of actual physical force applied to a cutting tool, and are therefore not subject to the same types of problems as are encountered in "conventional" machining operations.

1. Chemical Milling Operations

The chemical milling process is used to remove metal from the surface of large, thin formed or complex parts, such as panels. The depth of metal removal is usually shallow. The areas from which metal is not

to be removed are protected by a masking material, usually vinyl polymer. Typical production tolerances are ± 0.002 in. plus the tolerance of the thickness of the starting material. The following figures can be used as a guide to depth-of-cut limitations for chemical milling:⁽⁴⁾

Sheet and plate	- 0.500 in. max depth per surface
Extrusion	- 0.150 in. max depth per surface
Forging	- 0.250 in. max depth per surface

Since chemical milling proceeds sideways at about the same rate as down, the minimum widths that can be "machined" are about three times the etch depth. Typical industrial production rates are about 1.0-1.5 mils per minute, for either titanium or aluminum⁽⁴⁾.

It is reported that chemical milling costs for titanium and aluminum are about half the costs for steel, and that the surface obtained on chemical-milled titanium parts is the best of any metals handled⁽¹⁰⁾.

The techniques used for chemical milling are proprietary and therefore technical information on procedures, solutions, etc., have not been disclosed. "Chem-Size" is the name of a proprietary chemical dissolution process for improving the tolerances of as-rolled sheet and plate and of parts after forming. "Chem-Tol" is another proprietary chemical dissolution process specifically designed for the same application as the "Chem-Size" process. "Chem-Mill" is the name of another proprietary chemical-milling process⁽⁴⁾.

Effect of Chemical Milling on Mechanical Properties

Where there is no intergranular attack, selective etching, or pitting, chemical milling does not adversely affect the mechanical properties of metals. However, published data on this aspect is scarce. The susceptibility of several titanium alloys to hydrogen embrittlement as a result of chemical milling in a hydrofluoric acid-chromic acid bath has been determined. The all-alpha 5Al-2.5Sn alloy is not embrittled. The alpha-beta

6Al-4V alloy was slightly embrittled and the all-beta 13V-11Cr-3Al alloy was severely embrittled⁽⁴⁾. A hydrofluoric acid-nitric acid bath having a HNO_3 concentration above about 20 per cent with 2 per cent HF present is reported to restrict hydrogen pick-up⁽⁴⁾.

2. Electro-Chemical Metal Removal

ECMR is an inherently versatile metal removal process, because it offers the capability of stress-free cutting of practically all known metals and can produce shapes and cavities which are costly and extremely difficult (if not impossible) to produce with conventional machining methods. The types of basically different operations that may be performed by ECMR are:

- (a) Hole drilling
- (b) Cavity sinking
- (c) External shaping
- (d) Surfacing
- (e) Wire cutting.

Many examples of these applications are given in a paper by E. Evans Foertmeyer⁽¹¹⁾. Only one of these, hole drilling, will be mentioned here. Drilling rates for holes up to 0.05 in. diameter may be 0.05 ipm while up to 0.75 ipm may be obtained for larger holes. A dimensional tolerance of approximately ± 0.001 in. can be expected.

In the electro-chemical removal process, metal is removed by anodic dissolution. Therefore, there is no opportunity for hydrogen entry into the metal workpiece and, as a result, loss of ductility and danger of delayed failure in ECMR-processed parts because of hydrogen embrittlement, are not problems⁽¹²⁾. Some general information about the technical aspects of the process are given by E. Evans Foertmeyer⁽¹¹⁾. The significance of the following parameters on the quality and economics of the process are discussed:

Tool feed rate	Electrolyte temperature
Current density	Electrolyte composition
Electrolyte flow	Microstructure workpiece
Tool surface of electrolyte	Tool insulation.

Uniformity and close control of tool feed rate is of prime importance for precision work. There is a minimum level of current density that should be exceeded in order to obtain a polishing action. The side walls of cavities may have a matte finish because the main current flow is directly ahead of the tool-cutting face, while there is a "leakage current" flowing from and behind the trailing edge of the cutting face. The side walls of the cavity will be machined secondarily at a relatively low current density by this "leakage current", thereby creating this matte appearance⁽¹¹⁾.

