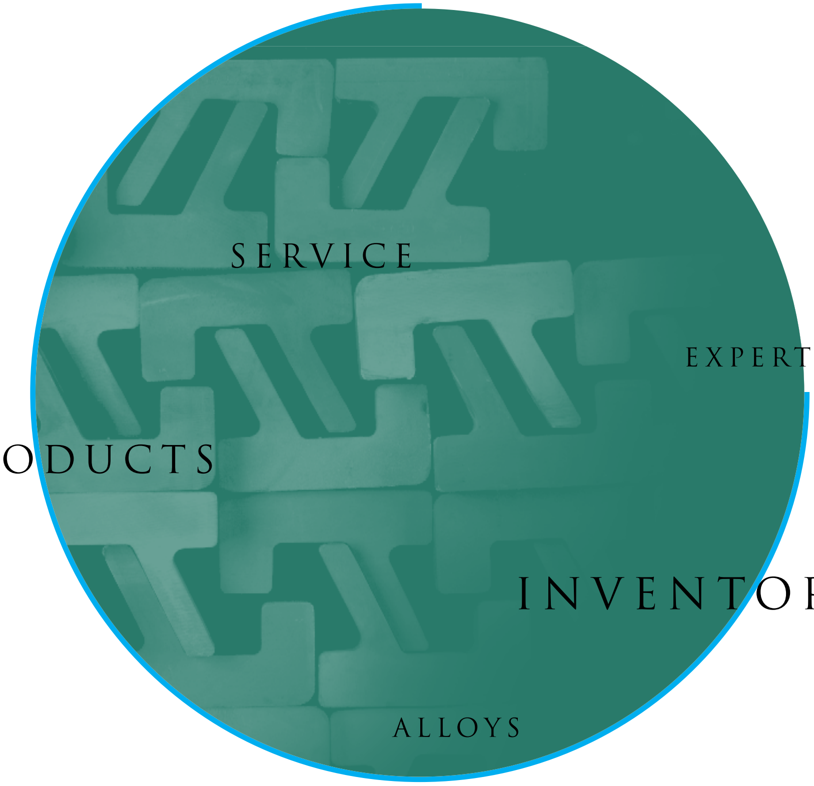
properties and processing of TIMETAL® 6-4

Titanium Metals Corporation

TIMET®

The world's
complete titanium resource



Titanium Metals
Corporation

This bulletin is published in dual units: English and SI. The primary units are English, with conversions appropriate to the situation. For example, a strength guarantee of 125 ksi is converted to 860 MPa rather than 862 because the latter implies more precision than is implicit in 125 ksi. Dual units are justified because both are, in fact, in extensive use.

The data and other information contained herein are derived from a variety of sources which TIMET believes are reliable. Because it is not possible to anticipate specific uses and operating conditions, TIMET urges you to consult with our technical service personnel on your particular applications. A copy of TIMET's warranty is available on request.

TIMET®, *TIMETAL*®, *CODEROLL*® and *CODEWELD*® are registered trademarks of Titanium Metals Corporation.

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INTRODUCTION

TIMETAL® 6-4 is the most widely used of all titanium alloys. Introduced in 1954, this “workhorse” of the industry has a broad spectrum of good to excellent properties. As such, *TIMETAL* 6-4 may rightfully be considered the general purpose titanium alloy. TIMET® has been in the business of producing *TIMETAL* 6-4 since its introduction and is the largest volume producer of the alloy.

TIMETAL 6-4 is available as sheet, plate, billet, bar and ingot. *TIMETAL* 6-4 responds to heat treatment and typically its full ultimate strength of 160 ksi (1100 MPa) can be developed in sections up to one inch (25mm) thick. Thicker sections can be heat treated but to lesser strength. *TIMETAL* 6-4 is characterized as an alpha rich alpha-beta titanium alloy.

With a density of 0.160 lbs/cu. in. (4.43 gm/cc), *TIMETAL* 6-4 possesses high structural efficiency.

Fatigue properties are excellent. Crack initiation is not affected by water nor by salt below 450°F (230°C). Crack propagation resistance is also excellent under static or dynamic load spectra. Salt water can affect crack propagation, the degree depending on interstitial content and load spectra. Crack initiation and propagation are both affected by heat treatment.

TIMETAL 6-4 is recommended for use at temperatures from -350° to 750°F (-210° to 400°C). Applications outside this temperature range are possible in certain situations.

The alloy is weldable. Complex shapes can be made via hot forming. It machines like an austenitic stainless steel.

There is a great wealth of data on *TIMETAL* 6-4. The alloy is the best known of the titanium alloys and is often selected for this reason alone. This publication is a summary of much of this information. Additional information is available from TIMET or by consulting the references.

CHEMICAL COMPOSITION

The properties available in *TIMETAL* 6-4 are influenced significantly by composition. Two basic levels of interstitial content are available from TIMET: standard *TIMETAL* 6-4 and *TIMETAL* 6-4 ELI. ELI is an acronym for **EXTRA LOW INTERSTITIAL**, meaning primarily low oxygen in practice. Typical compositions are given in *Table 1* as exemplified by AMS and Military Specifications.

Within either chemistry of *TIMETAL* 6-4, it is also possible to vary the composition aim within limits. This is most often done with oxygen and iron. Information on alternatives to *Table 1* is available upon request.

TABLE 1

SOME GENERALLY AVAILABLE AND STANDARD SPECIFICATIONS FOR TIMETAL 6-4

	Standard Wt.% *(AMS 4911 D)*(1)		*ELI Wt.%* *(AMS 4907 C)*(2)	
	Min.	Max.	Min.	Max.
Aluminum	5.50	6.75	5.50	6.50
Vanadium	3.50	4.50	3.50	4.50
Iron	–	0.30	–	0.25
Oxygen	–	0.20	–	0.13
Carbon	–	0.08	–	0.08
Nitrogen	–	0.05	–	0 05
Hydrogen	–	0.015	–	0.0125
Yttrium	–	0.005	–	–
Residual Elements, each	–	0.10	–	0.10
Residual Elements, total	–	0.40	–	0.30
Titanium	remainder		remainder	

(1) Equivalent to MIL-T-9046, Type lll, Composition C.
(2) Equivalent to MIL-T-9046, Type lll, Composition D.

PHYSICAL PROPERTIES

Most of the physical properties of titanium and its alloys depend on the direction in which they are taken. This feature arises for two reasons: 1) both alpha and beta crystals are anisotropic such that most physical properties will have values that depend on the direction in which they are measured in the crystal, and 2) both alpha and beta in *TIMETAL* 6-4 tend to be textured; that is, the crystallite axes tend to lie along preferred directions with respect to the direction of metal flow set up during processing. In general, therefore, any physical property that is not a simple scalar quantity will show at least some anisotropy in *TIMETAL* 6-4. In the following, those physical properties that depend on test direction will be so indicated.

Density

The density of *TIMETAL* 6-4 is 0.160 lbs/cu. in. (4.43 gm/cc). This density is only 56 percent that of steel.

Thermal Expansion

Figure 1 summarizes the reported data. The thermal expansion of *TIMETAL* 6-4 is about half of that of austenitic stainless steel and about one-third that of aluminum. The following equation may be used to approximate $\Delta L/L_o$ in percent. $\Delta L/L_o\ (\%) = -.220 + 5.992 \times 10^{-4}\ T + 5.807 \times 10^{-7}\ T^2 - 1.994 \times 10^{-10}\ T^3$. The attending error bar is approximately ± 0.025%. T is in °K.

Thermal Conductivity

Values reported are shown in *Figure 2* as functions of temperature. These values are similar to those for austenitic stainless steel.

Thermal Diffusivity

This quantity also varies with direction and the literature data are scattered. The trend line with temperature, along with two sigma values attending the data plotted, are given in *Figure 3*.

Specific Heat

Figure 4 illustrates some determinations of specific heat. The variations between investigations here are due to compositional variance or experimental error or both.

FIGURE 1

EFFECT OF TEMPERATURE ON THERMAL EXPANSION OF TIMETAL 6-4

(REF. 1)

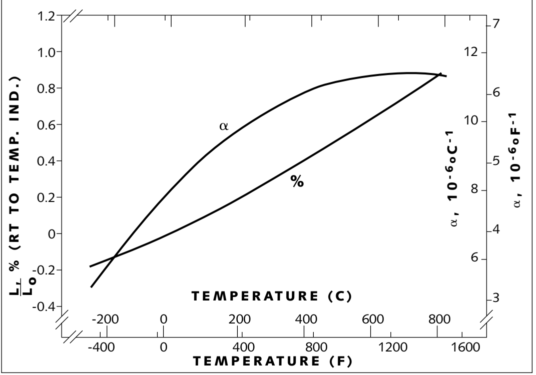


FIGURE 2

THERMAL CONDUCTIVITY OF TIMETAL 6-4

NUMBERS IN PARENTHESES INDICATE REFERENCES (REF. 4)

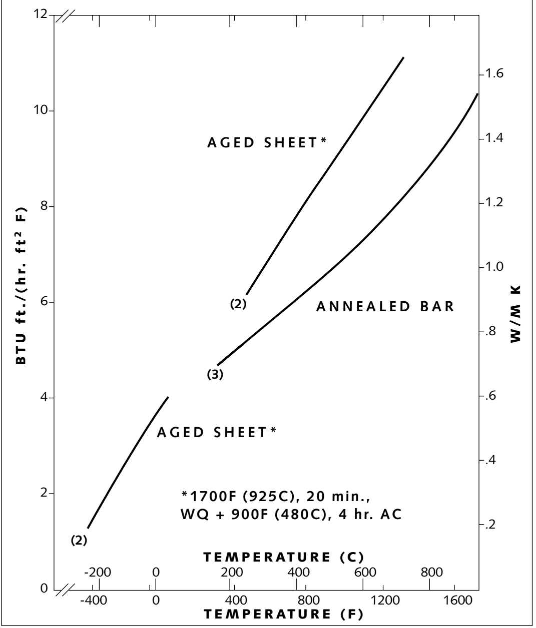
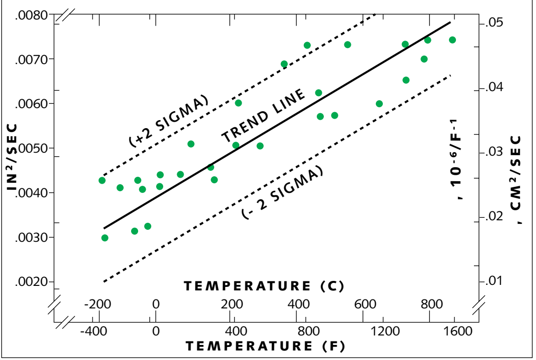


FIGURE 3

THERMAL DIFFUSIVITY FOR TIMETAL 6-4

(REF. 5)



Electrical Resistivity

The resistivity of *TIMETAL* 6-4 is shown in *Figure 5*. Resistivity depends on measurement direction. Therefore, the trend shown would be expected to have an associated scatter band ascribable to texture variation. These values are similar to those for austenitic stainless steel.

Emittance

Total emittance and spectral emittance for oxidized and polished surfaces are shown in *Figures 6* and *7*. Emittance is both temperature and wave length sensitive. Values given are in reference to a black body rated at unity.

Magnetic Permeability

At 20 oersteds, the permeability of *TIMETAL* 6-4 is given by one source(10) as 1.00005. The alloy is nonmagnetic. Permeability is direction dependent.

Melting Range

The melting range of *TIMETAL* 6-4 is 2965°-3000°F (1630°-1650°C). This compares with 3047°F (1675°C), the melting point of commercially pure titanium.

Phase Change

The $\alpha + \beta \rightarrow \beta$ phase change depends on composition. The standard grade transforms at 1825° ± 25°F (996° ± 14°C), whereas *TIMETAL* 6-4 ELI transforms at 1805° ± 25°F (985° ± 14°C). A NOTE OF CAUTION HERE: In cases of coarse or blocky alpha microstructures, longer solution times, up to one hour or more, may be required for metallographic evaluation of the phase change temperature. The coarse alpha, requiring a variable but finite time to dissolve, may lead one to conclude a higher transformation temperature by metallography or dilatometry than would be found under conditions of thermodynamic equilibrium. A beta solution treatment may be used prior to determination in such cases. One should note also, that under conditions of thermodynamic equilibrium, beta phase is present at room temperature.

FIGURE 4

SPECIFIC HEAT

NUMBERS IN PARENTHESES INDICATE REFERENCES

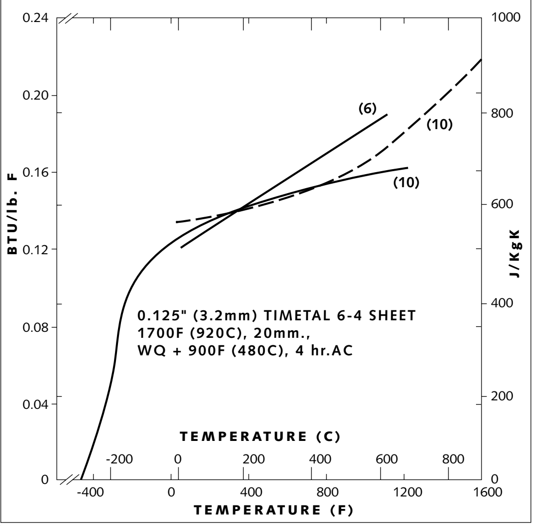


FIGURE 6

EMISSIVITY OF TIMETAL 6-4 AS DEPENDENT UPON TEMPERATURE AND SURFACE CONDITION

(REF. 7)

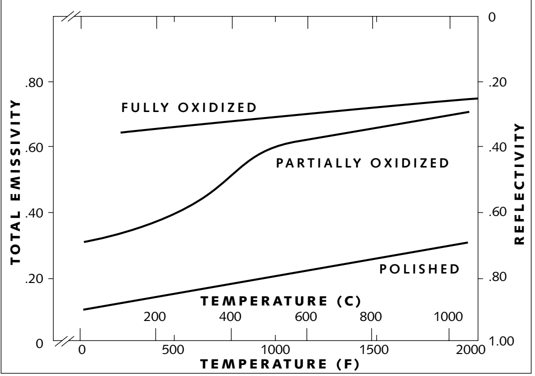


FIGURE 5

ELECTRICAL RESISTIVITY

(REF. 3)

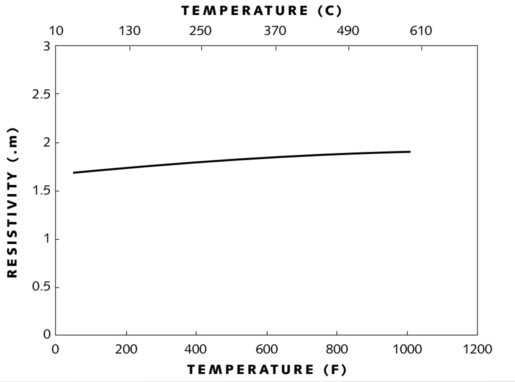
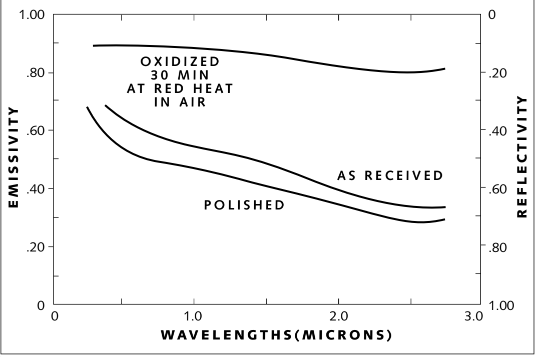


FIGURE 7

SPECTRAL EMISSIVITY OF TIMETAL 6-4 AS FUNCTION OF SURFACE CONDITION

(REF. 7)



TIMETAL 6-4 is consumable-electrode vacuum arc melted at least twice. Triple melted material is also available. During all stages of materials preparation and vacuum arc melting, extensive quality control procedures are employed to assure a high quality product.

TIMETAL 6-4 is available as ingot, bloom, billet, bar, plate and sheet.

Quality Assurance

TIMET uses two basic levels of ingot quality assurance.

Standard Quality – Product is intended for non-critical load carrying application. Raw materials meeting strict specifications are used in formulation. Melting control and quality control procedures are likewise strictly standardized.

Premium Quality – Product is intended for jet engine and helicopter rotating components and critical airframe structures. Only raw materials meeting the tightest specifications are used in the formulation. Likewise, melting control and quality control procedures are of the tightest variety.

In addition, material at either level of quality assurance may be either double vacuum arc melted or triple vacuum arc melted. Triple melt material provides additional melting time for the solution of any undesirable impurities. The following TIMET definitions apply:

Standard Double Melt Grade – Standard Quality double melt product.

Standard Triple Melt Grade – Standard Quality triple melt product.

Rotating Grade – Premium Quality double or triple melt product for critical blade applications.

Premium Grade – Premium Quality triple melt product for disc and associated rotating components.

One or more of the vacuum arc melts may be replaced by electron beam or plasma cold hearth melting. For certain standard grade applications a single cold hearth melt may be acceptable. For premium and rotating grade applications the final melt will be a vacuum arc melt.

Standard Double Melt Grade meets specifications listed in *Table 2*, whereas Standard Triple Melt Grade exceeds them.

Rotating Grade likewise exceeds the specifications in *Table 2* while meeting the Grade 1 requirements of AMS 2380 which cover premium quality product.

Premium Grade meets the highest Grade 2 requirements of AMS 2380 and is recommended for all parts where integrity is critical. TIMET Premium Grade product represents the ultimate in quality assurance.

