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Properties and Selection: Nonferrous Alloys and Special-Purpose Materials

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Table 2 Comparison of various specifications for commercially pure titanium mill products

Designation	Chemical composition, % max: C	H	O	N	Fe	Other	Total others	Tensile properties(a): Ultimate strength, MPa	Ultimate strength, ksi	Yield strength, MPa	Yield strength, ksi	Minimum elongation, %
JIS Class 1	...	0.015	0.15	0.05	0.20	...	...	275–410	40–60	165(b)	24(b)	27
ASTM grade 1 (UNS R50250)	0.10	(c)	0.18	0.03	0.20	...	...	240	35	170–310	25–45	24
DIN 3.7025	0.08	0.013	0.10	0.05	0.20	...	...	295–410	43–60	175	25.5	30
GOST BT1-00	0.05	0.008	0.10	0.04	0.20	...	0.10 max	295	43	...	...	20
BS 19–27t/in.^{2}	...	0.0125	...	...	0.20	...	...	285–410	41–60	195	28	25
JIS Class 2	...	0.015	0.20	0.05	0.25	...	...	343–510	50–74	215(b)	31(b)	23
ASTM grade 2 (UNS R50400)	0.10	(c)	0.25	0.03	0.30	...	...	343	50	275–410	40–60	20
DIN 3.7035	0.08	0.013	0.20	0.06	0.25	...	...	372	54	245	35.5	22
GOST BT1-0	0.07	0.010	0.20	0.04	0.30	...	0.30 max	390–540	57–78	...	...	20
BS 25-35t/in.^{2}	...	0.0125	...	...	0.20	...	...	382–530	55–77	285	41	22
JIS Class 3	...	0.015	0.30	0.07	0.30	...	...	480–617	70–90	343(b)	50(b)	18
ASTM grade 3 (UNS R50500)	0.10	(c)	0.35	0.05	0.30	...	...	440	64	377–520	55–75	18
ASTM grade 4 (UNS R50700)	0.10	(c)	0.40	0.05	0.50	...	...	550	80	480	70	20
DIN 3.7055	0.10	0.013	0.25	0.06	0.30	...	...	460–590	67–85	323	47	18
ASTM grade 7 (UNS R52400)	0.10	(c)	0.25	0.03	0.30	0.12–0.25 Pd	...	343	50	275–410	40–60	20
ASTM grade 11 (UNS R52250)	0.10	(c)	0.18	0.03	0.20	0.12–0.25 Pd	...	240	35	170–310	24.5–45	24
ASTM grade 12 (UNS R53400)	0.10	0.015	0.25	0.03	0.30	0.2–0.4 Mo, 0.6–0.9 Ni	...	480	70	380	55	12

(a) Unless a range is specified, all listed values are minimums. (b) Only for sheet, plate, and coil. (c) Hydrogen limits vary according to product form as follows: 0.015H (sheet), 0.0125H (bar), and 0.0100 H (billet). Source: Adapted from Ref 1

beta transus is about 910 ± 15 °C (1675 ± 25 °F) for commercially pure titanium with 0.25 wt% O_2 max and 945 ± 15 °C (1735 ± 25 °F) with 0.40 wt% O_2 max. For the various ASTM grades of commercially pure titanium, typical transus temperatures (with an uncertainty of about ±15 °C, or ±25 °F) are:

Designation	Typical β transus, °C	Typical β transus, °F	Typical α transus, °C	Typical α transus, °F
ASTM grade 1	888	1630	880	1620
ASTM grade 2	913	1675	890	1635
ASTM grade 3	920	1685	900	1650
ASTM grade 4	950	1740	905	1660
ASTM grade 7	913	1675	890	1635
ASTM grade 12	890	1635	...	...

Typical unit cell parameters for an alpha crystal structure at 25 °C (77 °F) are:

$$a = 0.2950 \text{ nm}$$
$$c = 0.4683 \text{ nm}$$

Impurity elements (commonly oxygen, nitrogen, carbon, and iron) influence unit cell dimensions. The typical unit cell parameter for the beta structure is 0.329 nm at 900 °C (1650 °F).

The microstructure of unalloyed titanium at room temperature is typically a 100% alpha-crystal structure. As amounts of impurity elements increase (primarily iron), small but increasing amounts of beta are observed metallographically, usually at alpha grain boundaries. Annealed unalloyed titanium may have an equiaxed or acicular alpha microstructure. Acicular alpha occurs during beta-to-alpha transformation on cooling through the transformation temperature range. Platelet width decreases with cooling rate. Equiaxed alpha can only be produced by recrystallization of material that has been extensively worked in the alpha phase. The presence of acicular alpha, therefore, is an indication that the material has been heated to a temperature above the beta transus. A beta structure cannot be retained at low temperatures in unalloyed titanium, except in small quantities in materials containing beta stabilizing contaminants such as iron.

Effect of Impurities on Mechanical Properties. Besides the effect on transformation temperatures and lattice parameters, impurities also have important effects on the mechanical properties of titanium. Residual elements such as carbon, nitrogen, silicon, and iron raise the strength and lower the ductility of titanium products. The effect of carbon, oxygen, and nitrogen is shown in Fig. 1.

Basically, oxygen and iron contents determine strength levels of commercially pure titanium. In higher strength grades, oxygen and iron are intentionally added to the residual amounts already in the sponge to provide extra strength. On the other hand, carbon and nitrogen usually are held to minimum residual levels to avoid embrittlement.

When good ductility and toughness are desired, the extra-low interstitial (ELI) grades are used. In ELI grades, carbon, nitrogen, oxygen, and iron must be held to acceptably low levels because they lower the ductility of the final product (see, for example, the effect of carbon, oxygen, and nitrogen in Fig. 1).

The titanium for ingot production may be either titanium sponge or reclaimed scrap. In either case, stringent specifications must be met for control of ingot composition. Most important are the hard, brittle, and refractory titanium oxide, titanium nitride, or complex titanium oxynitride particles that, if retained through subsequent melting operations, could act as crack initiation sites in the final product.

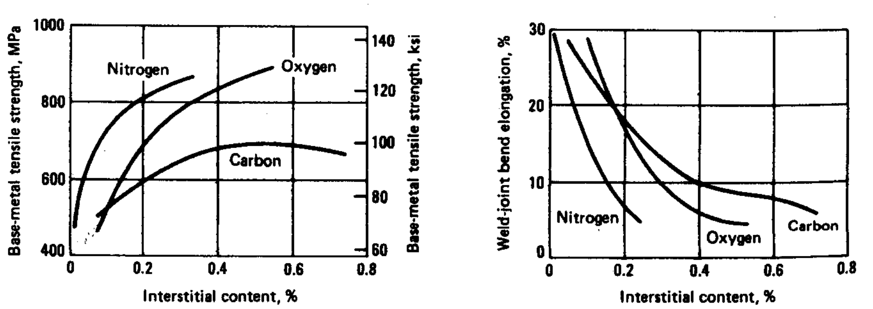

Fig. 1 Effects of interstitial-element content on strength and ductility of unalloyed titanium

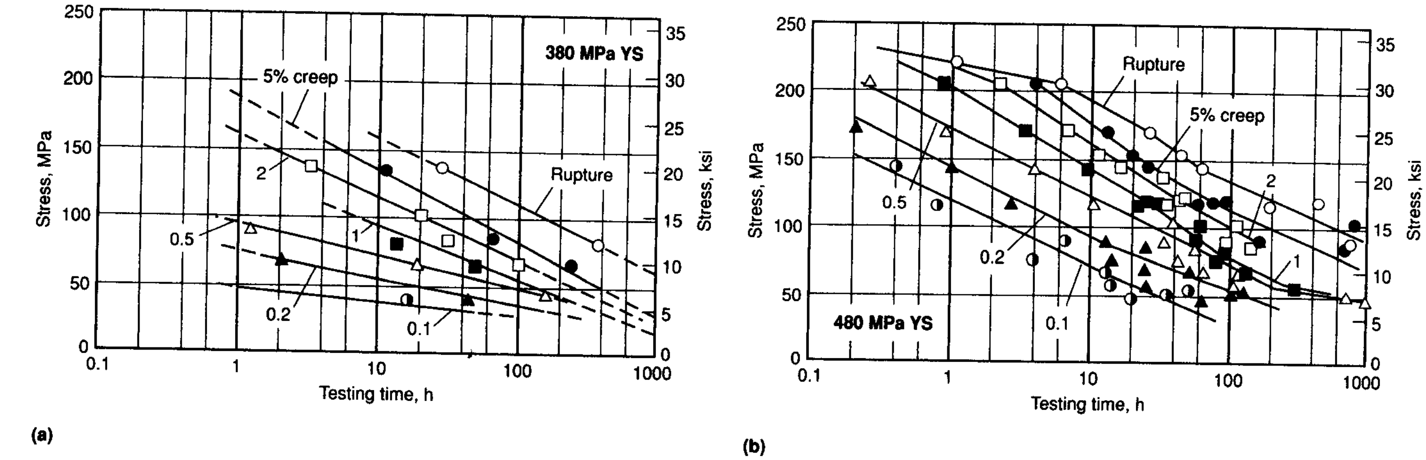

Fig. 5 Creep characteristics at 425 °C (800 °F) for mill-annealed titanium (99.0% Ti) with a 0.2% yield strength (YS) of (a) 380 MPa (55 ksi) and (b) 480 MPa (70 ksi)

ladium grades and alloy Ti-0.3Mo-0.8Ni (ASTM grade 12 or UNS R53400). The alloy contents allow improvements in corrosion resistance and/or strength.

Titanium-palladium alloys with nominal palladium contents of about 0.2% Pd (Table 2) are used in applications requiring excellent corrosion resistance in chemical processing or storage applications where the media is mildly reducing or fluctuates between oxidizing and reducing. The palladium-containing alloys extend the range of titanium application in hydrochloric, phosphoric, and sulfuric acid solutions (Table 4). Characteristics of good fabricability, weldability, and strength level are similar to those of corresponding unalloyed titanium grades.