In many complex tools the resultant discharge streams from the electrolyte passageways of the electrode tool will tend to oppose each other and create areas of electrolyte starvation. This condition may result in areas which do not have sufficient electrolyte flow to remove the reaction products rapidly enough, and a much lower metal removal rate develops in such locations. Problems of electrolyte starvation can also occur near very sharp corners. Tools should be designed to either minimize this condition or to allow for it⁽¹¹⁾.

Nicks, notches, scratches, etc., on the tool surface will produce a mirror image on the work surface. Surface defects in the electrolyte passages in the tools can cause a disturbance in the electrolyte flow pattern in the work gap of the tool, thereby causing irregularities. Care must therefore be observed to obtain a polished surface free from defects, by either mechanical or chemical polishing, in the preparation of tools for ECMR⁽¹¹⁾.

Electrolyte back pressure and electrolyte temperature can both have a marked effect on the rate of metal removal, and therefore on the control of dimensional tolerances. Variations in back pressure of from 0-80 psi are the most critical. Electrolyte temperature can have a marked effect on the economy of the ECMR operation. There will be some optimum temperature where the greatest over-all economy is achieved⁽¹¹⁾.

The microstructure of the workpiece can influence the surface finish obtained. Large grains might result in a rougher finish than that obtained with a fine grain size. Intermetallic precipitates at grain boundaries can cause grain boundary attack⁽¹¹⁾. Intergranular attack to a depth of 0.0005 in. can cause a 15% loss of fatigue life. This can be minimized by proper operation. Prolonged exposure of the workpiece to the electrolyte with the current shut off should be avoided, since this can cause chemical dissolution and hydrogen entry. The workpiece should be rinsed thoroughly immediately after processing⁽¹²⁾.

The surface finished by ECMR is stress free. Therefore the fatigue limit of components prepared by ECMR may be lower than the fatigue limit of the same components prepared by mechanical metal removal because the latter process creates a stressed surface layer which may enhance fatigue properties. To get equivalent properties by ECMR a post treatment, such as honing or shot peening, is suggested⁽¹²⁾. It is very likely that these same observations could apply to surfaces prepared by chemical milling operations.

3. Electric Discharge Machining (Spark Drilling)

In electrical discharge machining (EDM), metal is removed by the action of an electric discharge or spark. A dielectric coolant, such as kerosene, is used. This may also be used to carry away the debris resulting from the cutting action.

The extent to which EDM will "pay off" is determined by the advantages that are taken of its unique characteristics. These are:⁽¹³⁾

- (a) The ability to machine metals of high hardness levels.
- (b) The ability to machine metals without imposing mechanical forces on the workpiece; the tool never comes in contact with the workpiece.
- (c) The ability to machine metals with relatively inexpensive tool material. The spark does the actual cutting so that relatively inexpensive, soft material, such as brass, can be used as a tool.
- (d) The ability to machine metals in an automatic operation. The servo operation is completely automatic and will machine the metal at a rate that can be preset.

An example of a successful application of the EDM process to airframe fabrication is described by John J. Christiana⁽¹³⁾. This is the drilling of fastener holes in the speed brake door assembly of the F-105 aeroplane. This required the drilling of 800 holes per assembly. These holes range in diameter from 0.098-0.187 in. and in depth from 0.078-0.187 in. In certain areas, as many as 5 layers must be penetrated. All the holes in the outer and inner surfaces of the door are drilled simultaneously in two separate machines. Both machines are run by one operator. Cutting time for each surface of the door is $1\frac{1}{2}$ hours. This compares with conventional drilling times of 14.2 man hours for the outer surface and 11.8 man hours for the inner surface. In addition to this, there is a significant saving in the order of \$170.00 in tool costs.

In view of the nature of the electrical discharge machining process, it might be advisable to be rather cautious in its use. It is the author's opinion that a skin of thermally disturbed metal could be formed and that this skin might contain minute cracks generated by rapid heating. This could have an adverse effect on the fatigue life of a component. It might therefore be advisable to at least satisfy oneself on this point before using this type of process on production items.