TABLE 2

SOME GENERALLY AVAILABLE AND STANDARD SPECIFICATIONS FOR TIMETAL 6-4

Organization	*Specification**	*Product*
AMS	4906	Ann. Sheet , Strip
AMS	4906	Ann. Sheet, Strip
AMS	4907	ELI Ann. Sheet, Strip, Plate
AMS	4911	Ann. Strip, Sheet, Plate
AMS	4928	Ann. Bar and Forgings
AMS	4930	ELI Ann. Bar, Forgings, Rings
AMS	4934	STA Extrusions and Flash Welded Rings
AMS	4935	Ann. Extrusions and Flash Welded Rings
AMS	4954	Welding Wire
AMS	4956	ELI Welding Wire
AMS	4965	STA Bar, Forgings, Rings
AMS	4967	Ann. Heat Treatable Bar, Forgings, Rings
ASTM	B 265	Ann. Strip, Sheet, Plate
ASTM	B 348	Ann. Bar, Billet
ASTM	B 367	Castings
ASTM	B 381	Ann. Forgings
ASTM	B 382	Bare Welding Rods and Electrodes
ASTM	F 136	ELI for Surgical Implants
Military	MIL-T-9046 Std or ELI	Ann. or STA Strip, Sheet, Plate
Military	MIL-T-9047 Std or ELI	Ann. or STA Bar, Forging Stock
Military	MIL-T-46077	ELI Armor Plate
Military	MIL-T-81556 Std or ELI	Ann. or STA Extrusions
Military	MIL-F-83142 Std or ELI	Ann. or STA Forgings
British	T.A.10	Sheet, Strip
British	T.A.11	Bar
British	T.A.12	Forging Stock
British	T.A.13	Forgings
British	T.A.28	Fastener Rod
British	T.A.56	Plate
French	AIR 9183	Rod, Bar, Forgings
French	AIR 9184	Bolts
German	WL 3.7164 (sheet 1)	Sheet, Strip, Plate
German	WL 3.7164 (sheet 2)	Bar, Forgings
European	AECMA Ti P 63	Bar, Forgings, Ann. Sheet

* Use of latest revisions is recommended.

Ingot

Ingot is the beginning material from which all other TIMET products derive. A range of ingot sizes and weights are produced depending on application and alloy. Nominal ingot weights are typically from 7,000 lbs. (3,180 Kg) to 14,000 lbs. (6,365 Kg).

Bloom

Bloom is a semi-finished form of *TIMETAL* 6-4, forged above the α + β → β transformation temperature from an ingot. Except for ends, the surfaces are over-all coarse grit ground. Bloom may be produced from standard double melt grade, standard triple melt grade, rotating grade or premium grade. Exposed pipe is cropped for sizes over 12″. End enfoliations will have a height to depth ratio of 0.15 or less. Chemistry only is guaranteed.

Forging Billet and Bar

The distinction between TIMET billet and bar is made conveniently at four inch diameter or 16″ square inches (165,200 sq mm) for squares and rectangles, larger sizes being billet. Billet and bar in the form of rounds, squares and rectangles are available. Rectangle width to thickness ratio is limited to 5: 1 in thicknesses of two inches (51mm) or more and 10:1 otherwise. A special finish for immersion ultrasonic testing is available.

Forging billet and bar are supplied as hot worked or in the annealed condition for further forging. These products can be supplied as heat treated within the size limitations permitting heat treat response. The guaranteed annealed properties of *TIMETAL* 6-4 bar and billet are shown in *Table 3*.

These properties may be obtained in the bar or billet product without further forging in sizes up to five inches (127 mm) in the short transverse direction. When sections larger than that are to be used for further forging operations, a simulated forging acceptance test will be necessary to guarantee properties. The standard acceptance test types are:

TIMET Type I

Upset 2″ to 3/4″ (51 to 19mm) from 1750°F (955°C), anneal or heat treat and test.

TIMET Type II

Discontinued.

TIMET Type III

Test in condition to be supplied.

TIMET Type IV

Negotiated to meet special requirements.

In the case of billet larger than 22″ (560mm), a negotiated acceptance test may be used for the heat treat capability guarantee.

Table 4 shows the minimum guaranteed strength properties of STA *TIMETAL* 6-4 as these depend on size in bar and billet. The information presented here is pertinent to those situations where no further forging, only machining, is done to the mill product before it is put into use.

Because of the effect of oxygen on both annealed and aged strength, the foregoing guarantees apply to *TIMETAL* 6-4 in standard chemistry. For applications requiring higher heat treated strength, it is possible to use a slightly higher oxygen level. Such material is usable in the annealed condition. In situations requiring the very highest toughness, or when cryogenic temperatures are encountered, lower oxygen levels are recommended. This usually means *TIMETAL* 6-4 ELI. Relative to the standard grade, ELI provides significantly higher toughness at some sacrifice in strength. The property trade depends also on processing, heat treat-ment, and possibly hydrogen content. For all these reasons, inquiry is suggested for product forms and guarantees available in *TIMETAL* 6-4 ELI.

Billet macrostructure, microstructure and sonic guarantees, as described in AMS 2380, can be met. Inquiry is suggested if the user desires some other combination.

TABLE 3

TENSILE GUARANTEES FOR TIMETAL 6-4 BILLET

TEST TYPE III

Thickness		*Ftu*		*Fty*			
inches	*mm*	*ksi*	*MPa*	*ksi*	*MPa*	*El%*(1)	*RA%*(1)
			Rounds and Squares				
≥8	≥203	130	895	120	825	10	20
>8-12	>203-305	130	895	120	825	8	15
>12	>305	125	860	115	795	6	12
			Rectangles				
≥6	≥152	130	895	120	825	10	15
>6-8	>152-203	130(2)	895	120(2)	825	8	15
>18-12	>203-305	130(2)	860	120(2)	825	6	14

(1) LT direction

(2) Transverse only

TABLE 4

TENSILE GUARANTEES FOR TIMETAL 6-4 BILLET

TEST TYPE III

Thickness inches	Thickness mm	Ftu ksi	Ftu MPa	Fty ksi	Fty MPa	El-%(1)	RA-%(1)
Rounds and Squares							
>.5-1	>13-25	160	1105	150	1035	10	25
>1-1.5	>25-38	155	1070	145	1000	10	20
>1.5-2	>38-51	150	1035	140	965	6	12
>2-3	>51-76	140	965	130	895	10(8)(2)(3)	20(15)
Rectangle ≤ 4 in (102mm) width							
>0.5-1	≥13-25	155	1070	145	1000	10	20
>1-1.5	>25-38	150	1035	140	965	10	20
>1.5-2	>38-51	145	1000	135	930	10	20
>2-3	>51-76	135	930	125	860	10(8)	20(15)
Rectangle ≤ 10 in (254mm) width							
<0.5	<13	160	1105	150	1035	10	20
Rectangle > 4 to < 10 in (> 102 to < 254mm)							
>.5-1	>13-25	150	1035	140	965	10	20
>1-1.5	>25-38	145	1000	135	930	10	20
>1.5-2	38-51	140	965	130	895	10	20

(1) 1750°F WQ + 1000°F - 4 hr AC; 955°C WQ + 540°C - 4 hr AC

(2) Numbers in parentheses are for transverse direction.

(3) Width less than five times thickness.

TABLE 5

MECHANICAL PROPERTIES OF TIMETAL SHEET AND PLATE

	Sheet (Up to 0.187″)			*Plate (Over 0.187″)*	
	Annealed ksi (MPa)	*Solution Treated ksi (MPa)*	*Aged (1000°F-4 hr.) ksi (MPa)*	*Annealed ksi (MPa)*	*Aged (1000°F-4 hr.)*
Ftu					(3)
Guar. minimum	134 (925)		160 (1105)	130 (895)	
Typical	144 (990)	152 (1050)	168 (1160)	136 (940)	
Fty					(3)
Guar. minimum	126 (870)	145(1) (1000(1))	145(1) (1000(1))	120 (825)	
Typical	136 (940)	132 (910)	154 (1060)	128 (885)	
Elongation in 2″-%					
Guar. minimum					
<.026	8 (–)	≤.032 6 (–)	≤.032 4 (–)	All 10	to .75 8
.026 to .032	9 (–)	≤.032 8 (–)	>.032 to .049 5 (–)		.75 to 1 6
.032 & over	10 (–)		>.049 6 (–)		1 to 2 6
Typical					
<.026	10 (–)	≤.032 8 (–)	≤.032 6 (–)	All 16	to .75 12
.026 to .032	13 (–)	>.032 12 (–)	>.032 to .049 8 (–)		.75 to 1 10
over .032	14 (–)		>.049 9 (–)		1 to 2 10
Bond radius (R/T)					
Guar. minimum					
≤.070	4.5 (–)	≤.070 4.5 (–)	All 7.0 (–)	–	–
>.070	5.0 (–)	>.070 4.5 (–)		–	–

(1) Guaranteed maximum.

(2) Press-brake-105°.

(3) See Figure 8.

Sheet and Plate

These products are available as annealed, solution treated, or solution treated and aged. Properties are given in *Table 5* and *Figure 8.*

TIMETAL 6-4 alloy plate is available in thicknesses from 3/16 to 4″ (4.8 to 102mm), in widths up to 420″ (3.05m) and in lengths up to 420″ (10.67m). Not all these maxima are available simultaneously. Beginning ingot size is limited to a maximum of about 15,000 pounds (6800 kg). Plate width is 10″ (254mm) minimum and five times the thickness otherwise. Plate is normally supplied in the annealed, descaled and pickled condition. Polished plate required for special forming requirements can be supplied on request. Vacuum creep flattened plate is also available.

The distinction between plate and sheet is made at 3/16″ (4.8mm), thinner gauges being sheet. The standard sheet thickness minimum is 0.016″ (.41mm). Inquiry is suggested if thinner gauges are required. Sheet widths are available up to 48″ (1220mm). Cut lengths beyond 192″ (4880mm) are not standard; inquiry is suggested in such cases. Finish grinding on both sides is standard procedure.

Titanium-base alloy *TIMETAL* 6-4 is characterized as an alpha rich alpha-beta composition. The particular aluminum-vanadium balance provides attractive annealed strength, as well as heat treat response. Aluminum increases the allotropic transformation temperature of titanium. The six percent level is sufficient to markedly strengthen the low temperature alpha phase by solid solution, yet is not so high that embrittlement results. Vanadium stabilizes the high temperature beta phase which is manifest by a reduction of the allotropic transformation temperature. The four percent vanadium level exceeds the alpha solubility limit at all temperatures. This has the effect of stabilizing a small amount of beta to room temperature. Using rapid cooling rates from the solution temperature range permits age hardening of the retained or transformed beta through precipitation.

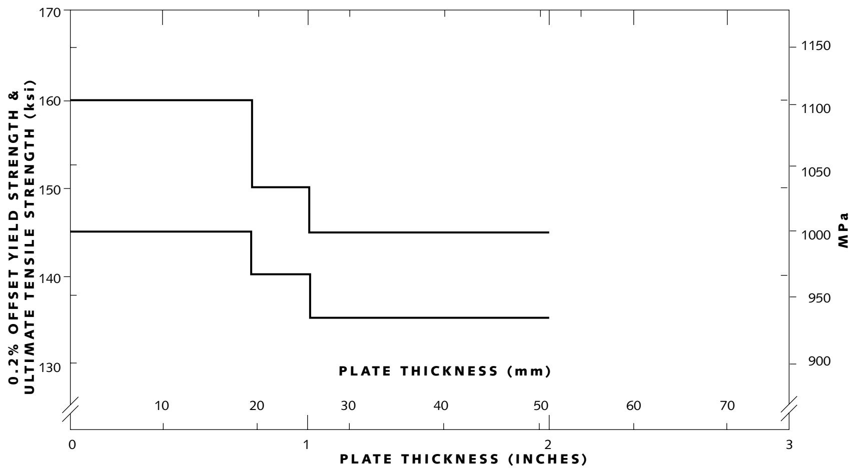
Although *TIMETAL* 6-4 is effectively heat treated by the classical solution treat and age procedure, the strengthening mechanism in *TIMETAL* 6-4 differs markedly in detail from that operative in most hardenable aluminum alloys and precipitation hardening steels. Whereas those materials precipitate submicroscopic compounds coherent with the matrix, *TIMETAL* 6-4 precipitates alpha incoherent with the beta matrix. *TIMETAL* 6-4 age hardens in a manner much like the 7000 series aluminum alloys given a T7 temper. Ti$_3$Al, a long-range ordered phase sharing the same basic crystallographic system as alpha, also may precipitate in the alpha phase. Ti$_3$Al differs basically from alpha in that every other atom in every other row in the basal plane is aluminum.

The strengthening effect from Ti$_3$Al precipitation is on the order of 5 ksi (35 MPa) and is usually accompanied by some loss in toughness and environmental resistance.

A further feature of the aging response in *TIMETAL* 6-4 is that synergistic effects are evident from the existence of two phases. That is, for identical compositions and solution treatment, there is a microstructural effect apparent in the aging response.

FIGURE 8

GUARANTEED STRENGTH LEVEL VERSUS GAUGE OF AGED TIMETAL 6-4 PLATE



Martensite occurs in *TIMETAL* 6-4 and other titanium alloys and is quite soft. Its decomposition to alpha plus beta during aging is associated with net strengthening, although the mechanism details are not well established.

The ultimate strength of annealed standard grade *TIMETAL* 6-4 is above 130 ksi (895 MPa). Most of this strength arises from aluminum and interstitials in solid solution. Vanadium contributes to strength mainly by stabilizing small amounts of beta phase which, when properly dispersed and age hardened, leads to net strengthening. This effect, however, is ordinarily not obtainable in thick sections and in most cases is small relative to what can be achieved through heat treatment. Vanadium also contributes some strengthening of the alpha phase through solid solution. Aluminum strengthens the alpha phase similarly.

The alpha stabilizing interstitials, oxygen, nitrogen and carbon, as well as the beta stabilizing interstitial, hydrogen, also play important roles in the metallurgy of *TIMETAL* 6-4. They all provide strength increases, but otherwise their effects on properties are largely negative. Oxygen content is varied in commercial practice depending on whether the end use is strength or toughness critical. Hydrogen can be removed by vacuum annealing at temperatures high enough to dissolve residual surface oxide films. Otherwise, surface cleanliness is crucial to vacuum degassing.

Finally, the flow stress for *TIMETAL* 6-4 depends on crystallographic texture. The reason for this is that the principal slip directions in alpha lie normal to the prism axis. Deformation parallel to the prism axis is simply more difficult to activate.

Nevertheless, information on *TIMETAL* 6-4 is so extensive that one can often predict with good accuracy the behavior of the alloy in a new application simply from prior experience.

TIMETAL 6-4 may be prepared for metallography by either mechanical polishing or electropolishing. A satisfactory general purpose etchant is 1%HF-12%HNO_3 balance water. If a more active etchant is desired, the HNO_3 content may be reduced to as little as 3%. Krolls Etch is the term most often used for these etchants.

Figure 9 illustrates the microstructure resulting from a typical solution treat and age heat treatment.

Microstructures resulting from various heat treatments are shown in *Figure 10*. Note the dramatic effects of heating temperatures and cooling rates. Water quenching from 1850°F (1010°C) or above produces martensite-like microstructures devoid of any primary alpha. Water quenching from 1800°F (982°C) produces a similar microstructure except that primary alpha (alpha existing at temperature) appears scattered throughout the transformed matrix. The nominal $\alpha + \beta \rightarrow \beta$ transformation temperature for the material used to develop *Figure 10* was 1820°F (993°C).

As cooling rate decreases, the transformed structure coarsens. After air cooling, the alpha platelets have a finite width and these are coarser still after cooling encapsulated in containers. After very slow cooling, the alpha plates are coarse indeed. For all but perhaps the fastest cooling rates, *TIMETAL* 6-4 transforms by nucleation and diffusion governed growth processes.

A fast cool must be used to fix the primary alpha content. This is because the primary alpha grains serve as sites for alpha regrowth during cooling. This is most dramatically seen in the *Figure 10* series of micrographs showing cooling rate effects from 1800°F (982°C). Therefore, the apparent fraction of primary alpha present in a sample does not necessarily fix the temperature from which cooling began. One must also know the cooling rate.

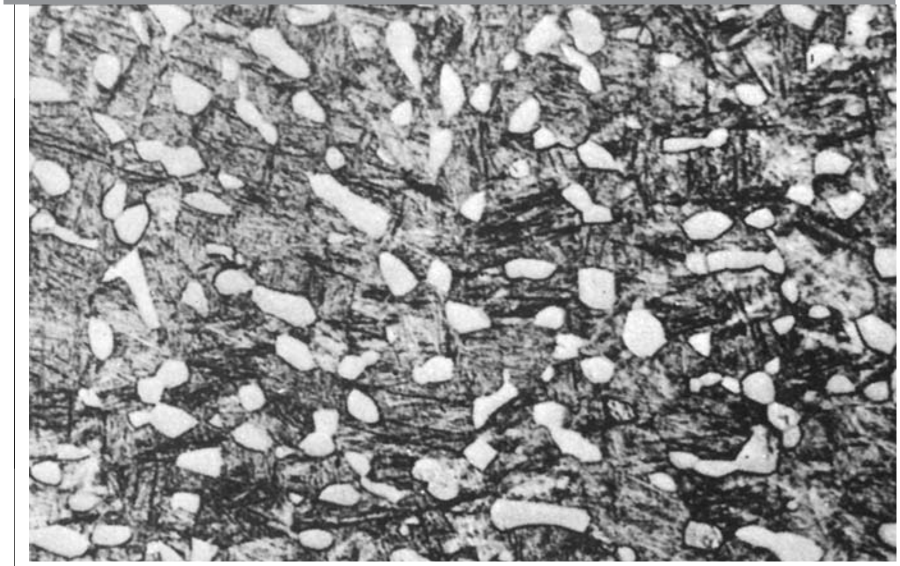
The micrographs for the encapsulated cool series render the effect of temperature on the microstructure for that particular cooling rate. Cooling rate of 1450°F (788°C) has no obvious effect on the microstructures. At higher temperatures, the amount of primary alpha is observed to decrease with increasing temperature.

Aging does not significantly change these microstructures at the usual optical magnifications.

Omega phase rarely occurs in *TIMETAL* 6-4. Ti_3Al may be present but is not observable by ordinary optical techniques.