Palladium additions of less than specified minimums are less effective in promoting an improved corrosion resistance. Excess palladium (above specified range) is not cost effective. Only alpha soluble amounts of palladium are added to make titanium-palladium alloys; therefore, microstructures are essentially the same as for equivalent grades of unalloyed titanium. Titanium-palladium intermetallic compounds formed in this system have not been reported to occur with normal heat treatments.

Alloy Ti-0.3Mo-0.8Ni (UNS R53400, or ASTM grade 12) has applications similar to those for unalloyed titanium but has better strength (Fig. 8) and corrosion resistance (Fig. 9). However, the corrosion resistance of this alloy is not as good as the titanium-palladium alloys. The ASTM grade 12 alloy is particularly resistant to crevice corrosion (Fig. 10) in hot brines (see the section "Corrosion Resistance and Chemical Reactivity" in this article for a brief discussion on crevice corrosion). The microstructure of R53400 is either equiaxed or acicular alpha with minor amounts of beta. Acicular alpha microstructures are found primarily in welds or heat-affected zones.

In a series of crevice corrosion tests, Ti-0.3Mo-0.8Ni was completely resistant in 500-h exposures to the following boiling solutions: saturated $ZnCl_2$ at pH of 3.0; 10% $AlCl_3$; $MgCl_2$ at pH of 4.2; 10% NH_4Cl at pH of 4.1; saturated NaCl, and saturated NaCl + Cl_2, both at pH of 1.0; and 10% Na_2SO_4 at pH of 1.0. In a similar test in boiling 10% $FeCl_3$, crevice corrosion was observed in metal-to-Teflon crevices after 500 h. Ti-0.3Mo-0.8Ni also exhibits the following typical corrosion rates:

Environment	Corrosion rate mm/yr	Corrosion rate mils/yr
Wet Cl_2 gas	0.00089	0.035
5% NaOCl + 2% NaCl + 4% NaOH(a)	0.06	2.4
70% $ZnCl_2$	0.005–0.0075	0.2–0.3
50% citric acid	0.013	0.5
10% sulfamic acid	11.6	455
45% formic acid	nil	nil
88–90% formic acid	0–0.56	0–22
90% formic acid(b)	0.56	2.2
10% oxalic acid	104	4100

(a) No crevice corrosion in metal-to-metal or metal-to-Teflon crevices. (b) Anodized specimens

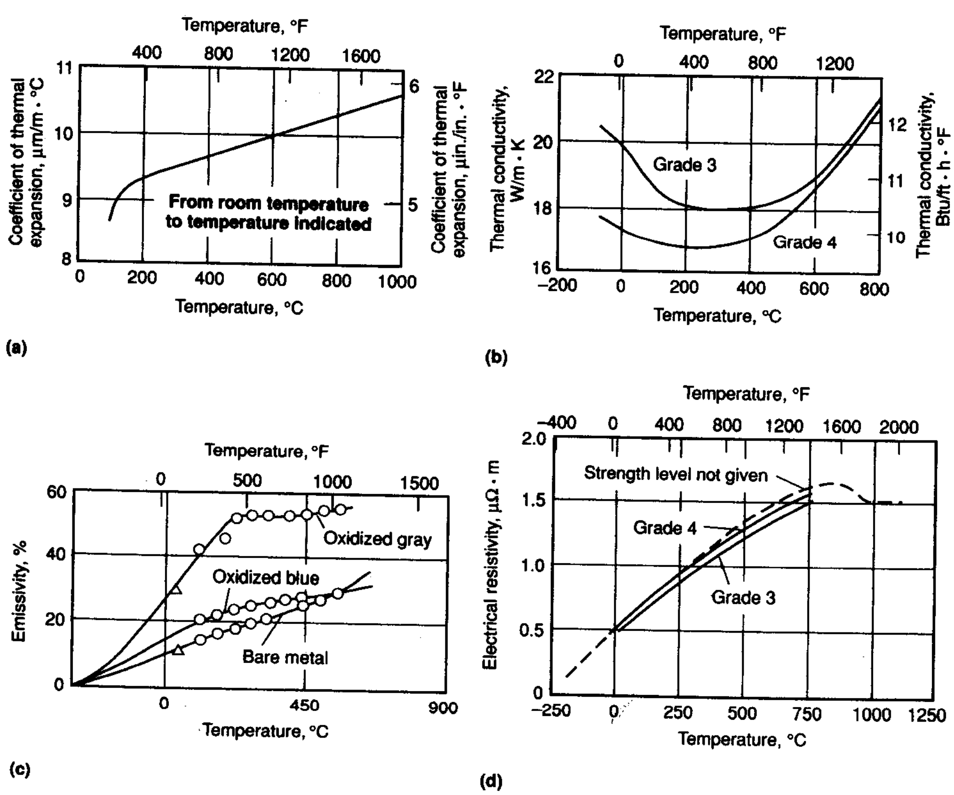

Fig. 6 Various thermal, electrical, and optical properties of unalloyed titanium at elevated temperatures. (a) Thermal expansion. (b) Thermal conductivity. (c) Optical emissivity. (d) Electrical resistivity

Titanium Alloys

Tables 5(a), 5(b), and 5(c) list the compositions of various titanium alloys. Because the allotropic behavior of titanium allows

Table 5(a) Compositions of various alpha and near-alpha titanium alloys

Product specification	Impurity limits, wt% max: N	C	H	Fe	O	Max total others or max each	Alloying elements, wt%(a): Al	Sn	Zr	Mo	Others
Ti-2.5Cu (AECMA designation, Ti-P11)											
Bars (AECMA standards prEN2523 and 2521)	0.05	0.08	0.01	0.2	0.2	0.4 total others	...	...	...	...	2.0–3.0Cu
Sheet or strip (prEN2128) and forgings (prEN2522 and 2525)	0.05	0.08	0.012	0.2	0.2	0.4 total others	...	...	...	...	2.0–3.0Cu
Ti-5Al-2.5Sn (UNS designation R54520)											
DIN17851 (alloy WL3.7115)	0.05	0.08	0.02	0.5	0.2	...	4.0–6.0	2.0–3.0	...	...	...
AMS 4910 (plate, sheet, strip)	0.05	0.08	0.02	0.5	0.2	0.005Y(b)	4.50–5.75	2.00–3.00	...	...	...
AMS 4926 (bars, rings) and AMS 4966 (forgings)	Impurity limits same as AMS 4910						4.00–6.00	2.00–3.00	...	...	...
ASTM B 265 (plate, sheet, strip)	0.05	0.10	0.02	0.4	0.2	(b)	4.00–6.00	2.00–3.00	...	...	0.12–0.25Pd
ASTM B 348 (bar, billet) and ASTM B 381 (forgings)	0.05	0.10	0.0125	0.4	0.2	(b)	4.00–6.00	2.00–3.00	...	...	...
3620-TA7 (Chinese)	0.05	0.10	0.015	0.3	0.2	0.15Si	4.00–6.00	2.00–3.00	...	...	...
Ti-5Al-2.5Sn-ELI (UNS designation R54521)											
AMS 4909 (plate, sheet, strip)	0.035	0.05	0.0125	0.25	0.12	O + Fe = 0.32, 0.005Y, 0.05 each, 0.3 total	4.50–5.75	2.00–3.00	...	...	...
AMS 4924 (bars, forgings)	0.035	0.05	0.0125	0.25	0.12	O + Fe = 0.32, others(b)	4.70–5.6	2.00–3.00	...	...	...
VT51 (U.S.S.R.)	0.05	0.10	0.015	0.30	0.02	0.15Si	4.00–5.00	2.00–3.00	...	...	...
Ti-8Al-1V-1Mo (UNS R54810)(c)											
AECMA, Ti-P66	Impurity limits not available						8	...	...	1	1V
AMS 4915, 4916, 4933 (rings), 4955 (wire), 4972 (bars, forgings), 4973 (forgings)	0.05	0.08	0.015	0.30	0.12	0.005Y, (b)	7.35–8.35	...	...	0.75–1.25	0.75–1.25V
MIL-R-81588 (ring, wire)	0.015	0.035	0.005	0.20	0.12	0.3 total	7.35–8.35	...	...	0.75–1.25	0.75–1.25V
Ti-6242 (UNS R54620)(c)											
AMS 4919, 4975, 4976	0.05	0.05	0.0125	0.25	0.15	(d), 0.1Si, 0.005Y	5.50–6.50	1.8–2.2	3.6–4.4	1.8–2.2	...
U.S. government (military)	0.04	0.05	0.015	0.25	0.15	0.13Si, 0.3 max others	5.50–6.50	1.8–2.2	3.6–4.4	1.8–2.2	...
Ti-6Al-2Nb-1Ta-0.8 Mo (UNS R56210)											
Typical	0.02	0.03	0.0125	0.12	0.10	...	6	...	...	0.8	2Nb, 1Ta
U.S. government (military)	0.03	0.05	0.0125	0.25	0.10	0.4 total	5.5–6.5	...	...	0.5–1.00	1.5–2.50Nb, 0.5–1.5Ta
Ti-679 (UNS R54790)											
Typical	0.04	0.04	0.008	0.12	0.17	...	2.25 (nom)	11	5	1	0.2Si, nom
AMS 4974 (bars, forgings)	0.04	0.04	0.0125	0.12	0.15	(b), 0.005Y	2.0–2.5	10.5–11.5	4.0–6.0	0.8–1.2	0.15–0.27Si
British TA.18, TA.19, TA.25, and TA.26	...	...	0.0125	0.20	...	...	2.0–2.5	10.5–11.5	4.0–6.0	0.8–1.2	0.1–0.5Si, 78.08 Ti min
British TA.20, TA.27	...	...	0.015	0.20	...	...	2.0–2.5	10.5–11.5	4.0–6.0	0.8–1.2	Same as TA.27
Other near-α alloys											
Ti-6242S(c)(e)	...	...	...	...	...	...	6	2	4	2	0.08Si
Ti-5Al-5Sn-2Zr-2Mo(f)	0.03	0.05	0.0125	0.15	0.13	...	5	5	2	2	0.25Si
Ti-6Al-2Sn-1.5Zr-1Mo	...	...	...	...	...	...	6	2	1.5	1	0.35Bi, 0.1Si
IMI 685	...	...	...	...	...	...	6	...	5	0.5	0.25Si
IMI 829	...	...	...	...	...	...	5.5	3.5	3	0.25	1Nb, 0.3Si
IMI 834	...	...	...	...	...	...	5.5	4.5	4	0.5	0.7Nb, 0.4Si, 0.06C
Ti-1100	...	...	...	0.02	0.07	...	6	2.75	4	0.4	0.45Si

(a) Unless a range is specified, values are nominal quantities. (b) 0.1 max each and 0.4 max total. (c) Depending on heat treatment, these alloys may be considered either near-α or α-β and are also listed in table 5(b) for α-β alloys. (d) 0.1 max each and 0.3 max total. (e) In the United States, alloy Ti-6242S is typically classified as a "superalpha" or "near-α" alloy, although it is closer to being an α-β alloy with its typical heat treatment. (f) Semicommercial alloy with a UNS designation of R54560

the alpha transus and the beta transus. Typically, beta stabilizers cause a widening (or flattening) between the alpha and beta transus temperature. In Fig. 11, for example, the lean beta stabilizer content of alloy IMI 829 produces a near-alpha alloy with a steep beta-transus approach curve. In contrast, an alloy with additional beta stabilizer (in this case Ti-6Al-4V) results in an alpha-beta alloy with a flattened approach curve.