Sheet Forming

The forming of titanium alloy sheet into contoured and shaped components required for airframe construction presents many problems not encountered when using aluminum alloys. It has been estimated that these types of operations on titanium alloys would cost about twice as much as the equivalent operations when using aluminum alloys⁽³⁾. However, titanium alloy components formed by hot forming or cold forming plus hot sizing are much more precisely made than cold-formed aluminum parts. Consequently, they require far less, if any, expensive hand rework on assembly⁽⁶³⁾.

The high yield strength of titanium alloys makes them difficult to form and this high yield strength combined with their relatively low modulus of elasticity exaggerates the problems of spring-back after forming. Both of these problems can be alleviated by forming at elevated temperatures and by using a prolonged forming cycle. The temperatures used for these operations may range from 480-675°C (900-1250°F). Since the strength of all the high-strength titanium alloys used depends on a solution treatment plus ageing cycle, with an ageing temperature in the order of 480°C (900°F), it is apparent that any manufacturing schedule involving hot forming must be carefully arranged to achieve the optimum balance between manufacturing costs and design properties.

The Titanium Alloy Sheet Rolling Program of the U.S. A. Department of Defense has developed general guidelines that should be followed when dealing with specific airframe design and manufacturing applications for titanium alloys involving sheet forming⁽¹⁴⁾. This report indicates the following:

- (a) The Bauschinger effect, which may be present as a result of straining, even at hot forming temperatures, is largely eliminated on subsequent ageing.

- (b) Hot forming may have to be accomplished at a temperature above the ageing temperature in order to gain satisfactory part definition. The effect on aged properties must be carefully determined. It is of particular importance that forming temperatures be known and controlled closely.
- (c) The effect of some fabrication schedules on resultant properties will have to be assessed by the user in establishing design allowables. It has been demonstrated that fabrication operations may in some instances alter ageing response, preventing full realization of high heat-treated strength levels. Each potential user is advised to examine his own anticipated operations and gain assurance of valid design allowables by exposure of test specimens to the simulated forming conditions of strain, temperature, and time. Careful attention to these details by the user is to be preferred over sweeping generalities, since such generalities might well result in unnecessary design penalties.

Experience has indicated that the optimum sequence of operations in the production of airframe components from high-strength titanium alloy sheet is:⁽¹⁵⁾

- (a) Solution heat treat.
- (b) Form, either hot or cold.
- (c) Hot size in restraining dies at some temperature that is above the ageing temperature. The time for this hot sizing process will be short, usually about fifteen minutes, and should be accurately controlled.
- (d) Age, unrestrained.

Stretch, Creep and Hammer Forming and Jogging

There are several distinctive types of forming operations, that may be used to form titanium alloys. Stretch-forming over heated contoured dies may be used to contour sheet panels. A castable ceramic is commonly used for the die material. Heating elements are incorporated in the die. The workpiece itself may be heated by a bank of heat lamps. Creep forming uses a mating pair of heated dies, usually ceramic. The dies are held closed on the workpiece for several minutes. Usually ten to fifteen minutes are sufficient⁽¹⁵⁾. Creep-formed panels with mild

contours may be subsequently aged without the need for restraining fixtures⁽¹⁵⁾. Hot hammer forming, followed by hot sizing using the hammer die inserts in a hot sizing press, is used where appropriate. The workpiece may be heated by a radiant heat lamp while in position on the forming tool. When the workpiece is up to temperature, the heat lamp is withdrawn and the forming blow struck.

Extruded and rolled structural shapes may be formed by stretch forming, rubber forming, and creep forming. The room temperature buckling limit for stretch forming and rubber forming for both stretch and shrink flanges can be increased by approximately thirty-five per cent when buckles are subsequently removed by reforming at an elevated temperature⁽¹⁵⁾.

Joggling would seem to be one forming operation that is preferably done at room temperature. Surface condition plays an important roll in fixing joggle limits. Etched material is best⁽¹⁵⁾.

According to Peterson⁽¹⁵⁾, the Ti-8Mn alloy would appear to be a much easier alloy to use than, for example, the Ti-4Al-3Mo-1V alloy, for sheet forming operations. He cites the following improvements in procedure that would be necessary on changing over from the 8Mn alloy to the 4Al-3Mo-1V alloy:

1. Uniform and improved temperature control for hot forming.
2. Fabrication of parts to closer contour prior to final forming.
3. Improved material uniformity with regard to control of minimum elongation limits and surface condition.