FIGURE 9

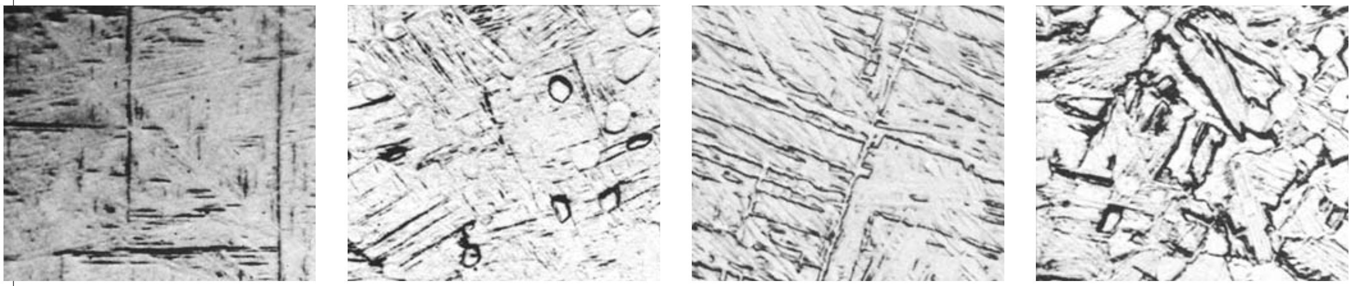
TYPICAL STA MICROSTRUCTURE FOR THIN SECTION TIMETAL 6-4



1750°F = 2hr WQ + 1100°F-2 hr AC (955°C WQ + 595°C-2 hr AC)

FIGURE 10

EFFECT OF HEATING TEMPERATURES AND COOLING RATES ON MICROSTRUCTURES OF TIMETAL 6-4

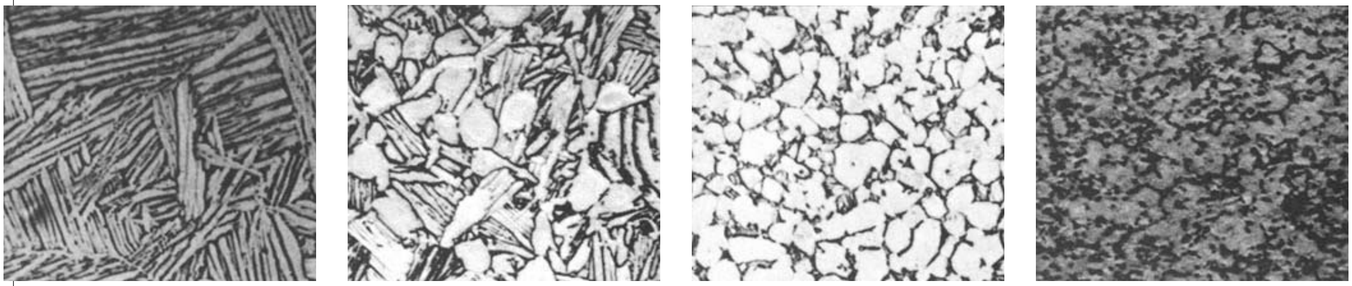


A. 1850°F (1010°C) 1hr. WQ
500x

B. 1800°F (982°C) 1hr. WQ
500x

C. 1850°F (1010°C) 1hr. AC
500x

D. 1800°F (982°C) 1hr. AC
500x

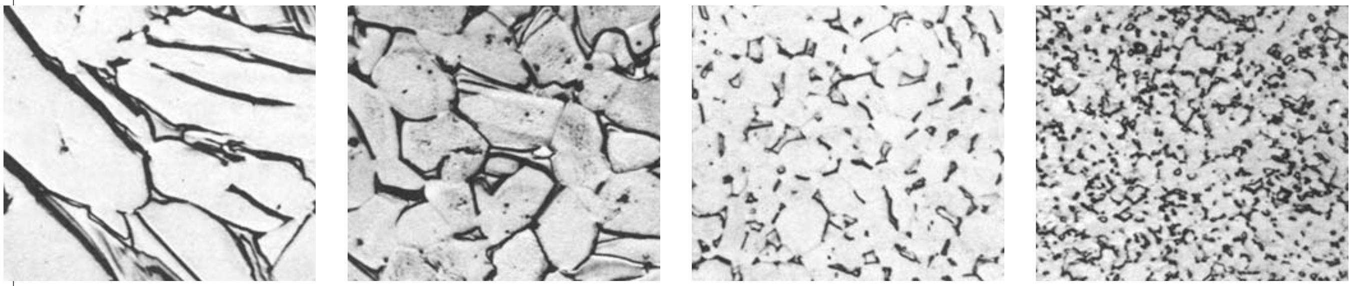


E. 1850°F (1010°C) 1hr.
Encapsulated Cool 500x

F. 1800°F (982°C) 1hr.
Encapsulated Cool 500x

G. 1700°F (927°C) 1hr.
Encapsulated Cool 500x

H. 1450°F (927°C) 1hr.
Encapsulated Cool 500x



I. 1850°F (1010°C) 1hr.
Very Slow Cool 500x

J. 1800°F (982°C) 1hr.
Very Slow Cool 500x

K. 1700°F (927°C) 1hr.
Very Slow Cool 500x

L. 1450°F (788°C) 1hr.
Very Slow Cool 500x

Heating temperatures and cooling rates have dramatic effects on the microstructure of *TIMETAL* 6-4. Cooling from the beta region, 1850°F (1010°C), produces 100% transformed structures. The fraction of primary alpha increases as the heating temperature descends into the alpha + beta phase field, below the transformation temperature (solvus) at 1820°F (993°C). As cooling rates decrease, the transformed structures coarsen and regrowth occurs. Regrowth can increase the apparent primary alpha content. Water quenching thin sections is necessary to fix the actual alpha content at temperature.

Note: Structures obtained after heating at 1800°F or below are obtained from material which has been processed in the alpha + beta field.

TABLE 6

TYPICAL HEAT TREATMENTS FOR TIMETAL 6-4

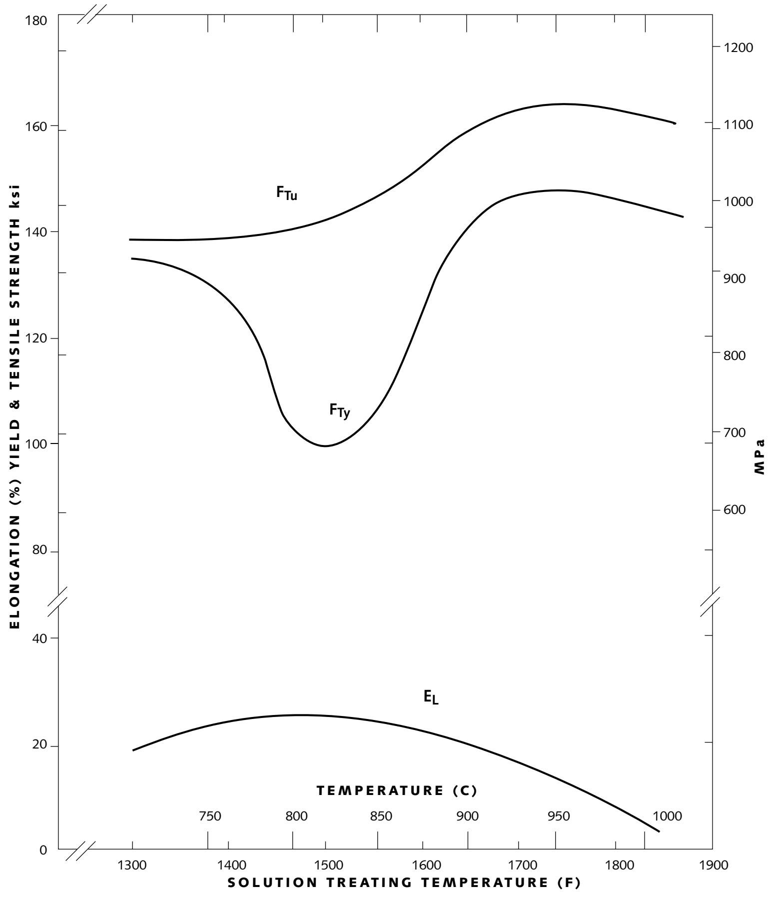
Product Form	*Annealing*(1)	*Solution Treating*(2)	*Aging*(2)
Sheet and light plate	1350° ± 25°F (730° ± 15°C) 1/2-4 hrs AC	1660° to 1700°F (905° to 925°C) 5 to 10 min WQ	1000°F-4 hrs AC (540°C)
Plate over 1/4 in. (6.4mm)	1350° ± 25°F (730° ± 15°C) 1/2-4 hrs AC	1700° to 1750°F (925° to 955°C) 1/2 hr WQ	1000°F-4 hrs AC (540°C)
Bar, Forgings	1350° ± 25°F (730° ± 15°C) 1/2-4 hrs AC	1750° ± 25°F (955° ± 15°C) 2 hr WQ	1000°F-4 hrs AC (540°C)

(1) Temperatures up to 1500°F (815°C) may be used provided a protective atmosphere is used. Any contamination resulting from annealing must be removed.

(2) Solution treating and aging cycles may be varied slightly from those listed for specific applications.

FIGURE 11

EFFECT OF SOLUTION TREATMENT TEMPERATURE ON THE SOLUTION TREATED TENSILE PROPERTIES OF TIMETAL 6-4



TIMETAL 6-4 provides attractive properties in both the annealed and heat treated conditions. The various recommended heat treatments are summarized in *Table 6*.

Solution Treating

Solution treating is affected by heating between 50° and 250°F (30° to 140°C) below the $\alpha + \beta \rightarrow \beta$ transformation temperature and immediately water quenching. The closer the solution temperature is to the transformation temperature, the greater is the amount of beta present at temperature. At temperatures above approximately 1550°F (845°C) the beta is not retained on quenching to room temperature. It is usual, therefore, for the beta present at solution temperature above 1550°F (845°C) to transform to martensite if the quench is fast enough or to "Widmanstatten" alpha plus beta if the quench is slower. The metallographic distinction between the two modes of transformation is subtle at critical quench rates. It is good practice to use x-ray or transmission electron microscopy if one needs to establish definitely which transformation mode is operative. The effect of solution temperature on tensile properties and aging response is shown in *Figures 11* and *12*.

Solution Annealing

Solution treatment temperature and cooling procedures influence toughness. Solution annealing in the beta field provides the highest plane-strain toughness capability. Crack tortuosity as the crack propagates through the transformed microstructure gives rise to this high toughness. By the same token, time to fatigue crack initiation is reduced by beta annealing.

Solution annealing above 1550°F (845°C) but below the $\alpha + \beta \rightarrow \beta$ transformation temperature adds the element of solute partitioning, whereby the primary alpha is somewhat enriched in aluminum and oxygen, and the beta is enriched in vanadium. Upon slow cooling, a toughened background of continuous regrowth alpha isolates the enriched, and rather less tough, primary alpha. *Figure 10* illustrates such microstructures. The result is a good combination of strength, ductility and toughness. Furnace cooling from this temperature range produces a so-called "recrystallized" microstructure. The microstructure is recrystallized in the sense that each phase is essentially dislocation free. If the starting microstructure is equiaxed, the "recrystallized" microstructure will be also. Given sufficient prior α + β work, a "recrystallization" anneal will produce equiaxed microstructures.

When high toughness is required and a recrystallization anneal is impractical, a high α + β anneal may be used. The element of solute partitioning is still there. The continuous background of transformed beta provides a degree of crack tortuosity and enhances toughness.

TIMETAL 6-4 reacts with the atmosphere when solution treated in air. See the following sections on Heat Treat Strategy and Fabrication Characteristics for cleanup information.

Aging

Aging treatments consist of exposures to temperatures from 900° to 1100°F (480° to 590°C) from 1 to 24 hours. The lower temperatures provide higher strengths.

Several things happen during aging:

1. Any metastable beta precipitate alpha.
2. Any martensite will decompose to alpha and beta.
3. The alpha present may precipitate Ti_3Al.

Below 1000°F (540°C), extending the aging times beyond those needed to achieve full strength has little further effect on strength.

Stress Relieving

In general, stress relief is accomplished after eight hours at 1200°F (650°C). If full stress relief is not required, lower temperatures can be used. Some lower temperature and time effects are illustrated in *Figure 13*. Stress relieving in fixtures to remove springback or warpage is common practice.

Annealing

All product forms of *TIMETAL* 6-4 can be annealed at temperatures from 1225° to 1600°F (660° to 870°C) in one-half to four hours. Cooling rates can be air cool or slower. Typical annealed microstructures for *TIMETAL* 6-4 sheet are similar to those shown in *Figure 10* for 1450°F (688°C).

Heat Treat Strategy

The choice of heat treatment depends on many factors. Section size and desired property mix are the main constraints. Sections greater than four inches do not effectively respond to solution treat and age (STA) type of heat treatment. Time delays in

FIGURE 12

EFFECT OF SOLUTION TREATMENT TEMPERATURE ON THE STA PROPERTIES OF TIMETAL 6-4 AGED AT 1000F (517C), 4 HR, AC

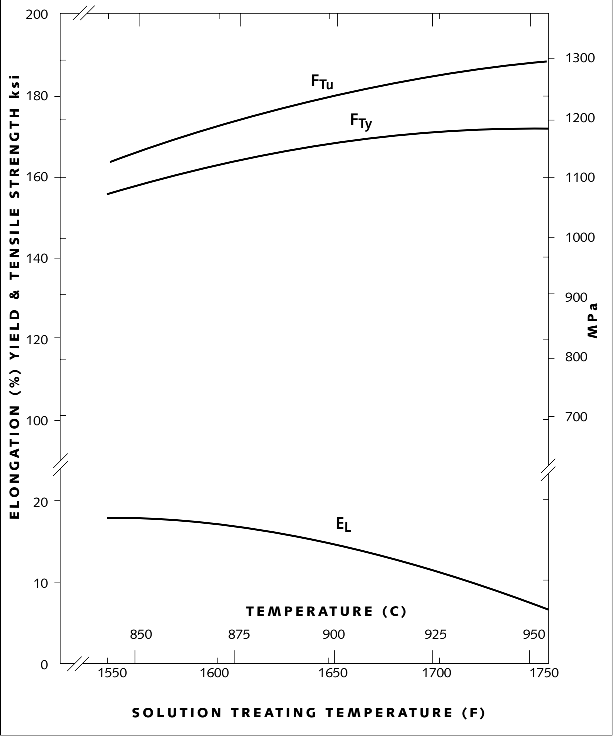
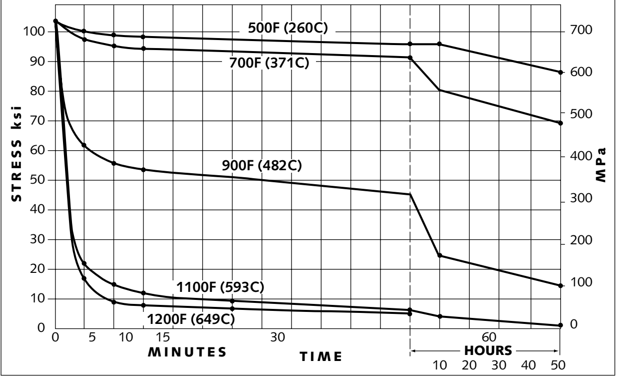


FIGURE 13

RELIEF OF RESIDUAL STRESS VERSUS TIME FOR TIMETAL 6-4

(REF. 6)



quenching can significantly degrade aged strength. This feature is shown in *Figure 14. Figure 15* illustrates the section size effect. Quench type heat treatments can lead to warpage depending on part configuration.

Because *TIMETAL* 6-4 is based on the reactive metal titanium, it oxidizes significantly at solution treating temperatures. Solution times and temperatures should, therefore, be minimized consistent with temperature equilibration and response to aging. The thinner the section, the more important oxidation becomes. Solution annealing is best done in vacuum.

Hydrogen pickup is another reason for limiting solution time and temperature. At solution temperatures, titanium and its alloys readily react with water vapor to form titanium dioxide. Hydrogen is liberated in the process and is largely absorbed in the metal. The less massive the section being treated, the more important this becomes.

Surface conditioning after solution treatment to remove any alpha case is critical. Any procedure must remove enough surface to expose uncontaminated metal. Surface contamination is not always visible macroscopically. *Figure 16* shows photomicrographs of contaminated surfaces.

Aging presents less cleanup difficulty; a light pickle suffices. Pickling solutions contain 2-5 percent HF and 15-35 percent HNO_3 at an approximate ratio of 1:7. HNO_3 tends to inhibit hydrogen absorption and brighten the metal. These subjects are discussed further under Fabrication Characteristics.

Microstructures to be avoided in most cases are grain boundary and blocky alpha. These features appear in *Figure 17*. Grain boundary and blocky alpha develop on slow cooling through the $\beta \rightarrow \alpha + \beta$ transformation temperature. Such alpha does not spheroidize during heating to the $\alpha + \beta$ field. Grain boundary and blocky alpha result in loss of ductility. It is evident from *Figure 17* that strain induced porosity is associated with blocky and grain boundary alpha.