The use of carbon to flatten the approach curve while also stabilizing the alpha phase is the basis for near-alpha alloy IMI 834 (Ref 10). Alloy IMI 834 is heat treated high in the alpha-beta region (Fig. 11) to give about 7.5 to 15 vol% of primary alpha in a fine grain (~0.1 mm) matrix of transformed beta. This combination of equiaxed alpha and transformed beta provides a good combination of creep and fatigue strength (Ref 9). Carbon also improves strength and fatigue performance.

Alloy Classes

Titanium alloys are classified as alpha alloys, alpha-beta alloys, and beta alloys. Alpha alloys have essentially all-alpha microstructures. Beta alloys have largely all-beta microstructures after air cooling from the solution treating temperature above the beta transus. Alpha-beta alloys contain a mixture of alpha and beta phases at room temperature. Within the alpha-beta class,

Table 5(b) Compositions of various alpha-beta titanium alloys

Product specification(s)	Impurity limits, wt% max						Alloying elements, wt%(a)				
	N	C	H	Fe	O	Max others, each or total	Al	Sn	Zr	Mo	Others
Ti-6Al-4V (UNS R56400)											
Typical	0.05	0.10	(b)	0.3	0.2	. . .	6	. . .	. . .	. . .	4
Alloy Ti-P63 in AECMA standard prEN2530 for bars	0.05	0.08	0.01	0.3	0.2	0.4 total	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
Alloy Ti-P63 in AECMA standard prEN2517 for sheet, strip, plate	0.05	0.08	0.012	0.3	0.2	0.4 total	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
DIN 17851 (alloy WL3.7165)	0.05	0.08	0.015	0.3	0.2	. . .	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
AMS 4905 (plate)	0.03	0.05	0.0125	0.25	0.12	(c), 0.005Y	5.6–6.3	. . .	. . .	. . .	3.6–4.4V
AMS 4906 (sheet, strip)	0.05	0.08	0.0125	0.30	0.20	0.4 total	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
AMS 4911 (plate, sheet, strip)	0.05	0.08	0.015	0.30	0.20	(c), 0.005Y	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
AMS 4920, 4928, 4934, and 4967 (rings, forgings, wires)	0.05	0.10	0.0125	0.30	0.20	(c), 0.005Y	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
AMS 4954 (wire)	0.03	0.05	0.015	0.30	0.18	(c), 0.005Y	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
ASTM B 265 (plate, sheet)	0.05	0.10	0.015	0.40	0.20	(c)	5.5–6.75	. . .	. . .	. . .	3.5–4.5V, 0.12–0.25Pd
ASTM F 467 (nuts) and F 468 (bolts)	0.05	0.10	0.0125	0.40	0.20	(c)	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
Ti-6Al-4V-ELI (UNS R56401)											
AMS 4907 and 4930	0.05	0.08	0.0125	0.25	0.13	(c), 0.005Y	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
AMS 4996 (billet)	0.04	0.10	0.0125	0.30	0.13–0.19	(d)	5.5–6.75	0.1 max	0.1 max	0.1 max	3.5–4.5V
ASTM F 135 (bar)	0.05	0.08	0.0125	0.25	0.13	. . .	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
ASTM F 467 (nuts) and F 468 (bolts)	0.05	0.10	0.0125	0.40	0.20	. . .	5.5–6.75	. . .	. . .	. . .	3.5–4.5V
Ti-6Al-6V-2Sn (UNS R56620)											
Typical	0.04	0.05	0.015	0.35–1.0	0.20	. . .	6	2	. . .	. . .	0.75Cu, 6V
AMS 4918, 4936, 4971, 4978	0.04	0.05	0.015	0.35–1.0	0.20	(c), 0.005Y	5.0–6.0	1.5–2.5	. . .	. . .	0.35–1.00Cu, 5.0–6.0V
AMS 4979 (bars, forgings)	0.04	0.05	0.015	0.35–1.0	0.20	(c)	5.0–6.0	1.5–2.5	. . .	. . .	Same as above
Other α-β alloys											
UNS 56080 (in AMS 4908)	0.05	0.08	0.015	0.50	0.20	. . .	. . .	. . .	. . .	. . .	8.0Mn
UNS 56740 (in AMS 4970)	0.05	0.10	0.013	0.30	0.20	. . .	7	. . .	. . .	4	. . .
Ti-6246 (UNS R56260)	0.04	0.04	0.0125	0.15	0.15	. . .	6	2	4	6	. . .
Ti-17 (see also Table 5c)	0.04	0.05	0.0125	0.30	0.13	. . .	5	2	2	4	4.0Cr
Ti-6Al-2Sn-2Zr-2Cr-2Mo	0.03	0.05	0.0125	0.25	0.14	. . .	5.25–6.25	1.75–2.25	1.75–2.25	1.75–2.25	0.20–0.27Si, 1.75–2.25Cr
IMI-551	. . .	. . .	. . .	. . .	. . .	. . .	4	4	. . .	4	0.5Si
Ti-3Al-2.5V (in AMS 4943)	0.02	0.05	0.015	0.30	0.12	. . .	2.5–3.5	. . .	. . .	. . .	2.0–3.0V
IMI 550	. . .	. . .	. . .	. . .	. . .	. . .	4	2	. . .	4	. . .
IMI 679	. . .	. . .	. . .	. . .	. . .	. . .	2	11	4	1	0.25Si
IMI 700	. . .	. . .	. . .	. . .	. . .	. . .	6	. . .	5	4	1Cu, 0.2Si
Ti-8Al-1Mo-1V(e)	0.05	0.08	0.015	0.30	0.12	. . .	8	. . .	. . .	1	1V
Ti-6242(e)	0.05	0.05	0.0125(f)	0.25	0.15	0.3 total	5.5–6.5	1.8–2.2	3.6–4.4	1.8–2.2	. . .
Ti-6242S(e)	. . .	. . .	. . .	. . .	. . .	. . .	6	2	4	2	0.08Si

(a) Unless a range is specified, values are nominal quantities. (b) Typical hydrogen limits of 0.0150H (sheet), 0.0125H (bar), and 0.0100H (billet). (c) 0.1 max each, 0.4 max total. (d) 0.1 max Cu, 0.1 max Mn, 0.001 Y, total others 0.20 max. (e) These alloys are considered either a near-α or an α-β alloy (see Table 5a). (f) 0.0100 max H for bar and billet and 0.0150 max H for sheet and forgings

an alloy that contains much more alpha than beta is often called a near-alpha alloy. The names super-alpha and lean-beta alpha are also used for this type of alpha-beta alloy. For the purposes of this discussion, the near-alpha alloys are grouped with the alpha alloys, even though they may have some microstructural similarities with the alpha-beta alloys.

Alpha alloys (Table 5a) such as Ti-5Al-2.5Sn are slightly less corrosion resistant but higher in strength than unalloyed titanium. Alpha alloys generally are quite ductile, and the ELI grades retain ductility and toughness at cryogenic temperatures. Alpha alloys cannot be strengthened by heat treatment because the alpha structure is a stable phase. The principal microstructural variable of alpha alloys is the grain size. For a fixed composition, short-time strength (yield) and long-time strength (creep rupture) are influenced by grain size and stored energy (if any) of deformation.

The principal alloying element in alpha alloys is aluminum, but certain alpha alloys, and most commercial unalloyed titanium, contain small amounts of beta-stabilizing elements. Alpha alloys that contain small additions of beta stabilizers (Ti-8Al-1Mo-1V or Ti-6Al-2Nb-1Ta-0.8Mo, for example) sometimes have been classed as superalpha or near-alpha alloys. Although they contain some retained beta phase, these alloys consist primarily of alpha and may behave more like conventional alpha alloys in that their response to heat treatment (age hardening) and processing more nearly follows that of the alpha alloys than the conventional alpha-beta alloys.