It is very likely that the above noted factors are ones that should receive specific attention in setting up any forming operations.

The recommended hot finish forming schedule for 4Al-3Mo-1V material that had been cold formed in the solution treated condition was found to be 15 minutes at $570 \pm 8^\circ\text{C}$ ($1075 \pm 15^\circ\text{F}$). It was also observed that the time interval between insertion of the part in the heated tool and closing the tool was critical due to the rapid onset of ageing of this material.

Superior parts were produced when this time interval was held to one-half minute or less⁽¹⁵⁾. This would suggest that the over-all time interval for the complete hot forming operation should be controlled within limits of one-half a minute of the nominal time.

It is recommended that Kirksite dies and lead punches used for hot forming titanium should be jacketed with mild steel on the contact faces to prevent lead contamination and melting of the lead. A generous coat of heavy weight oil on the die acts as a lubricant and a heat insulator⁽¹⁶⁾.

Stretch-Drawing⁽¹⁷⁾

Stretch-drawing is a means of forming shapes in sheet metal. This process combines conventional sheet forming with stretching. The sheet to be formed is gripped between two pairs of jaws and pulled to about 2% strain. The blank is then pulled down over the lower die and the top die delivers the forming blow. It is claimed that metal forms more easily when under tension and that therefore the required forming press capacity is reduced by about two-thirds. It is also claimed that titanium parts that require four or five hot forming operations can be produced in one blow by stretch-drawing.

Hydroforming⁽¹⁸⁾

Hydroforming is a proprietary sheet-forming process by which the developers claim any ductile metal can be formed into intricate or deep shapes without distortion, wrinkling or shearing. It is also claimed to be capable of forming sharp right angles, acute compound curves, and other shapes that would normally make a design impractical from a production standpoint. There is a minimum of localized thin-out. The material is displaced, rather than stretched into shape. The principle of this process is the use of hydraulic pressure which wraps the metal being formed around a male form.

It is claimed that hydroforming can produce parts that cannot be economically handled by any other process. In other applications, where parts can be made on conventional equipment, the break-even point, in comparison with hydroforming, is said to be at around the 1,000-10,000 piece figure. Above that point the advantage falls to conventional equipment.

The "Budd-Form" Process ⁽¹⁹⁾

This is a proprietary sheet-metal forming process that has apparently been developed for the production of deep-drawn hemispherical and ellipsoidal shapes. It is capable of cold forming hemispherical or ellipsoidal heads of diameter to thickness ratios of 5,000 to 1. Metals of low tensile elongation such as 20% Ni maraging steel, magnesium alloys and other metals with a tensile-yield-strength to ultimate-strength ratio close to 1, such as titanium, can be formed by this process.

The principle used in this process is that if a compressive stress of sufficient magnitude is added to a forming process that is predominantly tension, larger amounts of plastic deformation can be obtained. In practice, the workpiece is confined between expendable plates which are so joined at the periphery that a compression stress is introduced during the drawing process. The material to be drawn is placed at the neutral axis and the severity of bending stresses is reduced. This type of process can be carried out using standard design draw-dies on a double-action hydraulic press. Hemispherical heads as large as 35 in. in diameter have been produced.

Dimpling

Dimpling is probably one of the most important forming operations. It is usually performed on large sub-assemblies, and the rejection of one small dimple in hundreds can cause scrapping of an entire sub-assembly. Joseph L. Phillips ⁽⁷⁾ describes the development of a successful dimpling technique and associated equipment and tooling. The critical features are

the use of a die and pressure pad preheated to approximately 315°C (600°F) and the heating of the workpiece by the passage of electric current through it. Electrical contact with the work made from the punch to the die, rather than from the clamp to the die, is necessary for consistent results. When contact is made between the clamp and the die, the stretch zone in the centre of the dimple has a tendency to crack because of insufficient temperature rise. Die-to-punch contact eliminates this.

Tube Bending⁽²⁰⁾

Commercially pure titanium (Grade A-40) is being used for pneumatic systems of commercial aircraft. The diameter of tubing used for such systems may vary from one to six inches and the wall thickness will vary from 0.016-0.042 inch.