Applications of *TIMETAL* 6-4 in the aerospace industry are becoming more

FIGURE 14

EFFECT OF QUENCH DELAY ON TENSILE PROPERTIES OF TIMETAL 6-4 1/2" (13MM) BAR

SOLUTION TREATED 1759F (955C), 1 HR WQ, AGED 900F (480C), 6 HR, AC

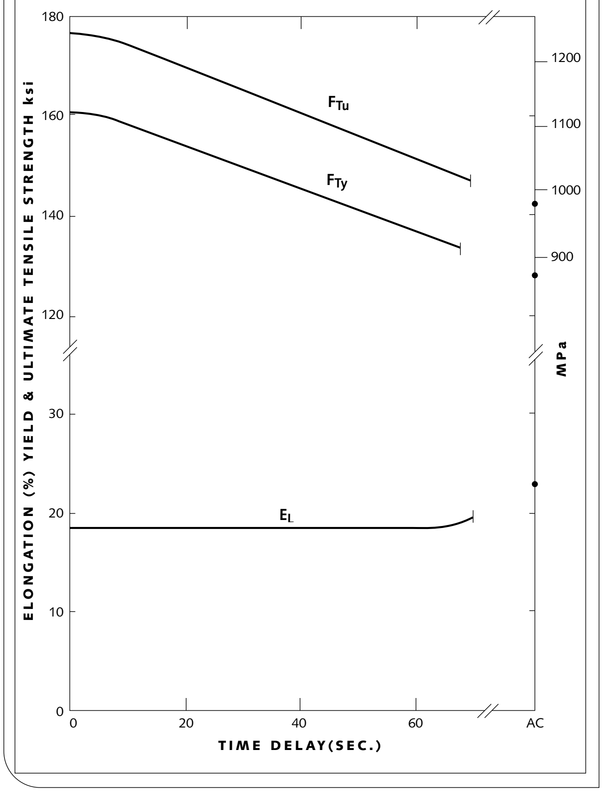
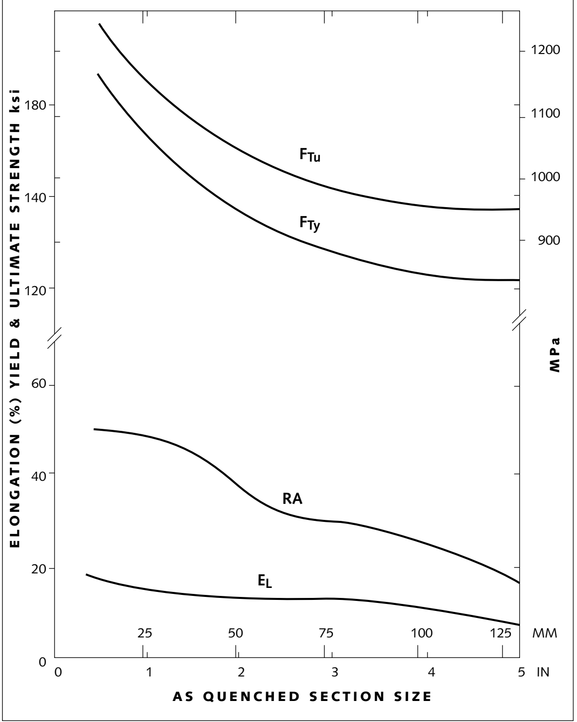


FIGURE 15

EFFECT OF QUENCHED SECTION SIZE ON THE TENSILE PROPERTIES OF STA TIMETAL 6-4



and more sophisticated. Not only is the alloy structurally efficient but its intrinsic resistance to corrosion practically eliminates maintenance in most environments. Also, *TIMETAL* 6-4 can be mated with most aerospace structural materials, including composites. See "Other Environments" for situations to be avoided (page 23).

The following brief data summary is cross referenced to more complete sources of information.

General Information Sources

The titanium material property handbook(39) contains significant amounts of information on *TIMETAL* 6-4. Other useful sources include the metals handbook(7) and the MIL-HDBK-5(8). The latter is of special significance because it provides design allowables presented on the following bases:

A Basis

The A mechanical property value is the value above which at least 99 percent of the population of values is expected to fall with a confidence of 95 percent.

B Basis

The B mechanical property value is the value above which at least 90 percent of the population of values is expected to fall with a confidence of 95 percent.

S Basis

The S mechanical value is the minimum value specified by the governing Federal (QQ), Military (MIL), or Aerospace Material Specification (AMS).

Typical Basis

The typical property value is an average value. No statistical assurance is associated with this value.

The A and B values in MIL-HDBK-5 are statistically determined in accordance with Chapter 9, "Guidelines for the Presentation of Data." In many cases, it is possible to calculate alternate design allowables of one's own choosing. However, it is conventional to use A and B values. Calculation of alternate allowables should not be

FIGURE 16

ALPHA CASE ARISING FROM OXIDATION

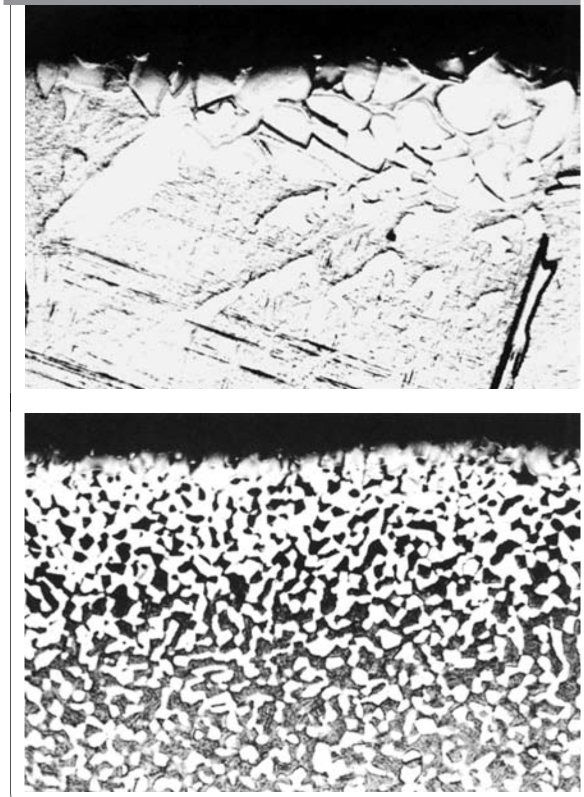


FIGURE 17

BLOCKY ALPHA WITH GRAIN BOUNDARY ALPHA DECORATING PRIOR BETA GRAIN BOUNDARIES

Note strain porosity associated with both types of alpha. Background is transformed beta.

FIGURE 18

MOLULUS OF ELASTICITY AT LOW AND ELEVATED TEMPERATURES FOR ANNEALED SHEET

(REF. 15-17)

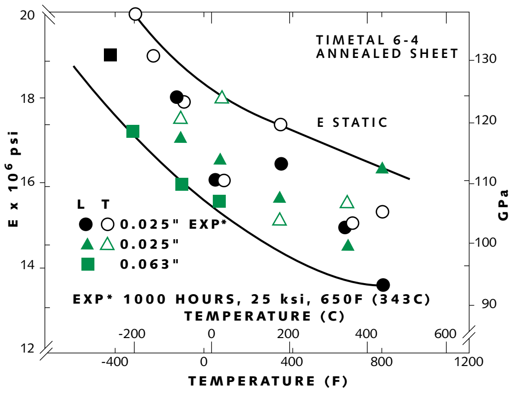


FIGURE 19

SPREAD OF ELASTIC MODULUS AT ROOM AND ELEVATED TEMPERATURE FOR EIGHT HEATS OF AGED SHEET

(REF. 20)

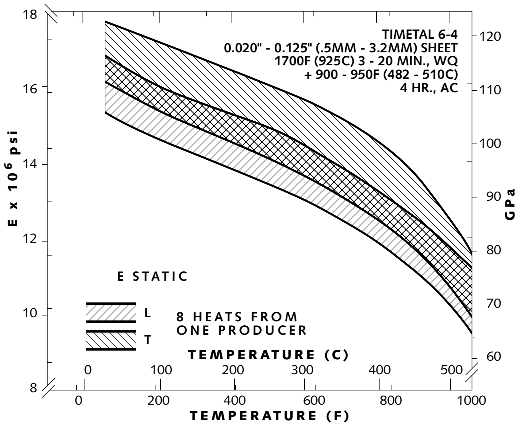
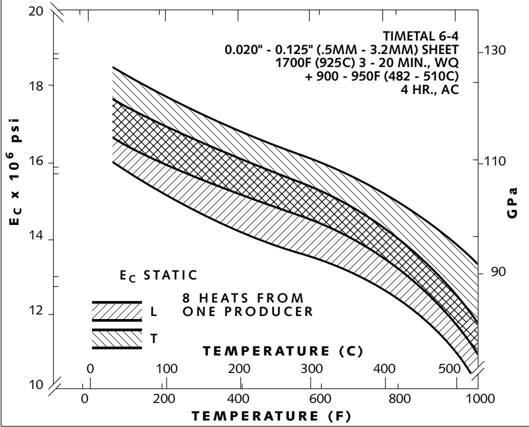


FIGURE 20

SPREAD OF ELASTIC COMPRESSIVE MODULUS AT ROOM TEMPERATURE AND ELEVATED TEMPERATURE FOR EIGHT HEATS OF AGED SHEET

(REF. 20)



undertaken without consulting the authors of the design properties of interest, as well as a competent statistician. (See appendix for MIL-T Specifications.)

That *TIMETAL* 6-4 has been so widely and successfully used is a testimony to its broad "forgiveness" as a structural metal. In the event that the prospective designer finds his needs are not met by consulting the handbooks, the Technical Services staff of TIMET can be contacted at the General Office for appropriate assistance. See back cover.

Specifications

There are a number of broadly applicable specifications covering the use of *TIMETAL* 6-4. In addition, a large number of organizations engaged in aerospace activities have developed their own specifications to fit a variety of specific needs. Some of the former are listed in *Table 2*.

This section serves several purposes. One is to acquaint the potential user with *TIMETAL* 6-4 in a general way. Another is to provide enough in-depth information to avoid certain recognized pitfalls in the process of designing to new highs in efficiency. Toward the first end, typical data are presented for several properties. Some potential pitfalls are discussed in the course of that development. Finally, there is a discussion of how several properties depend on the underlying metallurgy.

Modulus and Related Quantities

Tensile modulus depends strongly on crystallographic texture in both alpha and beta titanium. It also depends upon heat treatment. The temperature effect on an annealed sheet is illustrated in *Figure 18*. Also shown are the effects from thermal exposure.

Texture dependent directional effects in sheet are presented in *Figure 19*. Compressive moduli are shown in *Figure 20* where scatter again is largely due to texture and heat treatment effects.

The shear modulus at room temperature also depends on test direction. One reference gives 6.2×10^6 psi (43×10^3 MPa at room temperature.(8) Another reference(17) gives 6.66×10^6 psi (45.9×10^3 MPa) for the shear modulus. The variation may be due to texture.

Poisson's ratio depends on material texture and measurement directions. Ten observations at TIMET, using a two element rosette strain gauge, gave a mean value of 0.342 with a range of observations from 0.287 to 0.391(18). A further reference gives a single value of 0.31(8).

Internal Friction and Modulus Defects

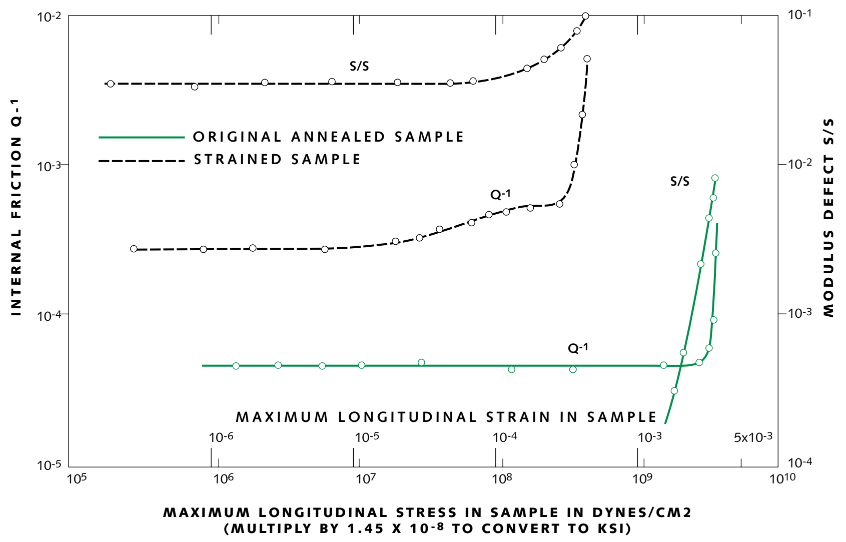
At low amplitudes, the internal friction Q^{-1} has been found in one investigation to be independent of frequency from 17 KHz to 10 MHz(19). Internal friction at low amplitudes is also relatively independent of temperature (within about 30 percent) from -452° to 621° F (-269° to 327°C). There may be an impurity-type peak at -135°F (-93°C). The internal friction Q^{-1} of annealed *TIMETAL* 6-4 has the low value of 4×10^{-3}. High amplitude measurements show that the internal friction is constant up to longitudinal strains of about 4×10^{-3}. Instability sets in at higher strains. *Figure 21* illustrates the internal friction Q^{-1} and the modulus defect $\Delta S/S$ as a function of maximum longitudinal stress(19).

The authors reported neither the texture nor test direction with respect to the material processing sequence. However, since internal friction is direction dependent in textured *TIMETAL* 6-4, these results may not be typical of all products.

FIGURE 21

TYPICAL INTERNAL FRICTION AND MODULUS DEFECT FOR AN ANNEALED SAMPLE OF THE ALLOY TIMETAL 6-4.

DASHED LINES SHOW THE RESULTS OBTAINED AFTER THE SAMPLE HAS BECOME UNSTABLE (REF. 19)



Tensile and Notch Tensile Properties

Table 7 shows typical tensile and notch tensile properties of 0.25″ plate as they depend on alloy oxygen content and test temperature. Note the excellent efficiency in the presence of a K_t = 6.7 notch. For the annealed condition, *TIMETAL* 6-4 retains its excellent ductility to liquid nitrogen temperatures. Both tensile and notch tensile properties of *TIMETAL* 6-4 may be directional if the hot work done below the transformation temperature has been unidirectional. When such processing cannot be avoided tensile strength in the transverse direction is typically high.

Figures 22 and *23* show the effects of alloyed oxygen and temperature on the tensile and notch tensile properties of *TIMETAL* 6-4 sheet. *TIMETAL* 6-4 ELI is to be recommended for service below -320°F (-196°C). Caution should be exercised when designing pressure vessels to contain hydrogen. High hydrogen pressure can lead to embrittlement(14).

In general, the effect of temperature on strength will trend as shown in *Figures 24* and *25*. The slightly flatter region between about 400° and 800°F (205° and 425°C) is thought to be caused in part by dynamic strain aging. Temperature affects bearing and shear values in an analogous way.

TABLE 7

TYPICAL TENSILE AND NOTCH TENSILE PROPERTIES OF TIMETAL 6-4, 1/4" (6.4MM) PLATE AT VARIOUS TEMPERATURE AND AT TWO OXYGEN LEVELS

Oxygen Content	*Test-Temp*		*UTS(1)*		*YS 0.2%*		*El*	*RA*	*NTS(2) K_t = 6.7*		
%	*°F*	*°C*	*ksi*	*MPa*	*ksi*	*MPa*	*%*	*%*	*ksi*	*MPa*	*NTS/UTS*
0.08	-320	-196	211	1455	201	1385	19	44	273	1880	1.29
0.08	-110	79	159	1095	152	1050	20	38	222	1530	1.40
0.08	RT	RT	134	925	126	870	21	44	201	1385	1.50
0.16	-320	-196	230	1585	216	1490	21	36	245	1690	1.07
0.16	-110	-79	177	1220	168	1160	24	35	220	1515	1.24
0.16	RT	RT	151	1040	143	985	21	42	209	1440	1.38
0.08	-320	-196	251	1730	236	1625	2	8	270	1860	1.08
0.08	-110	-79	194	1340	183	1260	16	46	240	1655	1.24
0.08	RT	RT	166	1145	153	1055	18	57	226	1560	1.36
0.08	340	171	142	980	123	850	18	66	214	1475	1.51
0.08	400	204	123	850	100	690	17	69	–	–	–
0.16	-320	-196	269	1855	251	1730	4	6	246	1695	0.91
0.16	-110	-79	212	1460	197	1360	12	29	230	1585	1.08
0.16	RT	RT	182	1255	169	1165	14	45	222	1530	1.22
0.16	340	171	156	1075	134	925	17	56	225	1550	1.44
0.16	800	427	132	910	102	705	16	67	–	–	–

(1) Smooth tensiles were 1/8″ dia. (3.2mm) x 112″ (12.7mm) gauge length.

(2) Notched tensiles were 0.133″ (3.4mm) notch diameter.

(3) 1725°F (940°C),1/2 hr WQ + 1000°F (540°C), 4 hr AC.