Because near-alpha alloys contain some beta stabilizers, near-alpha alloys can exhibit microstructural variations (Fig. 12) similar to that of alpha-beta alloys. The microstructures can range from equiaxed alpha (Fig. 12a), when processing is performed in the alpha-beta region, to an acicular structure (Fig. 12c) of transformed beta after processing above the beta transus. Because these microstructural variations are related to different property improvements (Table 8), the processing temperatures of near-alpha alloys generally influence properties in the following way:

Property	β processed	α/β processed
Tensile strength	Moderate	Good
Creep strength	Good	Poor
Fatigue strength	Moderate	Good
Fracture toughness	Good	Poor
Crack growth rate	Good	Moderate
Grain size	Large	Small

Table 5(c) Compositions of various beta titanium alloys

Designation	Specifications	Impurity limits, wt% max: N	C	H	Fe	O	Max others, each or total	Alloying elements, wt%(a): Al	Sn	Zr	Mo	Others
Ti-13V-11Cr-3Al (UNS 58010)	AMS 4917	0.05	0.05	0.025	0.35	0.17	(b)	2.5–3.5	...	...	...	12.5–14.5V, 10.0–12.
	AMS 4959 (wire)	0.05	0.05	0.030	0.35	0.17	(b), 0.005Y	2.5–3.5	...	...	...	12.5–14.5V, 10.0–12.
	MIL-T-9046, MIL-R-81588	0.05	0.05	0.025	0.15–0.35	0.17	0.4 total	2.5–3.5	...	...	...	12.5–14.5V, 10.0–12.
	MIL-T-9047; MIL-F-83142	0.05	0.05	0.025	0.35	0.17	...	2.5–3.5	...	...	...	12.5–14.5V, 10.0–12.
	High-toughness grade	0.015	0.04	0.008	...	0.11(max), 0.08(nom)	(c)	2.5–3.5	...	...	...	12.5–14.5V, 10.0–12.
Ti-8Mo-8V-2Fe-3Al (UNS R58820)	MIL-T-9046, MIL-T-9047, and MIL-F-83142	0.05	0.05	0.015	1.6–2.4	0.16	0.4 total	2.6–3.4	...	...	7.5–8.5	7.5–8.5V
Beta C (UNS R58640)	Same as above	0.05	0.05	0.015	0.30	0.12	0.4 total	3.0–4.0	...	3.5–4.5	3.5–4.5	7.5–8.5V
Beta III	AMS: 4977, 4980 ASTM: B 348, B 265, B 337, and B 338	0.05	0.10	0.020	0.35	0.18	0.4 total	...	3.75–5.25	4.5–7.5	10.0–13.0	...
Ti-10V-2Fe-3Al	Forging alloy	0.05	0.05	0.015	1.6–2.5	0.13	(c)	2.5–3.5	...	...	...	9.25–10.75V
Ti-15-3	Sheet alloy	0.03	0.03	0.015	0.30	0.13	(c)	2.5–3.5	2.5–3.5	...	...	14–16V, 2.5–3.5C
Ti-17(d)	Engine compressor alloy	0.05	0.05	0.0125	0.25	0.08–0.13	(c)	4.5–5.5	1.6–2.4	1.6–2.4	3.5–4.5	3.5–4.5Cr
Transage 175	High-strength, elevated-temperature	0.05	0.08	0.015	0.20	0.15	(b)(e)	2.2–3.2	6.5–7.5	1.5–2.5	...	12.0–14.0V
Transage 134	High-strength alloy	0.05	0.08	0.015	0.20	0.15	(b)(e)	2.0–3.0	1.5–2.5	5.5–6.5	...	11.0–13.0V
Transage 129	...	...	...	...	...	...	...	2	2	11	...	11.5V

(a) Unless a range is specified, values are nominal quantities. (b) 0.1 max each, 0.4 max total. (c) 0.1 max each, 0.3 max total. (d) Alloy Ti-17 is an α-rich near-β alloy that might be classified as an α-β a depending on heat treatment. (e) 0.005 max Y and 0.03 max B

In heat treating titanium alloys above the beta transus, a coarse beta grain size is likely unless adequate precautions are taken in forging and/or heat treatment. In contrast, a beta grain size of ≈0.1 mm can be achieved by processing near-alpha alloys high in the alpha-beta region (that is, near the beta transus) as compared to a typical beta grain size of 0.5 to 1.0 mm for beta-processed alloys. The quench rate also has a significant effect on the transformation product in that slow rates will give aligned alpha plates, which tend to be good for creep but somewhat worse than the faster quenched structures, basket-weave alpha, in fatigue.

Alpha-beta alloys (Table 5b), which contain one or more alpha stabilizers plus one or more beta stabilizers, can be strengthened by heat treatment or thermomechanical processing. Generally, when strengthening is desired, the alloys are rapidly cooled from a temperature high in the alpha-beta range or even above the beta transus. This solution treatment is followed by an intermediate-temperature treatment (aging) to produce an appropriate mixture of alpha and transformed beta products. Response to heat treatment is a function of cooling rate from the solution temperature and therefore may be affected by section size.

Like the near-alpha alloy in Fig. 12, the microstructure of alpha-beta alloys can take on different forms, ranging from equiaxed to acicular or some combination of both. Equiaxed structures are formed by working an alloy in the alpha-beta range and annealing at lower temperatures. Acicular structures (Fig. 13c) are formed by working or heat treating above the beta transus and rapid cooling. Rapid cooling from temperatures high in the alpha-beta range (Fig. 13d and e) will result in equiaxed primary (prior) alpha and acicular alpha from the transformation of beta structures. Generally, there are property advantages and disadvantages for each type of structure. Table 8 compares, on a relative basis, the advantages of each structure.

By a suitable manipulation of forging and heat treatment schedules, a wide range of properties is attainable in alpha-beta alloys. In particular, the alpha-beta alloys are more responsive to aging than the near-alpha alloys. The near-alpha alloys are less responsive to aging because little, if any, change in properties can be expected when phases are in a nearly equilibrium condition prior to aging.

In the alpha-beta alloys, the presence of nonequilibrium phases, such as alpha-prime or metastable beta, results in substantial increases in tensile and yield strengths following the aging treatment. Table 9, for example, shows the response to heat treatment for the widely used Ti-6Al-4V alloy. The tensile data show that no response to aging occurs upon furnace cooling from solution temperatures. Only a slight response occurs upon air cooling (microstructures in Fig. 13b and d), while the greatest response is experienced with water quenching from the solution temperature (microstructures in Fig. 13c and e). Good response to aging takes place upon water quench from the beta field (Fig. 13c); howev ductilities are quite low (Table 9). The b combination of properties can be produ by solution treating and rapidly quench from close to but below the beta tran temperature (Fig. 13d or e), followed by aging treatment (Table 9).

Beta alloys (Table 5c) are sufficiently r in beta stabilizers (and lean in alpha stabi ers) that the beta phase can be complet retained with appropriate cooling rates. B alloys are metastable, and precipitation alpha phase in the metastable beta is a me od used to strengthen the alloys. Beta all contain small amounts of alpha-stabilizing ements as strengthening agents.

As a class, beta and near-beta alloys of increased fracture toughness over alp beta alloys at a given strength level, w the advantage of heavy section heat tre ment capability. However, beta and ne beta alloys may require close control processing and fabrication steps to achi optimal properties, though this is not ways the case. In the past, beta alloys h rather limited applications, such as sprin and fasteners, where very high strength v required.

In recent years, however, beta allo have received closer attention because th fracture toughness characteristics respo to the increased need for damage tolera in aerospace structures. In addition, so beta alloys containing molybdenum ha good corrosion characteristics. Beta allo also exhibit:

Table 18 Typical tensile, bend, and hardness data for as-welded titanium and several titanium alloys

Material condition	Tensile strength		Yield strength		Elongation, %	Minimum bend radius	Hardness	
	MPa	ksi	MPa	ksi			Knoop	Rockwell
Ti Grade 1								
Unwelded sheet	315	46	215	31	50.4	0.7*t*	140	63.5 HRB
Single-bead weld	345	50	255	37	37.5	1.0*t*	140	55.8 HRB
Multiple-bead weld	365	53	270	39	37.7	...	...	...
Transverse weld	325	47(a)	...	...	...	...	...	...
Ti Grade 2								
Unwelded sheet	460	67	325	47	26.2	2.9*t*	165	80.6 HRB
Single-bead weld	505	73	380	55	18.3	2.9*t*	175	83.1 HRB
Multiple-bead weld	510	74	385	56	13.3	...	...	...
Transverse weld	475	69(a)	...	...	...	...	...	...
Ti Grade 3								
Unwelded sheet	545	79	395	57	25.9	1.9*t*	175	94.4 HRB
Single-bead sheet	605	88	475	69	15.5	4.7*t*	220	92.4 HRB
Multiple-bead weld	615	89	480	70	14.7	...	...	...
Transverse weld	560	81(a)	...	...	...	...	...	...
Ti Grade 4								
Unwelded sheet	660	96	530	77	22.3	3.2*t*	215	23.4 HRC
Single-bead weld	695	101	580	84	16.4	5.6*t*	240	21.2 HRC
Multiple-bead weld	710	103	585	85	16.0	...	...	...
Transverse weld	660	96(a)	...	...	...	...	...	...
Ti-5Al-2.5Sn-ELI								
Unwelded sheet	850	123	805	117	15.7	3.8*t*	265	33.2 HRC
Single-bead weld	920	133	770	112	9.8	5.9*t*	310	28.0 HRC
Multiple-bead weld	935	136	820	119	7.5	...	...	...
Transverse weld	850	123(a)	...	...	...	...	...	...
Ti-6Al-2Nb-1Ta-1Mo								
Unwelded sheet	895	130	855	124	9.7	2.8*t*	275	29.6 HRC
Single-bead weld	930	135	800	116	5.9	7.7*t*	300	27.7 HRC
Multiple-bead weld	945	137	815	118	5.7	...	...	...
Transverse weld	890	129(a)	...	...	...	...	...	...
Ti-3Al-2.5V								
Unwelded sheet	705	102	670	97	15.2	4.0*t*	230	23.6 HRC
Single-bead weld	705	102	600	87	12.7	5.4*t*	250	19.6 HRC
Multiple-bead weld	745	108	625	91	11.2	...	...	...
Transverse weld	710	103(a)	...	...	...	...	...	...
Ti-6Al-4V								
Unwelded sheet	1000	145	945	137	11.0	2.6*t*	320	32.2 HRC
Single-bead weld	1060	154	920	133	3.5	10.5*t*	350	35.9 HRC
Multiple-bead weld	1090	158	945	137	3.2	...	...	...
Transverse weld	1015	147(a)	...	...	...	...	...	...
Ti-8Al-1Mo-1V								
Unwelded sheet	1060	154	1020	148	15.0	2.9*t*	325	36.0 HRC
Single-bead weld	1085	157	930	135	5.5	7.0*t*	345	35.2 HRC
Multiple-bead weld	1115	162	960	139	3.2	...	...	...
Transverse weld	1060	154(a)	...	...	...	...	...	...
Ti-6Al-6V-2Sn								
Unwelded sheet	1060	154	1005	146	9.8	2.8*t*	350	34.0 HRC
Single-bead weld	1295	188	1255	182	0.3	25.6*t*	420	46.8 HRC
Multiple-bead weld	1280	186	...	...	0.1	...	...	...
Single-bead weld after furnace cool from 830 °C	1050	152	990	144	3.7	15.5*t*	...	...
Ti-13V-11Cr-3Al								
Unwelded sheet	965	140	910	132	13.9	2.7*t*	300	30.6 HRC
Single-bead weld	950	138	925	134	11.6	2.7*t*	320	30.1 HRC
Multiple-bead weld	925	134	875	127	9.1	...	...	...
Transverse weld	950	138(a)	...	...	...	...	...	...