These pneumatic systems characteristically have very few straight runs and a great number of elbows. Space limitations require that these elbows be bent on tight radii, usually $1\frac{1}{2}$ to 2 times the tube diameter.

Kollmorgen discusses in detail the technique developed by Boeing to carry out this tube bending operation⁽²⁰⁾. A draw bending process is used. This process employs a complex die assembly consisting of bend, wiper, pressure, and clamp dies. A ball mandrel inside the tube prevents collapse in the bend area. The tube is held between the bend and clamp dies, which are rotated. As the tube is bent, it is drawn through the wiper die and over the mandrel. The pressure die travels with the tube and provides the reaction force necessary to bend the tube.

Tubes three inches in diameter and larger should be bent hot. The optimum forming temperature was found to be 180-255°C (350-450°F). Tubes smaller than this could be bent cold. Heat is obtained by using a heated pressure die and mandrel body. The tubing does not need to be preheated.

Because of the high loads encountered during this operation, conventional lubricants did not provide the film strength needed to separate the tools from the workpiece. Tooling material had to be selected that would minimize the characteristic galling tendency that titanium exhibits under conditions of sliding friction with most other metals. These conditions exist in the wiper die and the mandrel, and for these components it was found that Ampco Grade 21 aluminum bronze was a satisfactory material.

The most effective lubricant for the elevated-temperature tube bending operation was found to be a grease having a high graphite content. However, this was not completely effective in preventing galling. A phosphate conversion coating on the tubes, to supplement the graphite lubricants, relieved this problem.

Bending speed is a critical factor and must be carefully regulated and controlled, if satisfactory results are to be obtained. The optimum bending speed will probably lie between 1/4-4 rpm.

Suggested bending limitations for commercially pure titanium tubing are given in Table 21⁽²⁰⁾.

The above comments have been selected from Kollmorgan's paper, which also covers raw material requirements, and gives details on the bending operation and type of machine used and modifications that have been made to it.

Miscellaneous Metal Forming Comments

Other metal forming operations, such as spin forming and shear forming, have been carried out on titanium alloys. From 40-60% maximum deformation can be attained on 6Al-4V and 13V-11Cr-3Al titanium alloys in a single pass at room temperature by shear forming⁽²¹⁾.

TABLE 21

Bending Limitations for Commercially Pure (Grade A-40)Titanium Tubing ⁽²⁰⁾

Tube		Minimum Bend Radius (inches)	Preferred Bend Radius (inches)	Maximum Bend Angle* (Degrees)	
Diameter	Wall Thickness (inches)			Minimum Bend Radius	Preferred Bend Radius
1-1/2	.016	2-1/4	3	90	120
	.020	2-1/4	3	100	160
2	.016	3	4	80	110
	.020	3	4	100	150
2-1/2	.016	3-3/4	5	70	100
	.020	3-3/4	5	90	140
	.035	3-3/4	5	110	180
Elevated Temperature Forming Requirements	3	.016	4-1/2	6	90
		.020	4-1/2	6	110
		.035	4-1/2	6	130
	3-1/2	.016	5-1/4	7	90
		.020	5-1/4	7	110
		.035	5-1/4	7	130
	4	.020	6	8	110
		.035	6	8	120
	4-1/2	.020	6-3/4	9	130
		.035	6-3/4	9	140
	5	.020	10	10	-
	6	.020	12	12	-
					110
					100

It has been observed that stress-corrosion cracking may be encountered during the forming and fabrication of the super-alpha alloys. This can be overcome by hand cleaning with methanol prior to heating in the case of the 8Al-1Mo-1V alloy. Stress-corrosion problems on the 7Al-12Zr and the 5Al-5Sn-5Zr alloys may be prevented by cleaning with an alkaline cleaner prior to elevated-temperature forming operations⁽²²⁾.

It has been observed that titanium alloy sheet can be formed into angle sections having a tighter bend radius by roll forming than by brake forming⁽²³⁾.