FIGURE 22

EFFECT OF OXYGEN CONTENT ON THE ROOM AND CRYOGENIC SMOOTH AND NOTCHED (KT=6.3) TENSILE PROPERTIES OF TIMETAL 6-4 SHEET

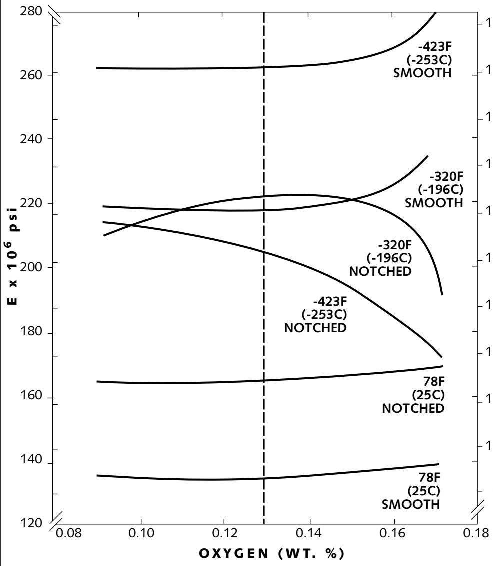


FIGURE 23

EFFECTS OF TEMPERATURE ON THE CRYOGENIC BEHAVIOR OF TIMETAL 6-4 ELI SHEET

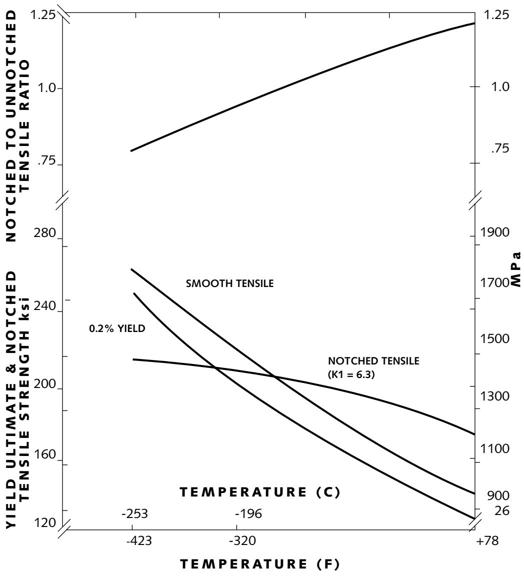


FIGURE 24

SPREAD OF TENSILE TEST DATA AT ROOM AND ELEVATED TEMPERATURES FOR ANNEALED SHEET AND BAR

(REF. 10, 21)

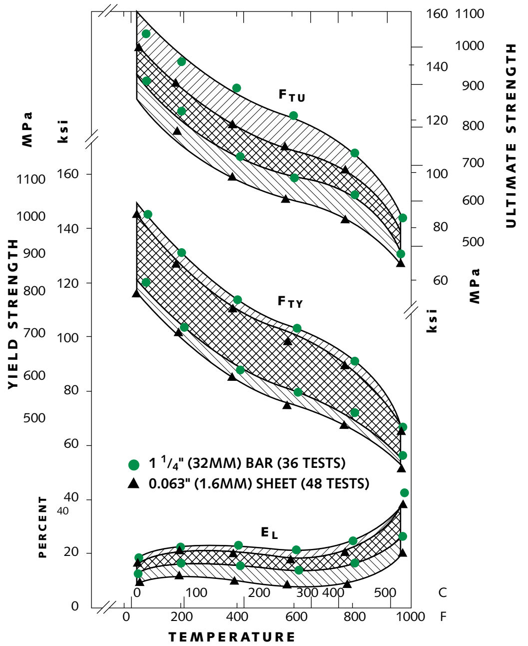
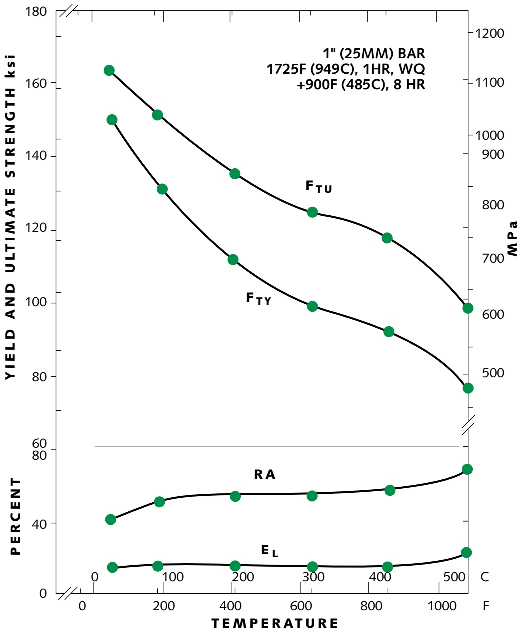


FIGURE 25

EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF AGED BAR

(REF. 22)



Charpy Impact Energy Absorption

Impact resistance of *TIMETAL* 6-4 depends inversely on strength and alloy interstitial content. The alloy exhibits good Charpy V-notch impact energy absorption as *Figure 26* shows. Note the absence of sharp transition behavior. Charpy impact energy absorption is a directional property.

Tangent Moduli

Typical tangent moduli are given in *Figure 27* for *TIMETAL* 6-4 annealed bar, at several temperatures. Again, while other product forms may differ somewhat in detail, *Figure 27* is illustrative of trends with temperature.

Creep and Stress Rupture Properties

Typical creep and stress rupture properties on bar are presented in *Figure 28*. A NOTE OF CAUTION: if one needs to extrapolate short time creep or rupture data to long time, it is generally unwise to employ any of the usual stress-time-temperature parameters such as Larson-Miller. It is better practice to establish the strain-time law for the stress and

FIGURE 26

EFFECT OF TEMPERATURE ON THE CHARPY V-NOTCHED IMPACT ENERGY ABSORPTION OF ANNEALED AND STA SHEET AND BAR

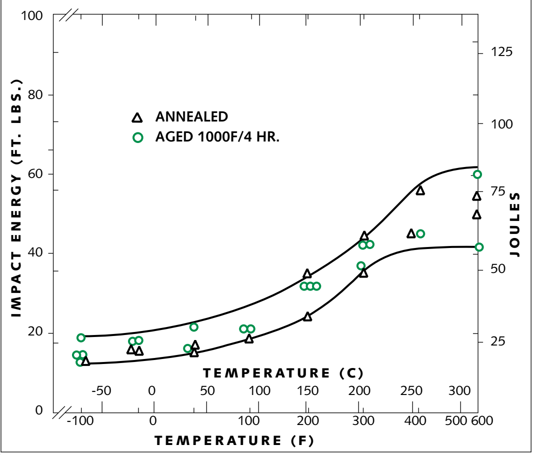
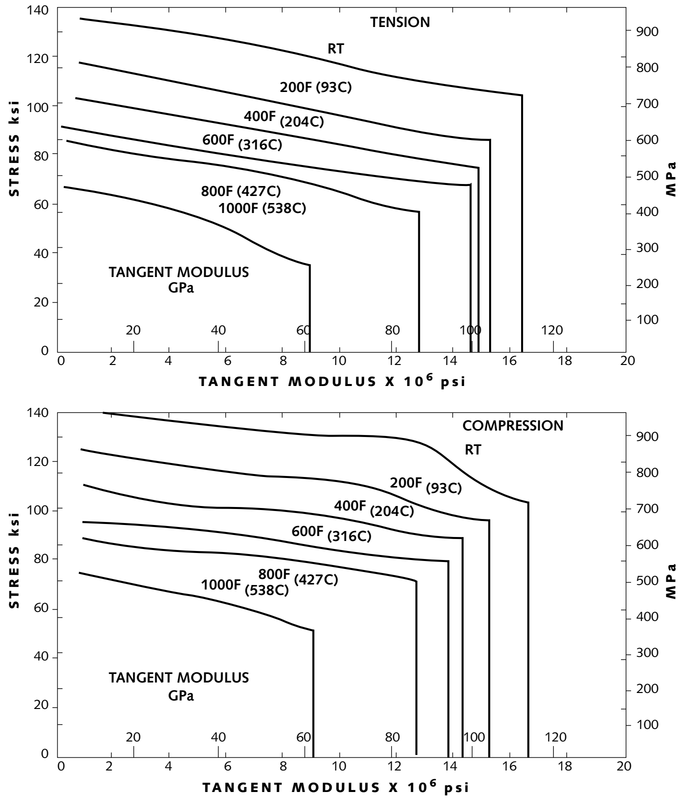


FIGURE 27

TYPICAL TANGENT MODULUS CURVES FOR ANNEALED TIMETAL 6-4



temperature of interest and develop design values by statistical means. One important reason for this is that creep mechanisms change with temperature, strain rate and possibly with strain and texture. Another reason is that the strain-time laws for creep can be nonlinear; the commonly observed steady state region may never appear. If one does employ a Larson-Miller or similar function to extrapolate creep data, it is good practice to determine the material constants for the product to be actually used by least squares or other acceptable means.

Creep Stability

Typical results are given in *Table 8*. Strength and ductility remain excellent after thermal stress exposure at temperatures to 850°F (455°C) and times to 1000 hours.

FIGURE 28

TYPICAL 100 HOUR CREEP AND RUPTURE STRESS VERSUS TEMPERATURE OF STA TIMETAL 6-4

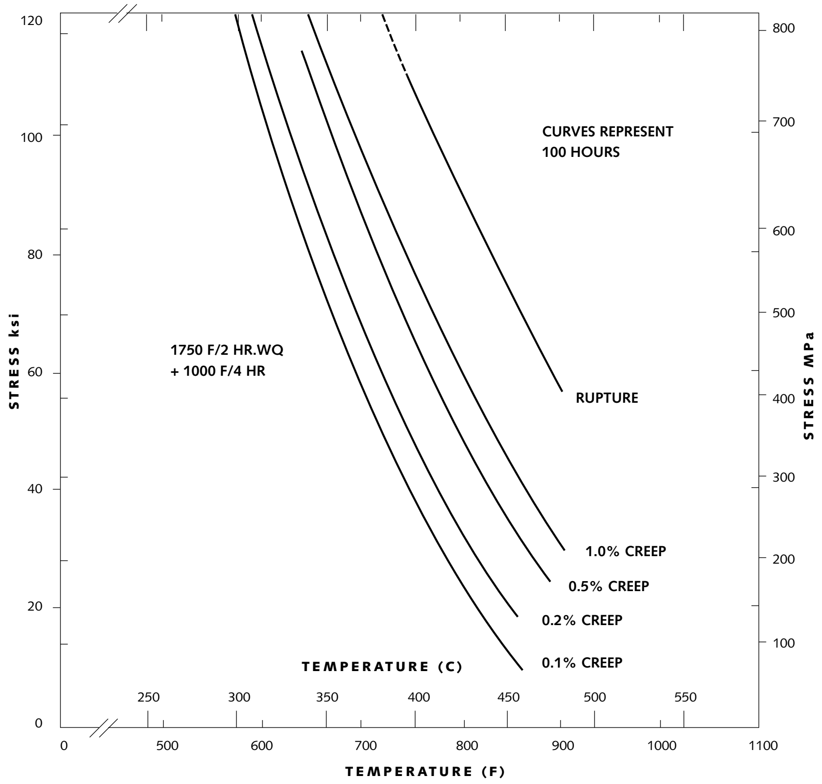


TABLE 8

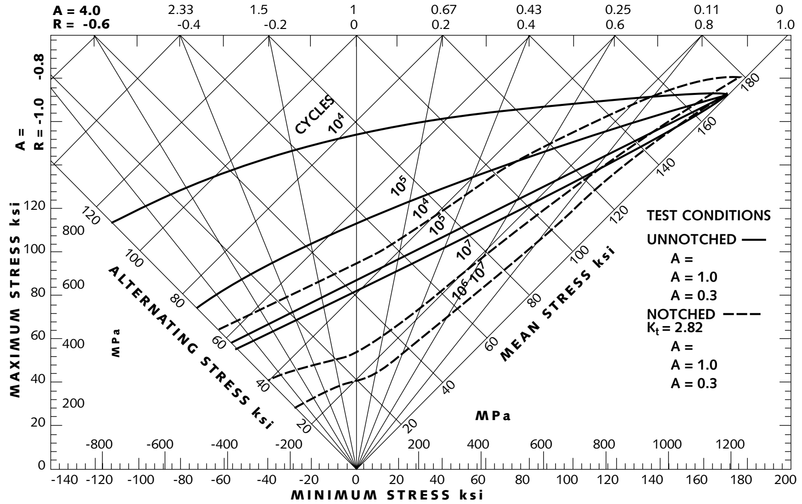
TYPICAL CREEP EXPOSED PROPERTIES FOR TIMETAL 6-4

		As Exposed Properties					
	Testing	UTS		0.2% YS		EL	RA
Test Condition	*Time Hr.*	*ksi*	*MPa*	*ksi*	*MPa*	*%*	*%*
Unstressed, 70°F (21°C)	–	134	925	124	855	20	42
Stress-50 ksi (345 MPa)	16	142	980	125	860	18	49
Temperature 650°F (343°C)	100	155	1070	133	915	15	44
	300	149	1025	133	915	18	40
	1000	149	1025	130	895	13	41
Stress-50 ksi (345 MPa)	16	146	1005	130	895	16	43
Temperature 750°F (399°C)	100	139	960	128	885	16	43
	300	148	1020	133	915	20	43
	1000	147	1015	130	895	17	45
Stress-50 ksi (345 MPa)	16	144	995	128	885	17	39
Temperature 850°F (454°C)	100	136	940	123	850	16	48
	300	143	985	133	915	17	34
	1000	156	1075	141	970	15	30
Unstressed		166	1145	153	1055	18	57
Stress-45 ksi (310 MPa)	150	171	1180	151	1040	16	55
Temperature 800°F (427°C)							

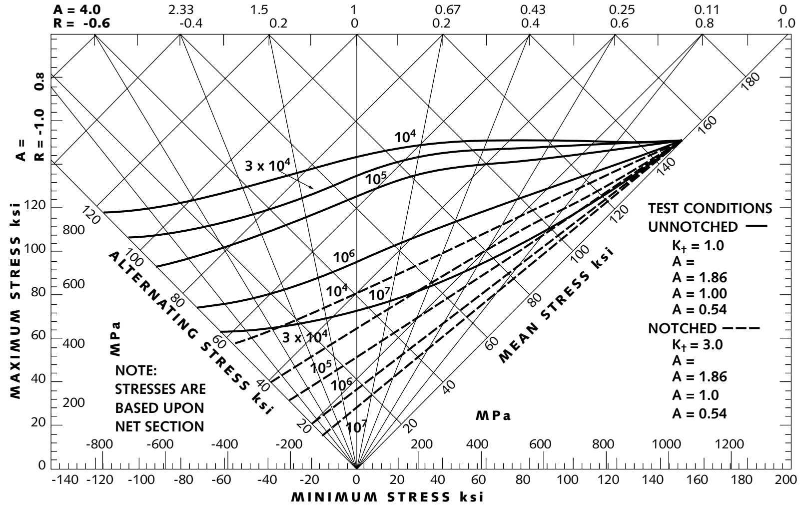
FIGURE 29

TYPICAL RT CONSTANT-LIFE FATIGUE DIAGRAM FOR TIMETAL 6-4

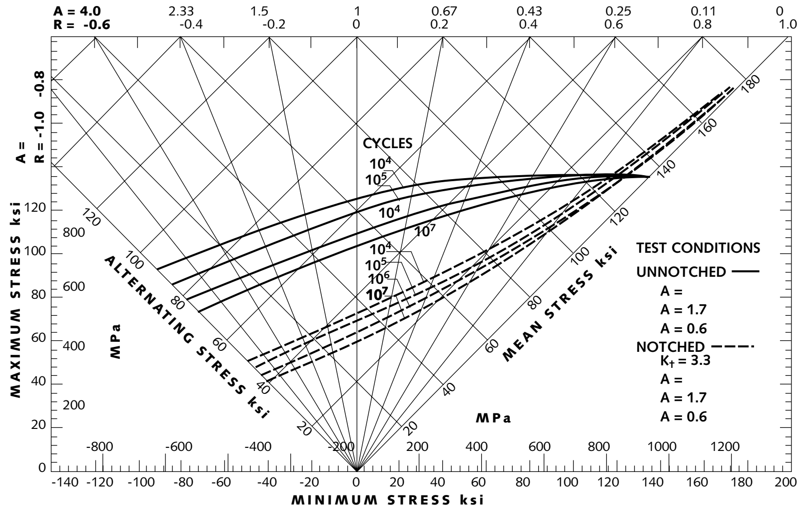
FTU FOR UNNOTCHED TESTS WAS 172 ksi (1186 MPa); FOR HOLE TYPE NOTCHED TESTS FTU WAS 180 KSI (1241 MPa). GAUGES: 0.063 AND 0.125-IN. (1.6 AND 3.2MM). SURFACES: AS ROLLED. EDGES: HAND POLISHED THROUGH 00 GRIT EMERY PAPER. HOLE (0.0625-IN, 1.59MM): AS DRILLED AND REAMED. TEST FREQUENCY: 25 AND 37 HZ (REF. 6)



FTU FOR NOTCHED PLATE WAS 154 ksi (1162 MPa). GAUGE: 1.025-IN. (26MM). SURFACES: AS MACHINED. NOTCHES: GROUND. TEST FREQUENCY: 100 HZ (REF. 6)



FTU FOR UNNOTCHED BAR WAS 136 ksi (938 MPA). BAR DIAMETER: 1.25-IN. (31.75MM) SURFACES: LONGITUDINAL POLISH THROUGH 600 GRIT EMERY BELTS. NOTCHES: POLISHED WITH 600 GRIT SLURRY. TEST FREQUENCY: 29 HZ. (REF. 6)



Fatigue Properties

Figure 29 presents typical constant life fatigue diagrams for sheet and bar at room temperature. Fatigue properties are very dependent on surface preparation of the specimen. Moreover, fatigue life often follows a log normal or Weibull statistical distribution. In the absence of pertinent experience and criteria, designers are therefore well advised to develop their own fatigue data and criteria for the actual part configuration and surface condition planned for use.

Crack Propagation

Crack propagation in *TIMETAL* 6-4 under static, rising or alternating loads is a still developing field of inquiry. In general, crack propagation depends on microstructure, texture, alloy content and environment. Moreover, correlations are not good among the three conditions of cracking: 1) sustained load, 2) rising load and 3) varying load. In addition, test configuration can affect results. Therefore, the designer is advised to develop his own relevant data for the application visualized.

Sustained Load

Given the complexity of stress concentration arising in design and service, designers are well advised to develop test procedures known to simulate their service conditions and life-test full scale assemblies if the ultimate in safety, design, efficiency and system performances is required. Another complication in service is environment. Collectively, these aspects preclude a complete rendition here.

Figure 30 shows some typical effects of H_2 on crack propagation under fast rising and sustained loads. Hydrogen has little apparent effect over the 40-200 ppm range but levels below the 40 ppm may provide significant improvement in sustained load carrying ability (23-25). The effect is pronounced at an oxygen content of 0.17%. At oxygen levels of 0.08-0.11% the H_2 vs. K_{1C} curve is flat up to 40ppm H_2 so the effect appears to depend on oxygen(25).

Rising Load

Figure 31 presents the trade-offs among fracture toughness (K_{1C}), alloy chemistry and yield strength. The diagram is divided into high and low oxygen regions. For a given section size, it is necessary to reduce both strength and oxygen to produce the highest toughness values. Other variables such as texture, microstructure and alloy content contribute to the scatter shown.