(a) Fracture occurred in base metal.

high in the alpha-beta field, material properties appear similar to those resulting from high-temperature annealing. With most alloys, a final low-temperature anneal will produce properties characteristic of typical annealed material.

Welding has the greatest potential for affecting material properties. In all types of welds, contamination by interstitial impurities such as oxygen and nitrogen must be minimized to maintain useful ductility in the weldment. Alloy composition, welding procedure, and subsequent heat treatment are highly important in determining the final properties of welded joints. Table 18 reviews mechanical properties for representative alloys and types of welds. The data can be summarized as follows:

- Welding generally increases strength and hardness
- Welding generally decreases tensile and bend ductility
- Welds in unalloyed titanium grades 1, 2,

Table 20 Typical physical properties of wrought titanium alloys

See Table 15 for transus temperatures.

Nominal composition, %	Coefficient of linear thermal expansion, μm/m · K (μin./in. · °F) At 20–100 °C (70–212 °F)	At 20–205 °C (70–400 °F)	At 20–315 °C (70–600 °F)	At 20–425 °C (70–800 °F)	At 20–540 °C (70–1000 °F)	At 20–650 °C (70–1200 °F)	At 20–815 °C (70–1500 °F)	Electrical resistivity(a), μΩ · m	Thermal conductivity(a), W/m · K	Density(a) g/cm³	Density(a) lb/in.³
Commercially pure titanium											
ASTM grades 1, 2, 3, 4, 7, and 11	8.6 (4.8)	· · ·	9.2 (5.1)	· · ·	9.7 (5.4)	10.1 (5.6)	10.1 (5.6)	0.42–0.52	16	4.51	0.163
α alloys											
5Al-2.5-Sn	9.4 (5.2)	· · ·	9.5 (5.3)	· · ·	9.5 (5.3)	9.7 (5.4)	10.1 (5.6)	1.57	7.4–7.8	4.48	0.162
5Al-2.5Sn (low O_2)	9.4 (5.2)	· · ·	9.5 (5.3)	· · ·	9.7 (5.4)	9.9 (5.5)	10.1 (5.6)	1.80	7.4–7.8	4.48	0.162
Near α											
8Al-1Mo-1V	8.5 (4.7)	· · ·	9.0 (5.0)	· · ·	10.1 (5.6)	10.3 (5.7)	· · ·	1.99	· · ·	4.37	0.158
11Sn-1Mo-2.25Al-5.0Zr-1Mo-0.2 Si	8.5 (4.7)	· · ·	9.2 (5.1)	· · ·	9.4 (5.2)	· · ·	· · ·	1.62	6.9	4.82	0.174
6Al-2Sn-4Zr-2Mo	7.7 (4.3)	· · ·	8.1 (4.5)	· · ·	8.1 (4.5)	· · ·	· · ·	1.9	7.1 at 100 °C	4.54	0.164
5Al-5Sn-2Zr-2Mo-0.25Si	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	10.3 (5.7)			4.51	0.163
6Al-2Nb-1Ta-1Mo	· · ·	· · ·	· · ·	· · ·	· · ·	9.0 (5.0)	· · ·	· · ·	6.4	4.48	0.162
IMI 685	9.8 (5.4)	9.3 (5.2)	9.5 (5.3)	9.8 (5.4)	10.1 (5.6)	· · ·	· · ·	1.68	4.2	4.45	0.161
IMI 829	· · ·	9.45 (5.3)	· · ·	9.8 (5.4)	· · ·	9.98 (5.5)	· · ·	· · ·	· · ·	4.54	0.164
IMI 834	· · ·	10.6 (5.9)	· · ·	10.9 (6.1)	· · ·	11 (6.1)	· · ·	· · ·	· · ·	4.55	0.164
α-β alloys											
8Mn	8.6 (4.8)	9.2 (5.1)	9.7 (5.4)	10.3 (5.7)	10.8 (6.0)	11.7 (6.5)	12.6 (7.0)	0.92	10.9	4.73	0.171
3Al-2.5V	9.5 (5.3)	· · ·	9.9 (5.5)	· · ·	9.9 (5.5)	· · ·	· · ·	· · ·	· · ·	4.48	0.162
6Al-4V	8.6 (4.8)	9.0 (5.0)	9.2 (5.1)	9.4 (5.2)	9.5 (5.3)	9.7 (5.4)	· · ·	1.71	6.6–6.8	4.43	0.160
6Al-4V (low O_2)	8.6 (4.8)	9.0 (5.0)	9.2 (5.1)	9.4 (5.2)	9.5 (5.3)	9.7 (5.4)	· · ·	1.71	6.6–6.8	4.43	0.160
6Al-6V-2Sn	9.0 (5.0)	· · ·	9.4 (5.2)	· · ·	9.5 (5.3)	· · ·	· · ·	1.57	6.6(b)	4.54	0.164
7Al-4Mo	9.0 (5.0)	9.2 (5.1)	9.4 (5.2)	9.7 (5.4)	10.1 (5.6)	10.4 (5.8)	11.2 (6.2)	1.7	6.1	4.48	0.162
6Al-2Sn-4Zr-6Mo	9.0 (5.0)	9.2 (5.1)	9.4 (5.2)	9.5 (5.3)	9.5 (5.3)	· · ·	· · ·	· · ·	7.7(c)	4.65	0.168
6Al-2Sn-2Zr-2Mo-2Cr-0.25Si	· · ·	· · ·	9.2 (5.1)	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	4.57	0.165
IMI 550	8.8 (4.9)	9.0 (5)	9.2 (5.1)	9.3 (5.2)	9.7 (5.4)	10.1 (5.6)	· · ·	1.58	7.5	4.60	0.166
IMI 679	8.2 (4.6)	8.9 (4.9)	9.3 (5.2)	9.4 (5.2)	9.6 (5.3)	· · ·	· · ·	· · ·	· · ·	4.84	0.175
β alloys											
13V-11Cr-3Al	9.4 (5.2)	9.9 (5.5)	10 (5.55)	10.1 (5.6)	10.2 (5.7)	10.4 (5.8)	· · ·	· · ·	· · ·	4.82	0.174
8Mo-8V-2Fe-3Al	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·			4.84	0.175
3Al-8V-6Cr-4Mo-4Zr	8.7 (4.8)	9 (5)	9.4 (5.2)	9.6 (5.3)	· · ·	· · ·	· · ·			4.82	0.174
11.5Mo-6Zr-4.5Sn	7.6 (4.2)	8.1 (4.5)	8.5 (4.7)	8.7 (4.8)	8.7 (4.8)	· · ·	· · ·	1.56	· · ·	5.06	0.183
15V-3Cr-3Al-3Sn	8.5 (4.7)	8.7–9 (4.8–5)	9.2 (5.1)	9.4 (5.3)	9.7 (5.4)	· · ·	· · ·	1.47	8.08	4.71	0.170
5Al-2Sn-2Zr-4Cr	9 (5)	9.2 (5.1)	9.4 (5.2)	9.5 (5.3)	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·	· · ·

(a) Room temperature. (b) At 93 °C (200 °F). (c) In solution treated and aged condition

notch strength, fracture toughness, and creep strength at strength levels similar to those obtained by regular annealing

- *Recrystallization annealing of Ti-6Al-4V or Ti-6Al-4V-ELI*: Heat 4 h or more at 925 to 955 °C (1700 to 1750 °F), furnace cool to 760 °C (1400 °F) at a rate no higher than 56 °C/h (100 °F/h), cool to 480 °C (900 °F) at a rate no lower than 370 °C/h (670 °F/h), air cool to room temperature. Advantages: improved fracture toughness and fatigue-crack-growth characteristics at somewhat reduced levels of strength. This is usually used with ELI material
- *Beta annealing of Ti-6Al-4V, Ti-6Al-4V-ELI, and Ti-6Al-2Sn-4Zr-2Mo. Ti-6Al-4V or Ti-6Al-4V-ELI*: Heat 5 min to 1 h at 1010 to 1040 °C (1850 to 1900 °F), air cool to 650 °C (1200 °F) at a rate of 85 °C/min (150 °F/min) or higher, then 2 h at 730 to 790 °C (1350 to 1450 °F), air cool. Advantages: improved fracture toughness, high-cycle fatigue strength, creep strength, and resistance to aqueous stress corrosion. Ti-6Al-2Sn-4Zr-2Mo: Heat ½ h at 1020 °C (1870 °F), air cool, then 8 h at 595 °C (1100 °F), air cool. Advantages: improved creep strength at elevated temperatures as well as improved fracture toughness

Post Heat Treating Requirements. Titanium reacts with the oxygen, water, and carbon dioxide normally found in oxidizing heat treating atmospheres and with hydrogen formed by decomposition of water vapor. Unless the heat treatment is performed in a vacuum furnace or in an inert atmosphere, oxygen will react with the titanium at the metal surface and produce an oxygen-enriched layer commonly called "alpha case." This brittle layer must be removed before the component is put into service. It can be removed by machining, but certain machining operations may result in excessive tool wear. Standard practice is to remove alpha case by other mechanical methods or by chemical methods, or by both.