Lubricants

The use of proper lubricants is an important consideration in both the hot and cold forming of titanium alloys in closed mating dies. Molybdenum disulphide is a good high-temperature lubricant and the one most widely used⁽²⁴⁾. Mitchell and Brotherton have reported on an extensive study of lubricants used in the press forming of titanium⁽²⁵⁾. They studied the following lubricants,

- (a) Sheet polythene, 0.002 in., applied to the die side of the blank;
- (b) Polytetra-fluorethylene (PTFE) dispersion in resin applied by dipping, painting, or spraying to the die side of the blank, followed by air drying;
- (c) MoS_2 dispersion in resins applied as in (b);
- (d) Trilac 635/8 (a methacrylic resin) dissolved in trichlorethylene and applied as in (b);
- (e) Liquid nitriding in a mixture of molten cyanide and carbonates for fifteen minutes at 570°C (1050°F) (not used for alloy EX 011);

for effectiveness in deep drawing of 20 SWG (0.036 in.) sheet of the following alloys:

- IMI 115 - alpha alloy - commercially pure
- IMI 160 - alpha alloy - commercially pure
- IMI 230 - alpha + Ti_2Cu - 2% Cu age hardening
- IMI 317 - alpha alloy - 5Al-2 $\frac{1}{2}$ Sn
- IMI 318A - alpha + beta - 5Al-4V
- IMI 011 - beta alloy - 15% Mo age hardening.

Their studies indicated that items (a) and (d) above were the most efficient lubricants, that efficient lubrication had more influence on deep drawability than on stretch formability, and that lubrication was completely ineffective for alloys IMI 317 and IMI 318A under the conditions of this investigation. This latter observation suggested to the authors that surface galling and poor friction are not primarily responsible for unsatisfactory press-forming characteristics of high strength titanium alloys.

A new "iodine" lubricant has recently been announced⁽²⁶⁾. It is claimed that this new lubricant is effective on titanium.

High-Velocity Metal Forming

Two sources of energy are commonly used for high-velocity forming on sheet metal. These are explosive and electric discharge. The most economical types of application for high-velocity forming is in the shaping of pre-formed hollow bodies, such as tubes, and in the formation of cup shapes from flat plate. A comparison of explosive and hydro-electric discharge forming is given in an article by E. W. Feddersen⁽²⁷⁾. He points out that hydro-electric forming, i. e. forming by the energy of an electrical discharge under water, has an advantage over explosive forming in that it can be used indoors and in closed dies. The discharge is well controlled. A typical power unit capable of producing 10,800 ft-lb of energy would consist of a condenser bank having a capacity of 1200 microfarads charged at 4,000 volts.

A rather more detailed description of high-velocity metal working processes based on the sudden release of electrical energy has been made available by the Defense Metals Information Center⁽²⁸⁾. This report discusses the advantages of using an exploding wire to give better control of the discharge path and to "shape" the shock wave. It also discusses metal forming by means of a condenser discharge through a magnetic coil and suggests that probably the most attractive application for this technique would be in the forming of tubular shapes without any contact with a tool or die. For example, assemblies can be made by this method by causing a tube to contract around a fitting in which circumferential grooves have been cut⁽²⁹⁾.

The Defense Metals Information Center has also prepared a detailed review of explosive metal working⁽³⁰⁾. This report deals with the principles involved, the characteristics of the different types of explosives that are used, the pressure conditions that can exist during the forming operation, and, in a general way, the effect of explosive forming on material properties. However, specific examples are not discussed. In some recently reported work by Potteiger of the Naval Weapons Laboratory, the results of studies of the alteration of mechanical properties of seven metals resulting from controlled detonation of high explosives in direct contact with the specimens are discussed⁽³¹⁾. Nickel, nickel alloys and steels, but no titanium alloys, were included in this program. The explosive shocking resulted in appreciable hardening and strengthening, accompanied by a marked drop in Charpy V-notch toughness.

Sheet Metal Formability

A new method is now available to the metal forming industry by which the sheet metal formability of any material can be determined, provided the geometrical parameters and the material mechanical properties are known⁽³²⁾. This method is presented in a paper by D. L. Norwood,

The paper contains data, design tables, and instructions for their use in predicting formability limits for several forming processes. It also discusses the underlying principles that were used in the development of this approach to formability problems.

Welding

A review of the weldability of titanium alloys has been prepared by Dr. K. Winterton of the Physical Metallurgy Division of the Mines Branch and has been published as Mines Branch Technical Bulletin TB 71, dated April 1965.

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