Temperature influences K_{1C} as shown in *Table 9*. A test direction effect may be present which could relate to texture, microstructure or both.

If higher toughness is required, one could select *TIMETAL* 6-4 ELI in a "recrystallization" anneal condition. The data are shown in *Table 10.* Comparison of *Tables 9* and *10* illustrates the magnitude-of-toughness gains available by going to ELI and using the specialized heat treatment. Beta annealing is also an effective means of improving toughness. Prospective users should consult References 11 and 28 for more complete information.

Varying Load

Figure 32 shows a typical effect of test environment on crack growth in *TIMETAL* 6-4 one-inch mill annealed plate under varying load. A 3.5 percent NaCl solution increases crack growth rates significantly at a test frequency of 0.1 Hz. *Figure 33* illustrates the very low crack growth rates that can be obtained in sump tank water.

A number of factors are known to influence crack growth rate, da/dN, in *TIMETAL* 6-4. Among them are tensile strength, specimen configuration, test parameters, microstructure, texture, material thickness, and material chemistry. It is also certain that significant scatter may exist within da/dN test and between specimens. The user should consult References 11 and 28 for further information.

FIGURE 30

FRACTURE TOUGHNESS UNDER RAPIDLY RISING LOAD K_{IX} AND SUSTAINED LOAD THRESHOLD K_{ITH}

SHOWS THE EFFECT OF HYDROGEN (REF. 23)

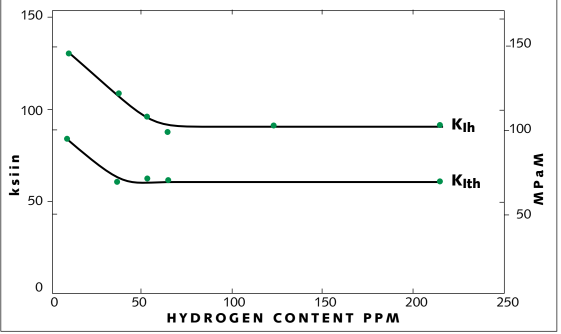


FIGURE 31

APPROXIMATE TRADE OFF REGIONS BETWEEN STRENGTH AND TOUGHNESS FOR TIMETAL 6-4

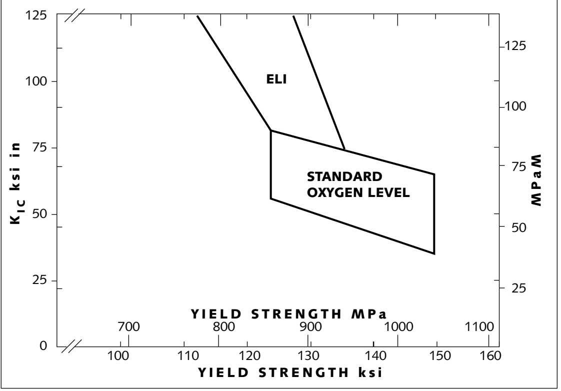


TABLE 9

EFFECT OF TEST TEMPERATURE AND ORIENTATION ON K_{IC} FRACTURE TOUGHNESS OF TIMETAL 6-4 FORGING ANNEALED 4 HRS AT 1300°F (705°C), 2.3" THICK (58MM) AVERAGES OF AT LEAST TWO RESULTS

(REF. 26)

Test Orientation	*75°F (24°C)*				*-65°F (-54°C)*			
	YS		*K_{IC}*		*YS*		*K_{IC}*	
	ksi	*MPa*	*ksi√in*	*MPa√m*	*ksi*	*MPa*	*ksi√in*	*MPa√m*
LT	129	889	58.1	63.9	145	1000	56.8	62.5
TL	132	910	62.2	68.4	151	1041	57.8	63.6
SL	128	883	68.1	74.9	146	1007	57.8	63.6
ST	128	883	58.1	63.9	146	1007	56.9	62.6

TABLE 10

TYPICAL TOUGHNESS CAPABILITY FOR TIMETAL 6-4 FORGINGS GIVEN "RECRYSTALLIZATION" ANNEAL OF 1700°F (925°C) 4 HR FC TO 1400°F (760°C) AC. ROOM TEMPERATURE DATA FROM SECTION 1.5-2.25" (38-57MM) THICK. OXYGEN IN 0.10-0.13% RANGE

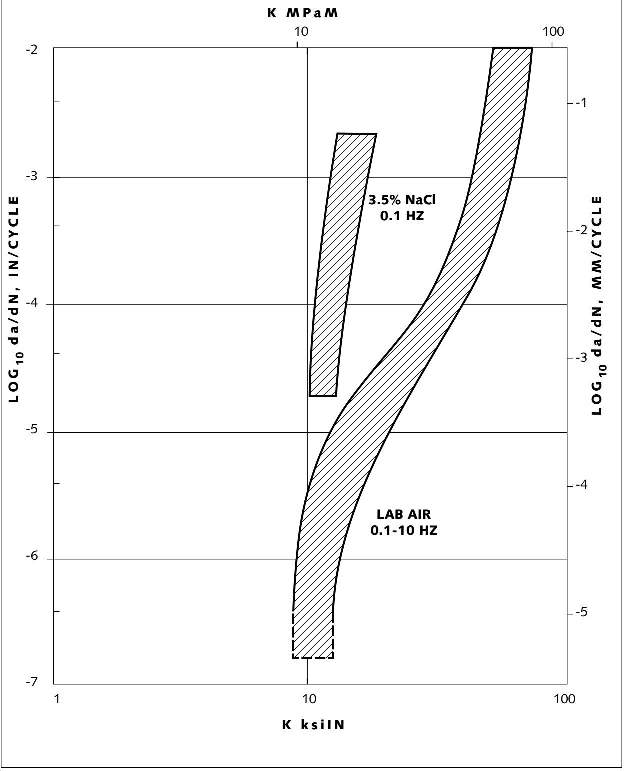
(REF. 11)

Direction	*YS*		*K_{IC}*	
	ksi	*MPa*	*ksi√in*	*MPa√m*
LT	122	841	83	91
TL	129	890	84	92

FIGURE 32

TIMETAL 6-4 AS 1" MILL ANNEALED PLATE, TL DIRECTION, TESTED AT ROOM TEMPERATURE

SHOWS STRONG EFFECT OF A SALT SOLUTION ON THE FATIGUE CRACK PROPAGATION RATE, DA/DN, FOR A GIVEN STRESS INTENSITY FACTOR RANGE, K (REF. 25)



Sea Water Environment

TIMETAL 6-4 is very resistant to general corrosion in sea water at normal ocean temperatures. When coupled with other metals, however, one of the pair may become anodic and corrode. *TIMETAL* 6-4 lies near the noble end of the electromotive series and behaves somewhat like austenitic stainless steel in galvanic couples. The resistance of *TIMETAL* 6-4 toward general corrosion in sea water is due to passivation which arises from a protective layer of TiO_2. *Figure 34* illustrates the cathodic polarization curve for *TIMETAL* 6-4 in 3.5% ASTM synthetic sea water solution at room temperatures. The polarization characteristics of *TIMETAL* 6-4 are very similar to those for unalloyed titanium.

The following formula may be used to calculate corrosion rates of the anodic member to be expected when galvanic currents exist:

$$R(\text{mpy}) = 0.13\,\frac{Ie}{\rho}$$

or

$$R(\text{mmpy}) = .0033\,\frac{Ie}{\rho}$$

Here I is current density in micro amps per square centimeter, e is equivalent weight of metal in grams, and ρ is density in grams per cubic centimeter. Galvanic couples are to be avoided in most situations or accounted for by proper system design.

Other Environments

There are certain environments to be avoided. Liquid oxygen, hydrogen under high pressure, red fuming nitric acid, methyl alcohol, nitrogen tetroxide, mercury, solid cadmium, solid silver and solid gold are environments reported to be destructive to titanium or *TIMETAL* 6-4 to at least some degree. Embrittlement by solid metal is usually temperature dependent. Cadmium potentially embrittles *TIMETAL* 6-4 at 300°F (150°C); silver and gold do likewise at 400°F (200°C) or higher. Thermal decomposition of certain organic compounds, such as phosphate-ester base fire resistant hydraulic fluids, can produce acidic by-products which can result in chemical attack and hydrogen embrittlement. Of course, contact with halides when temperatures exceed 450°F (230°C) is to be avoided under load carrying conditions. In some cases, the effects can be modified or eliminated.

FIGURE 33

TIMETAL 6-4 DB-1 PLATE T-L DIRECTION, SUMP TANK WATER ENVIRONMENT AT 70F

NOTE: MATERIAL IS RECRYSTALLIZED, ANNEALED AND BONDED AT 1725-1750F WITH SLOW HEATING AND COOLING RATES (REF. 26)

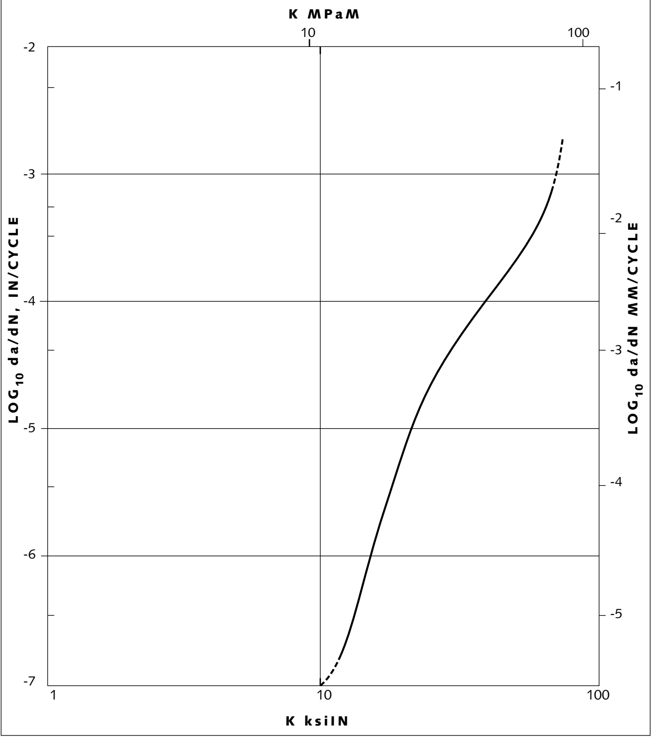
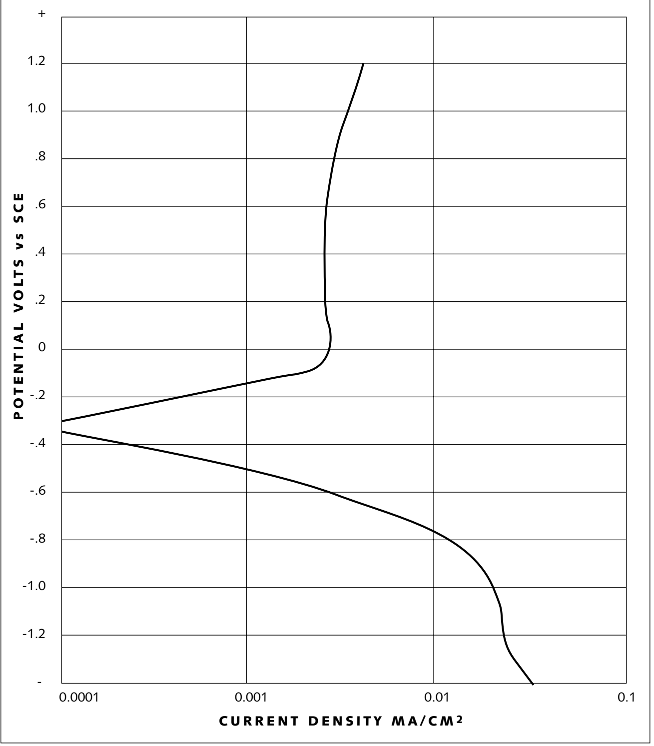


FIGURE 34

POLARIZATION CURVE FOR TIMETAL 6-4 IN ASTM SYNTHETIC SEAWATER PH 8 AMBIENT TEMPERATURE PICKLED SURFACE SCAN RATE 0.5 MV/SEC



Heating of TIMETAL 6-4

Certain fundamental precautions are advised during heating for forging, forming or heat treating. These precautions are general for all titanium alloys. See also the section on heat treat strategy.

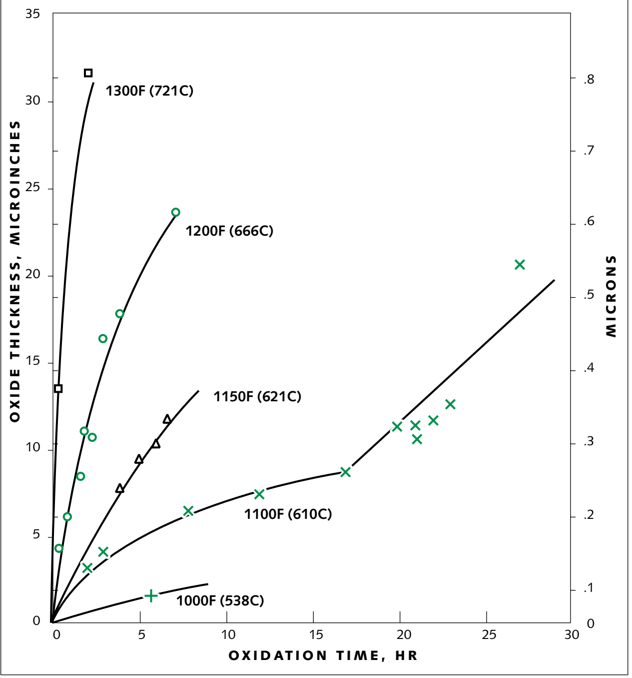
Furnace Temperature Control

Furnace temperature control is important because of the influence temperature has on the metallurgy of the finished part. *Figures 11* and *12* show how solution temperature changes will affect resulting properties of ST and STA material.

FIGURE 35

OXIDE THICKNESS FORMED ON TIMETAL 6-4 ALLOY AFTER VARIOUS AIR EXPOSURE TIMES AT SEVERAL TEMPERATURES

(REF. 6)



Furnace Atmospheres

Furnace atmosphere is also important. At forging temperatures, titanium is subject to contamination by the interstitial elements: hydrogen, oxygen, nitrogen and carbon.

Titanium will pick up hydrogen from a furnace atmosphere that is not perfectly dry. Electric furnaces are recommended where possible. Otherwise, the atmosphere should be neutral or slightly oxidizing.

Hydrogen contamination should be minimized since a higher hydrogen content (greater than 150 ppm) can lead to embrittlement at low temperature. Hydrogen diffuses so rapidly that the entire forging may be affected.

The reaction of hydrogen with titanium is reversible. By heating at 1300° to 1500°F (705° to 815°C) (or higher) in vacuums of one micron or less, the hydrogen content can be reduced. The rate of hydrogen removal depends on metal shape, bulk, time and temperature. Metal and furnace surfaces must be clean and without film for efficient dehydrogenation.

Oxygen contamination is limited to surface regions and is temperature-time dependent. See *Figure 35*. Oxidation causes surface embrittlement and can be observed metallographically. Oxygen dissolves extensively in, and stabilizes, the alpha phase. *Figure 16* shows typical alpha cases induced by surface oxidation.

Oxygen contamination during heating is minimized primarily by using shortest possible heating times. To provide a tough ductile surface, the contaminated layer must be completely removed. Either a chemical or mechanical means, or both, may be used. Deep cuts are recommended when alpha case is removed by machining. This improves tool life.

Nitrogen and carbon react with *TIMETAL* 6-4 in a manner similar to that for oxygen. However, normal control and removal of oxygen contamination prevents any problem. The use of protective coatings to prevent surface contamination is sometimes recommended in cases where long heating times are required or when subsequent conditioning is to be a minimum. Coating also affords lubrication during forging operations.

Under certain conditions of temperature, residual stress and chloride contamination, *TIMETAL* 6-4 may be susceptible to stress corrosion cracking. This phenomenon occurs above approximately 450°F (230°C). It is, therefore, important in sheet metal fabrication to use chlorine-free solvents and to remove all traces of chloride contamination, even fingerprints, prior to heating operations.

Forging

TIMETAL 6-4 is readily forged by a variety of methods depending on end properties and microstructures desired. Most commonly, forging is done near 1750°F (955°C) or about 75°F (25°C) below the $\alpha + \beta \rightarrow \beta$ transformation temperature.

Beginning with a transformed microstructure, the usual task of alpha-beta forging is to break up the platelet structure such that spheroidization of the primary alpha can occur during working and subsequent heat treatment. Generally, more than 50 percent alpha-beta reduction must occur before the alpha will spheroidize. The reduction required, of course, depends on other factors such as starting platelet width and the thermo-mechanical path taken from the initial to final configuration.

Slow cooling from the beta to the alpha field should be avoided prior to forging. The reason is that the resultant coarse "blocky alpha" is then very difficult to eliminate through conventional forging technique *(Figure 17)*.

Beta forging typically leads to microstructures similar to the transformed structures shown in *Figure 10*. Alpha may decorate the prior beta grain boundaries if cooling through the transformation region is not sufficiently fast. Microstructure control is effected in practice by properly controlling the forging temperature, reduction and heat treatment. Transformed beta structures yield excellent toughness and resistance to crack propagation and may be desired in certain cases. However, alpha-beta forging is recommended for maximum ductility and resistance to fatigue crack initiation. If beta forging seems indicated, close coordination between the forger and user is advised.

A further note of caution in forging is that at high strain rates, adiabatic heating can occur along localized shear planes and lead to microstructural inhomogeneity. The strain rate sensitivity of *TIMETAL* 6-4 influences the forging configurations that are possible.

Sheet Metal Forming

Standard sheet metal forming techniques can be used to form *TIMETAL* 6-4. Commonly used procedures include bending, stretching, joggling, dimpling, press forming, hammer forming, cup forming, shear spinning and hot sizing. Because *TIMETAL* 6-4 combines high strength with a low modulus, springback after cold forming may be greater than for other structural materials. For this reason, and because cold formability is limited, hot forming is usually practiced.