Hydrogen Contamination. Titanium is chemically active at elevated temperatures and will oxidize in air. However, oxidation is not of primary concern. The danger of hydrogen pickup is of greater importance than that of oxidation. This is not normally a problem, but it could be a problem if using a steel heat treating furnace with a reducing atmosphere. Use of these furnaces should only be after complete purging. Current specifications limit hydrogen content to a maximum of 125 to 200 ppm, depending on alloy and mill form. Above these limits, hydrogen embrittles some titanium alloys, thereby reducing impact strength and notch tensile strength and causing delayed cracking. Beta alloys are more susceptible to hydrogen contamination but are also more tolerant of hydrogen.

Heat Treatment Verification. Hardness is not a good measure of the adequacy of the thermomechanical processes accomplished during the forging and heat treatment of titanium alloys, unlike most aluminum alloys and many heat-treatable ferrous alloys. Therefore, hardness measurements are not used to verify the processing of titanium alloys. Instead, mechanical property tests (for example, tensile tests and fracture toughness) and metallographic/microstructural evaluation are used to verify the thermomechanical processing of titanium alloy

Table 21 Minimum and average mechanical properties of wrought titanium alloys at room temperature

Nominal composition, %	Condition	Minimum and average tensile properties(a): Ultimate tensile strength, MPa (ksi)	0.2% yield strength, MPa (ksi)	Elongation, %	Reduction in area, %	Average or typical properties: Charpy impact strength, J (ft · lbf)	Hardness	Modulus of elasticity, GPa (10^6 psi)	Modulus of rigidity, GPa (10^6 psi)	Poisson's ratio	Bend radius for thickness (t) over 1.8 mm (0.07 in.)
Commercially pure titanium											
99.5 Ti (ASTM grade 1)	Annealed	240–331 (35–48)	170–241 (25–35)	30	55	···	120 HB	102.7 (14.9)	38.6 (5.6)	0.34	2t
99.2 Ti (ASTM grade 2)	Annealed	340–434 (50–63)	280–345 (40–50)	28	50	34–54 (25–40)	200 HB	102.7 (14.9)	38.6 (5.6)	0.34	2.5t
99.1 Ti (ASTM grade 3)	Annealed	450–517 (65–75)	380–448 (55–65)	25	45	27–54 (20–40)	225 HB	103.4 (15.0)	38.6 (5.6)	0.34	2.5t
99.0 Ti (ASTM grade 4)	Annealed	550–662 (80–96)	480–586 (70–85)	20	40	20 (15)	265 HB	104.1 (15.1)	38.6 (5.6)	0.34	3.0t
99.2 Ti(b) (ASTM grade 7)	Annealed	340–434 (50–63)	280–345 (40–50)	28	50	43 (32)	200 HB	102.7 (14.9)	38.6 (5.6)	0.34	2.5t
98.9 Ti(c) (ASTM grade 12)	Annealed	480–517 (70–75)	380–448 (55–65)	25	42	···	···	···	102.7 (14.9)	···	2.5t
α alloys											
5Al-2.5Sn	Annealed	790–862 (115–125)	760–807 (110–117)	16	40	13.5–20 (10–15)	36 HRC	110.3 (16.0)	···	···	4.5t
5Al-2.5Sn (low O_2)	Annealed	690–807 (100–117)	620–745 (90–108)	16	···	43 (32)	35 HRC	110.3 (16.0)	···	···	···
Near α											
8Al-1Mo-1V	Duplex annealed	900–1000 (130–145)	830–951 (120–138)	15	28	20–34 (15–25)	35 HRC	124.1 (18.0)	46.9 (6.8)	0.32	4.5t
11Sn-1Mo-2.25Al-5.0Zr-1Mo-0.2Si	Duplex annealed	1000–1103 (145–160)	900–993 (130–144)	15	35	···	36 HRC	113.8 (16.5)	···	···	···
6Al-2Sn-4Zr-2Mo	Duplex annealed	900–980 (130–142)	830–895 (120–130)	15	35	···	32 HRC	113.8 (16.5)	···	···	5t
5Al-5Sn-2Zr-2Mo-0.25Si	975 °C (1785 °F) (½ h), AC + 595 °C (1100 °F) (2 h), AC	900–1048 (130–152)	830–965 (120–140)	13	···	···	···	113.8 (16.5)	···	0.326	···
6Al-2Nb-1Ta-1Mo	As-rolled 2.5 cm (1 in.) plate	790–855 (115–124)	690–758 (100–110)	13	34	31 (23)	30 HRC	113.8 (17.5)	···	···	···
6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si	β forge + duplex anneal	1014 (147)	945 (137)	11	···	···	···	···	···	···	···
IMI 685 (Ti-6Al-5Zr-0.5Mo-0.25Si)	β heat treated at 1050 °C, OQ, + aged 24h at 550 °C	882–917 (128–133)	758–815 (110–118)	6–11 (on 5D)	15–22	43 (32)	···	~125 (~18)	···	···	···
IMI-829 (Ti-5.5Al-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si)	β heat treated at 1050 °C, AC, + aged 2h at 625 °C	930 (min) (35)	820 (min) (119)	9 (min) on 5D	15 (min)	···	···	···	···	···	···
IMI-834 (Ti-5.5Al-4.5Sn-4Zr-0.7Nb-0.5Mo-0.4Si-0.06C)	α–β processed	1030 (min) (149)	910 (min) (132)	6 (min) on 5D	15 (min)	···	···	···	···	···	···
α–β alloys											
8Mn	Annealed	860–945 (125–137)	760–862 (110–125)	15	32	···	···	113.1 (16.4)	48.3 (7.0)	···	···
3Al-2.5V	Annealed	620–689 (90–100)	520–586 (75–85)	20	···	54 (40)	···	106.9 (15.5)	···	···	···
6Al-4V	Annealed	900–993 (130–144)	830–924 (120–134)	14	30	14–19 (10–14)	36 HRC	113.8 (16.5)	42.1 (6.1)	0.342	5t
	Solution + aging	1172 (170)	1103 (160)	10	25	···	41 HRC	···	···	···	
6Al-4V (low O_2)	Annealed	830–896 (120–130)	760–827 (110–120)	15	35	24 (18)	35 HRC	113.8 (16.5)	42.1 (6.1)	0.342	···
6Al-6V-2Sn	Annealed	1030–1069 (150–155)	970–1000 (140–145)	14	30	14–19 (10–14)	38 HRC	110.3 (16.0)	···	···	4.5t
	Solution + aging	1276 (185)	1172 (170)	10	20	···	42 HRC	···	···	···	···
7Al-4Mo	Solution + aging	1103 (160)	1034 (150)	16	22	18 (13)	38 HRC	113.8 (16.5)	44.8 (6.5)	···	···
	Annealed	1030 (min) (50)	970 (min) (140)	···	···	···	···	···	···	···	···
6Al-2Sn-4Zr-6Mo	Solution + aging	1269 (189)	1172 (170)	10	23	8–15 (6–11)	36–42 HRC	113.8 (16.5)	···	···	···

(continued)

(a) If a range is given, the lower value is a minimum; all other values are averages. (b) Also contains 0.2 Pd. (c) Also contains 0.8 Ni and 0.3 Mo. AC, air-cooled

Table 21 (continued)

Nominal composition, %	Condition	Minimum and average tensile properties(a): Ultimate tensile strength, MPa (ksi)	0.2% yield strength, MPa (ksi)	Elongation, %	Reduction in area, %	Average or typical properties: Charpy impact strength, J (ft · lbf)	Hardness	Modulus of elasticity, GPa (10^6 psi)	Modulus of rigidity, GPa (10^6 psi)	Poisson's ratio	Bend radius for thickness (t) over 1.8 mm (0.07 in.)
α–β alloys (continued)											
6Al-2Sn-2Zr-2Mo-2Cr-0.25Si	Solution + aging	1276 (185)	1138 (165)	11	33	20 (15)	...	122 (17.7)	46.2 (6.7)	0.327	...
	Annealed	1030 (min) (150)	970 (min) (140)	...	...	...	...	...	...	...	...
Corona 5 (Ti-4.5Al-5Mo-1.5Cr)	β annealed plate	910 (132)	817 (118)	...	...	...	...	...	...	...	...
	β worked plate	945 (137)	855 (124)	...	...	...	...	...	...	...	...
	α-β worked	935 (131)	905 (131)	...	...	...	...	...	...	...	...
IMI 550 (Ti-4Al-4Mo-2Sn-0.5Si)	Solution at 900 °C, AC, + aging of 25 mm (1 in.) slice	1100 (160)	940 (136)	7 on 5D	15	23 (17)	...	~115 (~17)	...	...	...
β alloys											
13V-11Cr-3Al	Solution + aging	1170–1220 (170–177)	1100–1172 (160–170)	8	...	...	...	101.4 (14.7)	42.7 (6.2)	0.304	...
	Solution + aging	1276 (185)	1207 (175)	8	...	11 (8)	40 HRC	...	...	...	...
8Mo-8V-2Fe-3Al	Solution + aging	1170–1310 (170–190)	1100–1241 (160–180)	8	...	...	40 HRC	106.9 (15.5)	...	...	...
3Al-8V-6Cr-4Mo-4Zr (Beta C)	Solution + aging	1448 (210)	1379 (200)	7	...	10 (7.5)	...	105.5 (15.3)	...	...	...
	Annealed	883 (min) (128 min)	830 (min) (120 (min))	15	...	...	...	...	...	...	...
11.5Mo-6Zr-4.5Sn (Beta III)	Solution + aging	1386 (210)	1317 (191)	11	...	...	...	103 (15)	...	...	...
	Annealed	690 (min) (100 (min))	620 (min) (90 (min))	...	...	...	...	...	...	...	...
10V-2Fe-3Al	Solution + aging	1170–1276 (170–185)	1100–1200 (160–174)	10	19	...	...	111.7 (16.2)	...	...	...
Ti-15V-3Cr-3Al-3Sn (Ti-15-3)	Annealed	785 (114)	773 (112)	22	...	...	...	...	...	...	...
	Aged	1095–1335 (159–194)	985–1245 (143–180)	6–12	...	...	...	...	...	...	...
Ti-5Al-2Sn-2Zr-4Mo-4Cr(Ti-17)	Solution + aging	1105–1240 (160–180)	1305–1075 (150–170)	8–15	20–45	...	...	...	...	...	...
Transage 134 plate	Solution + aging	1055–1380 (153–200)	1000–1310 (145–190)	5–12	10–38	...	...	...	...	...	...
Transage 175 (extruded bar)	Solution + aging	1305 (189)	1250 (180)	10	39						
Transage 175 at 425 °C (800 °F)	Solution + aging	1080 (157)	925 (134)	10	56	...	...	...	...	...	...