In hot forming, care must be exercised to deburr edges and otherwise maintain surface finish at least as fine as that obtainable from emery grit No. 180. Oil, grease, soluble matter, chlorides, fingerprints and chlorinated compounds should be removed using isopropyl alcohol or a light acid etch. Perchloroethylene or 1,1,1trichloroethane degreasing followed by alkaline cleaning is equally effective. Light acid etches may be used to remove light surface scratches. Before this is done, however, the material to be formed must be cleaned and degreased to remove all contaminants and mill stenciling. Surface sanding can also be employed, provided the grit used is appropriately fine.

Die cleanliness in hot forming is very important. Just as fingerprints on the product to be hot formed can lead to hot salt stress corrosion cracking, so also can any residual chlorides on dies or fixtures.

In general, hot forming temperatures in the 900°-1500°F (480°-815°C) range are recommended. Mild forming can be done at 400°-600°F (200°-315°C). The temperature to use depends on the forming operation. Coating to minimize oxidation is recommended. Forming time and temperature should be minimized to limit oxidation if the process is done in air. As rules of thumb, two hours at 1300°F (700°C) or 15 minutes at 1500°F (815°C) are maxima that include all heat times and hot forming operations. Protective atmospheres are recommended outside these time-temperature limits. Oxidation is significant above 1100°F (590°C). Use of temperatures higher than 1350°F (730°C) requires ideal conditions. Electric heating of dies is usually preferred when forming above 1000°F (540°C) since flame heating usually induces poor temperature control and working conditions. Removal of any alpha case arising from hot forming is recommended.

The bendability of *TIMETAL* 6-4 increases with temperature (see *Table 11)*. Uniform elongation behaves similarly. In hot forming annealed sheet, it is recommended that temperatures be controlled at or below the annealing temperature lest mechanical properties be affected.

Hot forming solution treated sheet can be done only to a limited extent. This is because aging or overaging can occur during forming. Forming below 500°F (260°C) presents no such problem. At temperatures of 900° to 1000°F (450° to 540°C) full aging can potentially occur during forming. Overaging occurs at 1100°F (590°C) and above.

Aged sheet can be formed only to a limited extent. Gently contoured shapes can often be formed, however.

Cold forming is only occasionally practiced. Aside from the forming limit, the user should recognize the Bauschinger effect which can reduce the compressive yield strength by 15-20 percent after a stretching elongation operation of as little as 3 percent. The Bauschinger effect also attends warm forming.

TABLE 11

EFFECT OF TEMPERATURE ON MINIMUM BEND RADIUS OF ANNEALED TIMETAL 6-4 SHEET

Temperature		*Bendability**	*Bendability*
°F	*°C*	*r/t Minimum*	*r/t Typical*
70	21	4.5	3.3
400	205	4 0	3 0
600	315	4.0	2.7
800	425	4.0	2.4
1000	540	3.0	1.8
1200	650	2.5	0.8
1400	760	1 5	–
1500	815	1.0	–

*r = Bend radius for 105° angle.

t = Thickness of sheet.

Superplastic forming has become a routine procedure. It is a special method of hot forming in an inert atmosphere producing complex shapes, and better definition than that achievable with other forming methods. The process requires the placing of tooling in a titanium retort, with a titanium diaphragm, i.e., part to be formed, which, under heat and argon pressure, deforms to form the parts. The forming temperature is approximately 1650°F (899°C) which limits elongations to about 300 percent, beyond which excessive thinning occurs. Special attention to preprocess cleaning is required for retorts, tooling and the diaphragm to be formed. Good shop practice requires the removal of .005-.010 inch (.0127-.0254mm) of surface material to eliminate alpha case.

Descaling, Pickling and Cleaning

Descaling of *TIMETAL* 6-4 can be accomplished by either mechanical or chemical means. Grinding or grit blasting are accepted methods as are acid pickling or immersion in molten caustic or sodium hydride baths. For very light scales formed at temperatures below 1100°F (590°C), an HNO_3-HF pickle (in a 7:1 ratio e.g.s. 35 HNO_3:5 HF: 60 H_2O) is usually sufficient. Acid strength and temperature are effective in controlling pickle rate. The caustic or hydride baths are more suitable for thicker scale removal. Oxidizing additives such as nitrates are recommended for use in caustic or hydride baths to reduce the tendency for *TIMETAL* 6-4 to pick up hydrogen. HNO_3 serves that function in the acid bath. In any case, the greater the surface to volume ratio, the greater the danger of hydrogen pickup.

Degreasing before pickling is important. Nonchlorinated solvents or alkaline cleaners are recommended. Pickling solutions can be weaker than descaling solutions; 20 HNO_3 - 2 HF at 120°F (50°C) is typical. Immersion should be just long enough to remove the oxide film.

Chem Milling

Chem milling is widely used to shape, fabricate, machine or blank metal parts to specific configurations. It is often an economical alternate or adjunct to standard fabrication procedures. It is particularly useful for complex parts.

Cleaning should be thorough and vinyl polymers are useful masking agents. Users should recognize that metal removal proceeds sideways as well as down so the minimum width that can be machined is about three times the machined depth. Aqueous solutions are generally mixtures such as HNO_3-HF, CrO_3-HF, or HF. Hydrogen pickup is always a consideration and is enhanced by transformed microstructures.

Electric Discharge Machining – EDM

This procedure is most useful for complex parts having fine detail. The dielectric fluid should be carefully selected to optimize metal removal and electrode wear. Frequently used hydrocarbons include heavy transformer oils, paraffin oils, light oils, kerosenes and various mixtures thereof. Silicone oils, polar compounds and deionized water have also been used.

EDM procedures can alter properties such as fatigue through surface contamination and residual surface stresses. In this area, there is no substitute for experience. Nevertheless, EDM is a commonly used technique for *TIMETAL* 6-4.

Machining

TIMETAL 6-4 can be readily machined even though:

1) Titanium, a poor conductor of heat, permits a rapid heat buildup at the cutting interface.

2) Titanium tends to react with the cutting tool by smearing, galling and welding.

3) Titanium's low modulus allows the work piece to move away from the cutting tool more easily than in the case of ferrous metals.

Five basic rules apply to machining *TIMETAL* 6-4:

1) Use low cutting speeds and heavy feed rates for removing contaminated surfaces or rough machining.

2) Use a large volume of non-chlorinated cutting fluid. Chlorinated fluids are often more efficient and may be used if adequate care is taken for their complete removal.

3) Use sharp tools and replace at the first sign of wear.

4) Never stop feeding while tool and work are in moving contact.

5) Use rigid setups.

High speed steels are most commonly used for straddle milling, profiling and end milling. Cemented carbides are generally used for face milling and lathe turning.

A weak solution of rust inhibitor and water soluble oil is the best coolant for high speed cutting operations. For slow speed and complex operations, however, oils do a better job of reducing frictional forces, galling and seizing tendencies.

For hard wheel grinding of titanium, vitrified-bonded wheels are the most effective. Aluminum-oxide gives the best results but is limited to the lower grinding speeds, less than 2000 surface feet per minute (610 m/min). If higher speeds are necessary, silicon-carbide wheels can be used. For belt grinding, a silicon-carbide abrasive is recommended over aluminum oxide.

Welding

Reliability of welded *TIMETAL* 6-4 has been demonstrated in a host of applications. Typical of these are solid propellant rocket motor cases, high pressure storage vessels, tankage, jet engine components and airframe components.

Being a reactive metal, titanium will react with oxygen, nitrogen, hydrogen and carbon and indeed with most refractories and metals. Therefore, the art of welding *TIMETAL* 6-4 is, in large measure, the art of excluding foreign substances.

Electric arc sources are commonly used to form fusion welds. Tungsten electrodes, metal wire electrodes, or inert gas plasma using argon or argon-helium mixtures are used to transfer energy to the fusion zone. Electron beam, laser welding and spot welding are also used extensively as is friction welding.

Fusion Welding

There are a number of guidelines to be followed as appropriate to each situation. They are:

- Keep the weld area clean. All jigs, fixtures, clamps, etc., should be cleaned prior to use.
- Thoroughly clean and degrease the metal to be welded. Clean all sides back to at least 1″ (25mm) from the edges to be joined. It is good practice to clean the entire set of components to be welded to prevent dirt transfer to the weldment.
- Use a sharp file to deburr edges.
- Do not contaminate with brush metal when removing tough dirt.
- Never use steel wool or sand paper to prepare the surfaces to be welded.
- Use alcohol or acetone to degrease the metal. Never use chlorinated solvents.
- Avoid fingerprinting any area to be welded. Use of clean cotton gloves is recommended.
- Blanket all sides of the area to be welded with helium or argon. Avoid drafts.
- Ventilate the work place.
- *Shielding is the most important consideration in welding titanium.* The best practice is to employ an inert atmosphere (argon) chamber whenever feasible.
- Use the minimum gas flow rate that will provide adequate shielding.
- Excessive flow may cause turbulence and result in atmospheric contamination. The best grade of inert gas available should be used.
- Always weld a test sample before attempting a production weld.
- Clamp the pieces to be welded. Tacks may be used, provided they are made with the same care and shielding as the primary weld.
- Clean the filler wire by clipping off the end that may have been contaminated when withdrawn from a previous weld.
- Use filler wire when fusion-welding gauges of 3/32″ (2.4mm) or greater. Filler metal is good practice for thinner gauges as well, in order to minimize undercutting and/or under flushing.
- Handle filler wire with the same care as the work piece. Degrease and use clean gloves.
- Never touch the work piece with the electrode.

- Fit-up must be good, especially on thin gauges. Gaps are difficult to fill.
- Use ELI wire, especially when shielding cannot be perfect.
- Feed the wire into the weld zone at the junction of the weld joint and arc cone using as short an arc length as possible.
- Feed the wire continuously into the puddle. Do not dab it in.
- When using tungsten electrodes, the thoriated varieties retain their points longer and operate cooler.
- Never strike an arc unless the job has been thought through.

Weld color is one indicator of weld quality. The weld should be bright and shiny. Depending on the application and weld procedure used, some light straw discoloration may be acceptable but this should be confirmed by testing sufficient welded parts to establish the desired level of confidence.

Settings for tungsten arc welding of .062in. (1.6mm) *TIMETAL* 6-4 sheet are given in *Table 12*.

When all the normal precautions are observed, good quality welds can be made in *TIMETAL* 6-4. Some typical weld mechanical property values are listed in *Tables 13* to *15*. *Table 15* gives properties of welds after various thermal treatments. The excellent toughness of *TIMETAL* 6-4 welds is demonstrated by the as-welded notch tensile values in *Table 14*.

The weld, in the as-welded condition, is generally stronger than in the annealed parent metal if unalloyed filler metal is not used. A tensile test with weld transverse to the test direction will usually fail in the parent metal with little or no measurable elongation across the weld zone. Failure outside the weld does not demonstrate that the weld is satisfactory, but only that joint efficiency is 100 percent, or better. A test of the weld longitudinal to the test direction will be a test of the weld itself, since the failure has to occur in the weld area.

TABLE 12

RECOMMENDED WELD SETTING FOR TUNGSTEN ARC MACHINE WELDING OF 0.062" (1.6MM) TIMETAL 6-4 SHEET

	Without Filter	*With Filter*
Electrode Dia. inch (mm)	1/16 (1.6)	1/16 (1.6)
Filler Wire Dia. inch (mm)		1/16 (1.6)
Wire Feed Rate, ipm (mmpm)		22 (560)
Voltage	10	10
Amperes	90-100	120-130
Nozzle ID. in (m)	9/16 to 5/8 (9.5-15.9)	9/16 to 5/8 (9.5-15.9)
Primary Shield, cfh-Argon (cmh)	15 (.42)	15 (.42)
Trailing Shield, cfh-Argon (cmh)	30 (.84)	40 (1.13)
Back-up Shield, cfh-Helium (cmh)	4 (.11)	5 (.14)
Back-up Material	Cu or Steel	Cu or Steel
Back-up Groove in. (in)	1/4 x 1/16 deep	1/4 x 1/16 deep
	6.4 x 1.6	6.4 x 1.6
Electrode Travel, ipm (mm/min)	10 (254)	12 (305)
Power Supply	DC	DC
Polarity	Straight	Straight

TABLE 13

MECHANICAL PROPERTIES OF AS-WELDED 0.062" (1.6MM) TIMETAL 6-4 SHEET WELDMENTS USING TIMETAL 75A FILLER WIRE

Weld Direction in Relation to the	*Test Temp.*		*Bendability*	*UTS*		*YS*		
Test Direction	*°F*	*°C*	*r/t*	*ksi*	*MPa*	*ksi*	*MPa*	*%*
Transverse	RT	RT	7.0	135	930	126	870	6
Transverse(1)	RT	RT	7.0	141	970	133	915	6
Transverse	400	205		96	660	95	655	6
Transverse	600	315		95	655	81	560	7
Transverse	800	425		92	635	77	530	8
Transverse	1000	540		78	540	62	525	15

(1) Given a post weld stress relief of 1000°F (540°C) - 24 hours.

TABLE 14

MECHANICAL PROPERTIES OF AS-WELDED 0.062" (1.6MM) TIMETAL 6-4 SHEET WELDMENTS USING TIMETAL 75A FILLER WIRE

Weld Direction in Relation to the	*Test Temp.*		*Bendability*	*UTS*		*YS*		*El*	*NTS Kt = 3*	
Test Direction	*°F*	*°C*	*r/t*	*ksi*	*MPa*	*ksi*	*MPa*	*%*	*ksi*	*MPa*
Longitudinal	RT	RT	10.0	147		139	960	5	164	1130
Transverse	RT	RT	10.0	140	965	127	875	8	164	1130
Transverse	600	315		97	670	87	600	6		
Transverse	800	425		91	625	79	545	11		
Transverse	1000	540		72	495	60	415	18		
Longitudinal	1000	540		82	565	67	460	7		
Longitudinal	-100	-75		167	1150	155	1070	2	180	1240
Longitudinal	-320	-195		221	1525	210	1450	2	204	1405
Longitudinal	-423	-255		275	1895	267	1840	2	217	1495

Solution treatment and aging of *TIMETAL* 6-4 welds is not recommended because of the resultant low ductility.

Stress relieving is always recommended. Refer to *Figure 13*.

One technique used under certain conditions for welding of forged *TIMETAL* 6-4 components is worth describing. This procedure is to fully heat treat and machine the individual forgings prior to welding. Fusion welding, using commercially pure (unalloyed) welding wire, then produces a diluted weld with toughness characteristics that are superior to a weld with *TIMETAL* 6-4 filler. The lower strength in the diluted weld is compensated for by thickening the wall in the weld area. A 1000°F (540°C) treatment after welding stress relieves the weld but has no effect on the STA parent metal strength or ductility. To employ this technique, however, requires that the hydrogen level be controlled to low levels, preferably below 80 ppm. Otherwise, delayed embrittlement from hydride precipitation in, or near, the dilute weld-base metal interface may occur(29).

Electron Beam Welding

EB welding is quite attractive. All welding is done in a high vacuum chamber by mechanized equipment. The procedure yields a low distortion weld where the fusion zone has a high depth-to-width ratio. Filler wire is not normally used. EB welding has been used to fabricate net shape assemblies of large complicated parts. The surfaces to be welded must be clean. The cleaning procedures discussed above may be used.

TABLE 15

ROOM TEMPERATURE MECHANICAL PROPERTIES OF 0.062” (1.6MM) TIMETAL 6-4 SHEET WITH MATCHING OR NO FILLER AT VARIOUS HEAT TREATING CYCLES(1)

	UTS		YS		Elongation			
					2″	1/2″	1/8″	Failure
Thermal Treatment	*ksi*	*MPa*	*ksi*	*MPa*	*(51mm)*	*(13mm)*	*(3.2mm)*	*Location*
Weld + 1000°F (540°C)-24 hrs	141	970	130	895	8			
Weld + 1150°F (620°C)-24 hrs	136	940	126	870	9			
Weld + 1350F (730°C)-24 hrs	130	895	125	860	9			
STA + Weld	167 (93.2)(2)	1150	157	1085	1	6	8	HAZ
St + Weld + 900°F (480°C)-4hrs (97.2)	170 (97.7)	1170	159	1095	1	11	15	HAZ

(1) All welds transverse to testing direction.
(2) Figures in parentheses are joint efficiencies.

TABLE 16

RECOMMENDED SPOT WELDING PARAMETERS AND TYPICAL PROPERTIES OF SPOT WELDED TIMETAL 6-4 SHEET

	Sheet Thickness			
	0.035 (.9mm)	*0.062 (1.6mm)*	*0.070 (1.8mm)*	*0.090 (2.3mm)*
Joint Overlap (Inches)	1/2	5/8	5/8	3/4
(mm)	13	16	16	19
Squeeze Time (Cycles)	60	60	60	60
Weld Time (Cycles)	7	10	12	16
Hold Time (Cycles)	60	60	60	60
Electrode Type	3″ (76mm)		5/8″ (16mm)	
	Spherical Radius,		Diameter Class 2 Copper	
Electrode Force (lbs)	600	1500	1700	2400
(kg)	270	680	770	1090
Weld Current (Amps)	5500	10600	11500	12500
Cross-tension Strength (lbs)	600	1000	1850	2100
(kg)	270	450	840	950
Tension-shear Strength (lbs)	1720	5000	6350	8400
(kg)	780	2270	2880	3810
Ratio C-T/T-S	0.35	0.20	0.29	0.25
Weld Diameter (Inches)	0.255	0.359	0.391	0.431
(mm)	6.48	9.12	9.93	10.95
Nugget Diameter (Inches)		0.331		
(mm)		8.4		
Weld Penetration (%)		87.3		
Electrode Indentation (%)		3.1		
Sheet Separation (Inches) 0.0091	0.0047	0.0087	0.0079	

For very thick material, the first pass is usually made at such a high power density that undercutting may occur. Undercutting can be reduced by making a second lower power pass with a slightly defocussed beam. Alternately, filler metal can be used to reduce undercutting entirely. If the undersides of EB welds have undesirable contours, acceptable surfaces are usually obtained by appropriate metal removing techniques(27).

EB welds have high integrity and EB welding is recommended where the ultimate in weld quality is desired. Power setting and focus conditions, however, may vary among machines for a given weld result. Therefore, if one lacks experience with a given machine, sufficient trials to develop suitable welding parameters are recommended.

Fit-up is also very important. Generally, the better the fit-up the better the weld.

If excessive porosity occurs, fit-up, cleanliness, equipment settings and procedure should all be reviewed and revised as necessary.

Resistance Welding

Resistance welding of *TIMETAL* 6-4 is done in much the same manner as with other metals. It differs from fusion welding in that inert gas protection is not necessary because of the close proximity of the mating surfaces and the short period of the welding cycle. The surfaces to be welded must be clean. The above cleaning procedures may be used.

Since titanium and stainless steel have similar thermal and electrical conductivities and strength at elevated temperatures, the resistance welding characteristics are also similar. This has led to the utilization of stainless steel resistance welding techniques for titanium.

Flash Welding

Flash welding is achieved by inducing an electric arc between work pieces in light contact, then upsetting at the moment of fusion such that the impurities are expelled from the joint. The size and cross section to be flash welded are, of course, limited by the electric power and upsetting force available in the machine. Similarly, the weldment profile cannot be too complex. *TIMETAL* 6-4 is commonly flash welded in air.

Inertia Welding

Inertia welding (friction welding) has become a viable production welding method for parts having radial symmetry such as compressor drums. In this process, the metal preparation procedures are the same as for other techniques. The essence of the method is to convert rotational kinetic energy into heat to bring about controlled degrees of fusion and extrusion. Inertia welding can be done in air.

Brazing

Brazing *TIMETAL* 6-4 is a seldom used technique. However, it may find use in assembling sandwich structures and in joining to dissimilar metal.

The applications of *TIMETAL* 6-4 are continuing to grow as its unique properties are recognized. Dimensions discussed in this section include new fabrication and processing technologies as well as new potential applications.

Two primary purposes of current development work are to reduce system life cycle cost or improve system performance, or both. Material selection is obviously an important key. In fabrication, the essence is to achieve net or near-net shape using techniques specific for titanium instead of simply adapting procedures used for other metals. In processing, the goal is to provide higher design values for some property of interest.

TIMETAL 6-4 has several unique aspects.

Diffusion Bonding

Heating *TIMETAL* 6-4 to about 1700°F (925°C) will dissolve any trace amounts of oxide on its surface. In a clean vacuum, therefore, *TIMETAL* 6-4 will readily weld to itself on contact. Under modest pressure and with the proper restraint the diffusion bonded area can be made to flow into almost any arbitrary fillet radius. Under proper pressure and sufficiently high vacuum the bond line will be free of all porosity.

The process requires a press capable of exerting triaxial forces on the work pieces at temperature. Following are the advantages of the diffusion bonding process:

1) Parts can be made that are not feasible by other methods.
2) Parts can be made to net shape requiring little, if any, machining.
3) Complex assemblies can be built up that would require several parts if conventional procedures were to be used.
4) It is compatible with superplastic forming because each occurs at the same temperature for *TIMETAL* 6-4.

TABLE 17

EFFECT OF NEUTRON RADIATION ON TIMETAL 6-4

REF. 33*

Neutron Fluence, cm^{-2} x 10^{-20}		*UTS*				
		Smooth		*$K_t = 3$*		*El*
Thermal	*Energy = 1.0MeV*	*ksi*	*MPa*	*ksi*	*MPa*	*%*
0	0	160	1105	245	1690	10
.25	.022	173	1195	248	1710	7
2.3	.20	189	1305	258	1780	4
3.7	31	184	1270	249	1715	5
9.6	.77	196	1350	255	1760	4
73	9.7	196	1350	235	1620	3

*Irradiation at about 160°F (70°C) with tensile tests done at RT.

TABLE 18

THERMAL NEUTRON CROSS SECTION FOR ELEMENTS IN TIMETAL 6-4

REF. 35

Natural Abundance-%	*Element or Isotope*	*Absorption Cross Section - Barns*	*Scattering Cross Section - Barns*
–	22^{Ti}	5.8 ± 0.4	4 ± 1
7.93	Ti^{46}	.6 ± 0.2	2 ± 2
7.28	Ti^{47}	1.7 ± 0.3	4 ± 1
73.94	Ti^{48}	8.3 ± 0.6	4 ± 2
5.51	Ti^{49}	1.9 ± 0.5	1 ± 1
5.34	Ti^{50}	0.2	3 ± 1
	Al^{27}	241 ± 3 mb	
	23^{V}	5.00 ± 0.1	5 ± 1
	26^{Fe}	2.62 ± 0.06	11 ± 1

TABLE 19

EROSION AND CAVITATION RATES FOR TIMETAL 6-4 COMPARED WITH OTHER MATERIALS

REF. 36

	Corrosion-Erosion Rate(1)		*Cavitation Rate*(2)	
Material	*Mils/yr*	*mm/yr*	*Inches/yr*	*mm/yr*
TIMETAL 6-4	1	.025	.8	20
AM355	2.5	.064	1.35	34
Hastalloy C	3	.076	.6	15
Inconel 718	4	.102	.5	13
K Monel	9.5	.241	1.05	27

(1) 30 day exposure, sea water at 90 knots, 45 degrees impingement angle.

(2) Double amplitude 0.001" (.025mm), 22,000 Hz, 8-hour exposures, sea water.

Texture Strengthening

Texture strengthening is an old concept and holds some potential for *TIMETAL* 6-4. Texture strengthening in *TIMETAL* 6-4 occurs because deformation in the alpha phase preferentially occurs in prism planes in a direction normal to the crystallographic c axis rather than with some component parallel to it. The trick in texture strengthening is to align all crystallographic c axes in one direction so that the alpha phase of the material is highly textured. Such a perfect texture is never really possible. To the extent that it can be achieved, however, the alloy will be stronger and will have a higher modulus in that direction. For example, when thin sections can be made strong through the thickness, cylinders or domes exhibit yield strengths in biaxial stress fields that are higher than the von Mises criteria would predict for isotropic materials.

Texture strengthening of titanium is not yet a commonly used technique although both process and product research continue. It is discussed here mainly to indicate technical feasibility and potential.

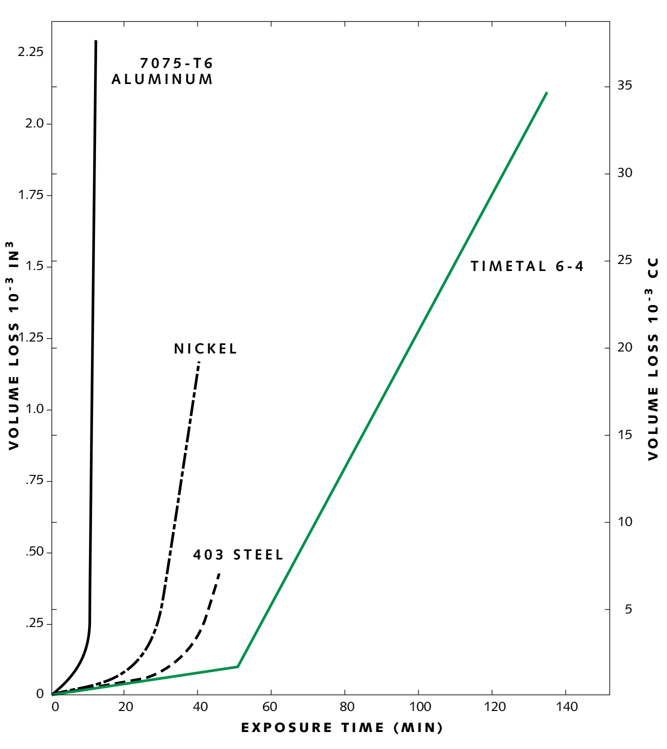
Radiation Environments

When irradiated by neutrons, significant changes in substructure occur. Precipitates and dislocation loops are observable by electron microscopy. These changes result in strength increases and ductility losses as shown in *Table 17*.

FIGURE 36

RAIN EROSION BEHAVIOR OF TIMETAL 6-4 ALLOY AT 1120 FT/S 341 M/S DROPLET VELOCITY COMPARED WITH OTHER DUCTILE METALLICS

(REF. 34, 38)



The principle radioactive transmutation elements that will occur in *TIMETAL* 6-4 under neutron bombardment are scandium, calcium, magnesium, silicon, and manganese in decreasing order of residual radioactivity at the cessation of irradiation(34). Iron-55 and aluminum-26 also occur.

Table 18 presents the absorption and scattering cross sections for the principle elements of *TIMETAL* 6-4.

Hydrospace and Power Generation

Immune to general attack by sea water at normal ocean temperatures and highly efficient structurally, *TIMETAL* 6-4 is a natural candidate for ocean going environments. The same properties may be useful in the conversion of geothermal energy.

Table 19 shows that the corrosion-erosion resistance of *TIMETAL* 6-4 is outstanding and there are indications that this can be improved by carbonitriding the surface. Resistance to cavitation is adequate.

Rain erosion behavior is shown in *Figure 36*.

TIMETAL 6-4 has potential in pressure steam turbines. Titanium offers greater corrosion and erosion resistance to steam than does the standard 12Cr steel commonly used. Compared with steel blades, *TIMETAL* 6-4 permits longer blades for the same root stress or lower root stress for the same blade length.

Technical Services

TIMET maintains a Technical staff whose responsibility it is to assist the user in developing new applications for titanium. The reader may call or write for information at the General Office. See back cover.

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M-11 I Trade Brochures, available from metal producers.

M-12 R. Boyer, G. Welsch, E.W. Collings. Materials Properties Handbook: Titanium. ASM International, Materials Park OH 44074, 1994.

Fabrication of Titanium

F-10 See M-10, also references 7, 12 and 13 of text.

F-2 Trade Brochures, available from metal producers.

DESIGN DATA

ENGLISH UNITS

Specification	*MILT-9046*							
Form	*Sheet-Plate*							
Condition	*Annealed*						*STA*	
Thickness or diameter, in	*≤0.1875*		*0.1875 to 2.000*		*2.001 to 4.000*	*≤0.1875*	*0.1875 to 0.750*	*0.751 to 1.000*
*Basis**	*A*	*B*	*A*	*B*	*S*	*S*	*S*	*S*
Mechanical Properties:								
F_{tu},ksi:								
L	134	139	130[c]	135	130	160	160	150
LT	134	139	130[c]	138	130	160	160	150
F_{ty},ksi:								
L	126	131	120	125	120	145	145	140
LT	126	131	120[c]	131	120	145	145	140
F_{cy},ksi:								
L	132	138	126	131	126	154	150	145
LT	132	138	126	138	126	162	–	–
F_{su},ksi	79	81	76	79	76	100	93	87
F_{bru}ksi:								
(e/l = 1.5)	197	204	191	198	191	236	248	233
(e/l = 2.0)	252	261	245	254	245	286	308	289
F_{bry},ksi:								
(e/l = 1.5)	171	178	163	170	163	210	210	203
(e/l = 2.0)	208	216	198	206	198	232	243	235
e, percent:								
In 2 in.	8[a]	10	–	–	10	5[b]	8	6

[a] 8 if 0.025 to 0.062 in.; 10 if 0.063 in. and above.

[b] 5 if 0.050 in. and above; 4 if 0.033 to 0.049 in.; 3 if 0.032 in. and below.

[c] The A values are higher than specification values as follows: F_{tu}(L) = 131 ksi, F_{tu}(LT) = 132 ksi, and F_{ty}(LT) = 123 ksi

*Mil Handbook 5 Determination of Confidence Limit.

ENGLISH UNITS

Specification	*MILT-9047*											
Form	*Rolled and forged bar*											
Condition	*Annealed*			*STA*								
Thickness, in	*<0.500*	*0.500 - 3.000*		*5 000*	*0.501 - 1.000*		*1.001 - 1.500*		*1.501- 2.000*		*3.001*	*4.000*
*Basis**	*S*	*A*	*B*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*
Mechanical Properties:												
F_{tu},ksi:												
L	130	130[b]	138	160	155	150	150	145	145	140	135	130
LT	130	130[b]	140	160	155	150	150	145	145	140	135	130
F_{ty},ksi:												
L	120	120[c]	129	150	145	140	140	135	135	130	125	120
LT	120	120[c]	129	150	145	140	140	135	135	130	125	120
F_{cy}ksi:												
L	126	126	135	–	–	–	–	–	–	–	–	–
LT	126	126	135	–	–	–	–	–	–	–	–	–
F_{su},ksi	80	80	84	92	–	–	–	–	–	–	–	–
F_{bru}ksi:												
(e/D = 1.5)	196	196	206	–	–	–	–	–	–	–	–	–
(e/D = 2.0)	248	248	261	–	–	–	–	–	–	–	–	–
F_{bry},ksi												
(e/D = 1.5)	174	174	187	–	–	–	–	–	–	–	–	–
(e/D = 2.0)	205	205	220	–	–	–	–	–	–	–	–	–
e, percent:												
L	10	10[d]	–	10	10	10	10	10	10	10	8	6
LT		7	10	10	10	10	10	10	10	8	6	–
E,10^3ksi				16.0								
E_c,10^3ksi				16.4								
G,10^3ksi				6.2								
μ				0.31								

[a] Values apply to sections with a maximum cross-sectional area of 10 square inches.

[b] The A values are higher than specification values as follows: F_{tu}(L) = 132 ksi and F_{tu}(LT) = 134 ksi.

[c] The A values are higher than specification values as follows: F_{ty}(L) and (LT) = 123 ksi.

[d] The A value is higher than specification value as follows: e(L) = 11 percent.

* Mil Handbook 5 Determination to Confidence Limit.

DESIGN DATA

SI UNITS (SOFT CONVERSION)

Specification	*MILT-9046*							
Form	*Sheet-Plate*							
Condition	*Annealed*					*STA*		
Thickness or diameter, mm	*≤4.76*		*4.76 to 50.8*		*50.83 to 101.6*	*≤4.76*	*4.76 to 19.05*	*19.08 to 25.4*
*Basis**	*A*	*B*	*A*	*B*	*S*	*S*	*S*	*S*
Mechanical Properties:								
F_{tu},MPa:								
L	924	958	896[c]	931	896	1103	1103	1034
LT	924	958	896[c]	952	896	1103	1103	1034
F_{ty},MPa:								
L	869	903	827[c]	903	827	1000	1000	965
LT	869	903	827	862	827	1000	1000	965
F_{cy},MPa:								
L	910	952	869	903	869	1062	1034	1000
LT	910	952	869	952	869	1117	–	–
F_{su},MPa	545	558	524	545	524	690	641	600
F_{bru}MPa:								
(e/l = 1.5)	1358	1407	1317	1365	1317	1627	1710	1607
(e/l = 2.0)	1738	1800	1689	1751	1689	1972	2124	1993
F_{bry},MPa:								
(e/l = 1.5)	1179	1227	1124	1172	1124	1448	1448	1400
(e/l = 2.0)	1434	1489	1365	1420	1365	1600	1675	1620
e, percent:								
In 2 in.	8[a]	–	10	–	10	5[b]	8	6

[a] 8 if .635 to 1.58mm; 10 if 1.60mm and above.

[b] 5 if 1.27mm and above; 4 if 0.84 to 1.245mm; 3 if 0.813mm and below.

[c] The A values are higher than specification values as follows: F_{tu}(L) = 903MPa, F_{tu}(LT) = 910 MPa, and F_{ty}(LT) = 848 MPa.

*Mil Handbook 5 Determination of Confidence Limit.

SI UNITS (SOFT CONVERSION)

Specification	*MILT-9046*											
Form	*Rolled and forged bar*											
Condition	*Annealed*			*STA*								
Thickness, mm	*<12.7*	*12.7 - 76.2*		*12.7*	*12.75 - 25.4*		*25.45 - 38.1*		*38.11 -50.8*		*76.25*	*102*
*Basis**	*S*	*A*	*B*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*	*S*
Mechanical Properties:												
F_{tu},MPa:												
L	896	896[b]	952	1103	1069	1034	1034	1000	1000	965	931	896
LT	896	896[b]	965	1103	1069	1034	1034	1000	1000	965	931	896
F_{ty},MPa:												
L	827	827[c]	889	1034	1000	965	965	931	931	896	862	827
LT	827	827[c]	889	1034	1000	965	965	931	931	896	862	827
F_{cy},MPa:												
L	869	869	931	–	–	–	–	–	–	–	–	–
LT	869	869	931	–	–	–	–	–	–	–	–	–
F_{su},MPa	552	552	579	634	–	–	–	–	–	–	–	–
F_{bru}MPa:												
(e/D = 1.5)	1351	1351	1420	–	–	–	–	–	–	–	–	–
(e/D = 2.0)	1710	1710	1800	–	–	–	–	–	–	–	–	–
F_{bry},MPa:												
(e/D = 1.5)	1200	1200	1289	–	–	–	–	–	–	–	–	–
(e/D = 2.0)		1413	1413	1517	–	–	–	–	–	–	–	–
e, percent:												
L	10	10[c]	–	10	10	10	10	10	10	10	8	6
LT	–	7	10	10	10	10	–	10	10	10	8	6
$E,10^3$MPa	110											
$E_c,10^3$MPa	113											
$G,10^3$MPa	43											
μ	0.31											

[a] Values apply to sections with a maximum cross-sectional area of 254 square mm.

[b] The A values are higher than specification values as follows: F_{tu}(L) = 910MPa and F_{tu}(LT) = 924MPa.

[c] The A values are higher than specification values as follows: F_{ty}(L) and (LT) = 848MPa.

[d] The A value is higher than specification value as follows: e(L) = 11 percent.

* Mil Handbook 5 Determination of Confidence Limit.

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