(a) If a range is given, the lower value is a minimum; all other values are averages. (b) Also contains 0.2 Pd. (c) Also contains 0.8 Ni and 0.3 Mo. AC, air-cooled

forgings. Mechanical property and microstructural evaluations vary, ranging from the destruction of forgings to the testing of extensions and/or prolongations forged integrally with the parts.

Properties

The titanium alloys, with their high strengths and low densities, can often bridge the properties gap between aluminum and steel alloys, providing many of the desirable properties of each. For example, titanium, like aluminum, is nonmagnetic and has good heat-transfer properties (despite its relatively low thermal conductivity as discussed in the section "Commercially Pure Titanium" in this article). The thermal expansion coefficient of titanium alloys (Table 20), ranging from about 9 to 11 ppm/°C (5 to 6 × 10^{-6} in./in. · °F), is slightly lower than that of most steels and less than half that of aluminum. In addition, titanium is nontoxic and biologically compatible, making it useful for surgical-implant devices.

Other important characteristics of titanium alloys depend on the class of alloy (Fig. 23) and the morphology of the alpha constituents (Table 8). In the near-alpha and alpha-beta alloys, the variations in the alpha morphology are achieved with different heat treatments (Table 19). A fine equiaxed alpha (which is associated with high tensile strength, good ductility, and resistance to

Table 22 Yield strength and plane strain fracture toughness of various titanium alloys

Alloy	α morphology or processing method	Yield strength, MPa	Yield strength, ksi	Plane-strain fracture toughness (K_{Ic}), MPa $\sqrt{m}$	Plane-strain fracture toughness (K_{Ic}), ksi $\sqrt{in.}$
Ti-6Al-4V	Equiaxed	910	130	44–66	40–60
	Transformed	875	125	88–110	80–100
	α–β rolled + mill annealed(a)	1095	159	32	29
Ti-6Al-6V-2Sn	Equiaxed	1085	155	33–55	30–50
	Transformed	980	140	55–77	50–70
Ti-6Al-2Sn-4Zr-6Mo	Equiaxed	1155	165	22–23	20–30
	Transformed	1120	160	33–55	30–50
Ti-6Al-2Sn-4Zr-2Mo forging	α + β forged, solution treated and aged	903	131	81	74
	β forged, solution treated and aged	895	130	84	76
Ti-17	α-β processed	1035–1170	150–170	33–50	30–45
	β processed	1035–1170	150–170	53–88	48–80

(a) Standard oxygen (~0.20 wt%) Source: Adapted from Ref 1, Ref 13, Ref 15

THERMOPHYSICAL PROPERTIES OF MATTER
VOLUME 1

THERMAL CONDUCTIVITY

Metallic Elements and Alloys

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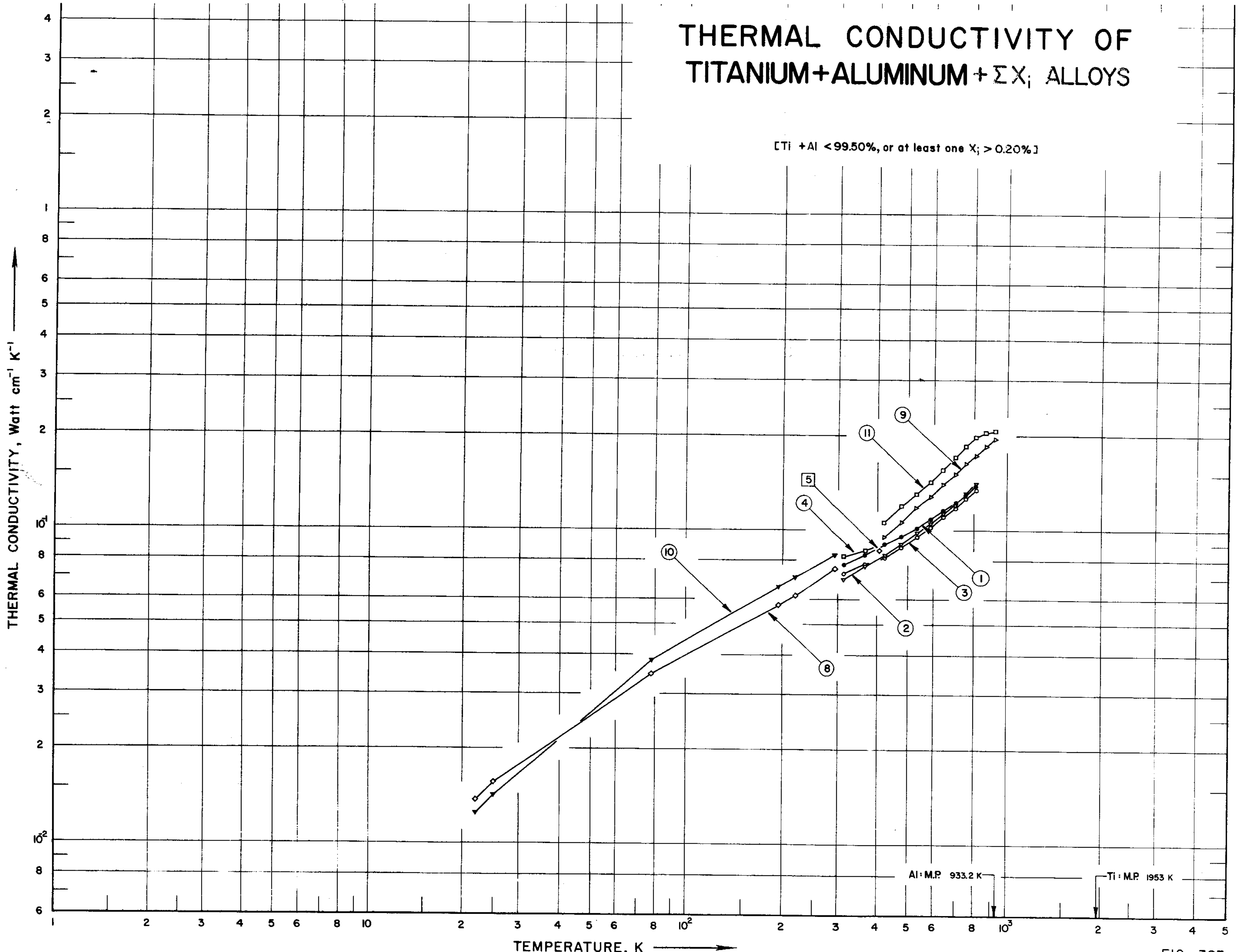

THERMAL CONDUCTIVITY OF
TITANIUM+ALUMINUM+ΣXi ALLOYS
[Ti +Al <99.50%, or at least one Xi > 0.20%]
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
Al: M.P. 933.2 K
Ti: M.P. 1953 K
1
2
3
4
5
8
9
10
11

FIG 303

SPECIFICATION TABLE NO. 303 THERMAL CONDUCTIVITY OF [TITANIUM + ALUMINUM + ΣX_i] ALLOYS

(Ti + Al < 99.50% or at least one X_i > 0.20%)

[For Data Reported in Figure and Table No. 303]

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	Al	V	Cr	Fe	Mo	Sn	Mn	Composition (continued), Specifications and Remarks
1	231	C	1958	311-811	<5	A-110 AT	Bal.	5.0					2.5		Nominal composition; specimen in mill-annealed condition; lead used as comparative material.
2	231	C	1958	311-811	<5	C-130 AM	Bal.	4.0						4.0	Nominal composition; formerly designated as RC-130B; in mill-annealed condition.
3	231	C	1958	311-811	<5	Ti-6Al-4V	Bal.	6.0	4.0						Nominal composition; in mill-annealed condition.
4	231	C	1958	311-811	<5	Ti-155A	Bal.	5.0		1.4	1.5	1.2			Nominal composition; in mill-annealed condition.
5	555		1956	408.2			Bal.	7.0							0.5 Si.
6	831	L	1963	23-299	±5	6Al-4V	Bal.	5.89	3.87		0.15				0.02 C, 0.015 N, and 0.005 H; the alloy produced by Mallory-Sharon Metals Corp.; heat treated at 1199.8 K for 20 min, oil quenched, aged at 755 K for 4 hrs and air cooled; measured under vacuum (<10^{-6} mm Hg).
7	831	L	1963	25-300	±5	4Al-3Mo-1V	Bal.	4.4	1.0		0.10	3.0			0.03 C, 0.011 N, 0.0057 H; the alloy produced by Crucible Steel Co.; heat-treated at 1175 K, aged at 769 K for 12 hrs and measured under vacuum (<10^{-6} mm Hg).
8	939	L	1962	22-294		6Al-4V	Bal.	5.89	3.87		0.15				0.2 C, 0.015 N; specimen 4 in. x 0.375 in. x 0,125 in.; supplied by Reactive Metals. Inc.; solution heat-treated at 1200 K for 20 min and aged at 755 K for 4 hrs; density 4.4 g cm^{-3}
9	939	L	1962	422-922		6Al-4V	Bal.	5.89	3.87		0.15				0.2 C, 0.015 N; specimen 10 in. x 0.5 in x 0.125 in.; supplied by Reactive Metals inc., Niles, Ohio; solution heat-treated at 1200 K for 20 min and aged at 755 K for 4 hrs; density 4.4 g cm^{-3}.
10	939	L	1962	22-294		4Al-3Mo-1V	Bal.	1.0			0.10	3.0			0.03 C, 0.011 N; specimen 4 in. x 0.125 in.; supplied by Crucible Steel Co. of America, Pittsburg, Penn.; solution heat-treated at 1175 K for 15~30 min and aged at 769 K for 12 hrs; density 4.51 g cm^{-3}.

SPECIFICATION TABLE NO. 303 (continued)

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	Al	V	Cr	Fe	Mo	Sn	Mn	Composition (continued), Specifications and Remarks
11	939	L	1962	422-922		4Al-3Mo-1V	Bal.	4.4	1.0		0.10	3.0			0.03 C, 0.011 N; specimen 10 in. x 0.5 in. x 0.125 in.; supplied by Crucible Steel Co. of America, Pittsburg, Penn.; solution heat-treated at 1175 K for 15~30 min and aged at 769 K for 12 hrs; density 4.51 g cm^{-3}.

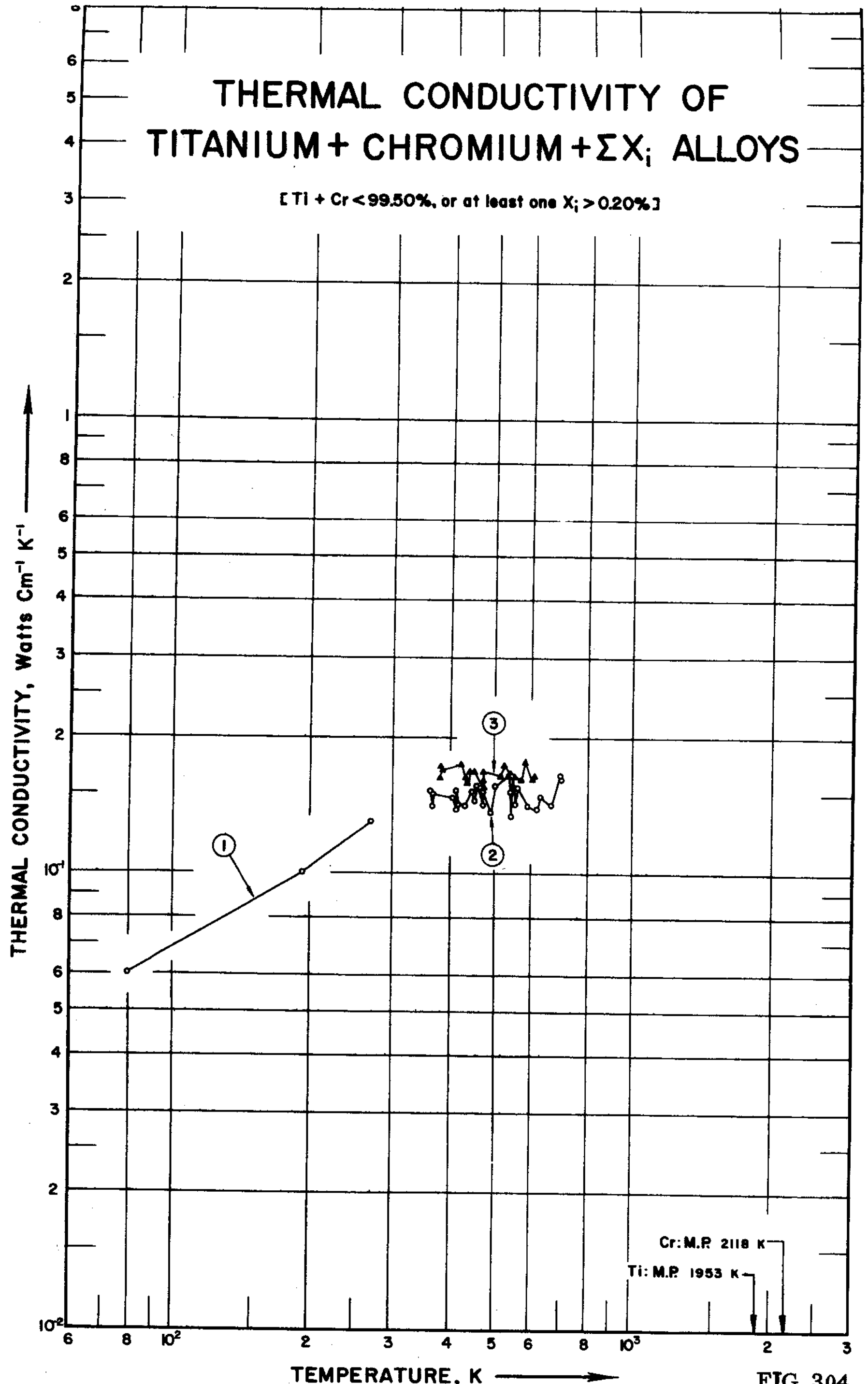
DATA TABLE NO. 303 THERMAL CONDUCTIVITY OF [TITANIUM + ALUMINUM + ΣX_i] ALLOYS

(Ti + Al < 99.50% or at least one X_i > 0.20%)

[Temperature, T, K; Thermal Conductivity, k, Watt $cm^{-1} K^{-1}$]

T	k
CURVE 1	
311.00	0.0782
366.00	0.0837
422.00	0.0900
477.00	0.0958
533.00	0.1021
589.00	0.1088
644.00	0.116
700.00	0.123
755.00	0.130
811.00	0.138
CURVE 2	
311.00	0.0698
366.00	0.0770
422.00	0.0837
477.00	0.0908
533.00	0.0987
589.00	0.1058
644.00	0.114
700.00	0.122
755.00	0.131
811.00	0.140
CURVE 3	
311.00	0.0728
366.00	0.0770
422.00	0.0820
477.00	0.0887
533.00	0.0958
589.00	0.104
644.00	0.112
700.00	0.119
755.00	0.127
811.00	0.135
CURVE 4	
311.00	0.0828
366.00	0.0866
422.00	0.0908*
CURVE 4 (cont.)	
477.00	0.0958*
533.00	0.101*
589.00	0.107*
644.00	0.113*
700.00	0.120*
755.00	0.128*
811.00	0.138*
CURVE 5	
408.2	0.0862
CURVE 6*	
23.39	0.0146
24.17	0.0156
24.64	0.0154
24.64	0.0155
25.40	0.0160
25.42	0.0160
81.90	0.0358
81.90	0.0359
82.06	0.0359
205.55	0.0594
215.83	0.0611
219.02	0.0621
281.76	0.0725
282.10	0.0720
299.38	0.0766
CURVE 7*	
25.38	0.0133
23.60	0.0132
23.63	0.0131
24.38	0.0138
24.51	0.0136
25.17	0.0150
82.17	0.0400
82.23	0.0394
208.73	0.0674
224.65	0.0721
CURVE 7 (cont.)*	
224.67	0.0720
283.09	0.0814
300.45	0.0843
300.45	0.0846
CURVE 8	
22	0.0137
25	0.0156
78	0.0348
194	0.0575
219	0.0618
294	0.0751
CURVE 9	
422	0.095
478	0.106
533	0.118
589	0.128
644	0.140
700	0.151
755	0.163
811	0.173
867	0.185
922	0.196
CURVE 10	
22	0.0125
25	0.0142
78	0.0382
194	0.0656
219	0.0703
294	0.0832
CURVE 11	
422	0.106
478	0.119
533	0.130
589	0.142
CURVE 11 (cont.)	
644	0.156
700	0.170
755	0.185
811	0.197
867	0.204
922	0.206

*Not shown on plot



THERMAL CONDUCTIVITY OF
TITANIUM + CHROMIUM + ΣXi ALLOYS
[Ti + Cr < 99.50%, or at least one Xi > 0.20%]
THERMAL CONDUCTIVITY, Watts Cm⁻¹ K⁻¹
TEMPERATURE, K
Cr: M.P. 2118 K
Ti: M.P. 1953 K
1
2
3

FIG 304

SPECIFICATION TABLE NO. 304 THERMAL CONDUCTIVITY OF [TITANIUM + CHROMIUM + ΣX_i] ALLOYS

(Ti + Cr < 99.50% or at least one X_i > 0.20%)

[For Data Reported in Figure and Table No. 304]

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	Cr	Fe	O	Mo	C	Composition (continued), Specifications and Remarks
1	119, 718	L	1951	87-278	5-10	Ti 150A	96.2	2.8	1.3				0.02 N, and trace O ; specimen ~ 8 mm in dia and 72 mm long.
2	340	L	1956	364-705	10	Ti 150A(2)	95.65	2.71	1.4	0.105		0.05	0.076 N, 0.0092 H; specimen 0.75 in. in dia; supplied by Watertown Arsental.
3	340	L	1956	382-615	10	Cr-Mo	96.3	3.38	0.13	0.131	2.10	0.02	0.032 N, 0.0077 H; specimen 0.75 in. in dia; supplied by Watertown Arsental.

DATA TABLE NO. 304 THERMAL CONDUCTIVITY OF [TITANIUM + CHROMIUM + ΣX_i] ALLOYS

($Ti + Cr < 99.50\%$ or at least one $X_i > 0.20\%$)

[Temperature, T, K; Thermal Conductivity, k, Watt $cm^{-1}K^{-1}$]

T	k
CURVE 1	
87	0.062
194	0.103
278	0.131
CURVE 2	
363.7	0.152
369.3	0.141
370.7	0.150
406.8	0.147
412.3	0.138
414.6	0.152
419.3	0.142
433.2	0.141
447.1	0.152
452.6	0.145
459.6	0.156
474.8	0.141
474.8	0.152
492.9	0.136
503.4	0.156
539.6	0.165
542.9	0.152
549.0	0.134
549.0	0.165
560.1	0.143
568.4	0.155
596.2	0.141
625.7	0.138
634.6	0.148
672.1	0.141
700.7	0.165
704.6	0.161
CURVE 3	
381.8	0.163
383.2	0.173
387.3	0.168
426.2	0.175
434.6	0.164
CURVE 3 (cont.)	
438.7	0.159
440.7	0.168
452.6	0.168
477.6	0.156
477.6	0.161
477.6	0.167
518.4	0.165
526.8	0.174
546.2	0.166
552.6	0.164
574.0	0.161
588.7	0.176
610.1	0.161
614.6	0.165

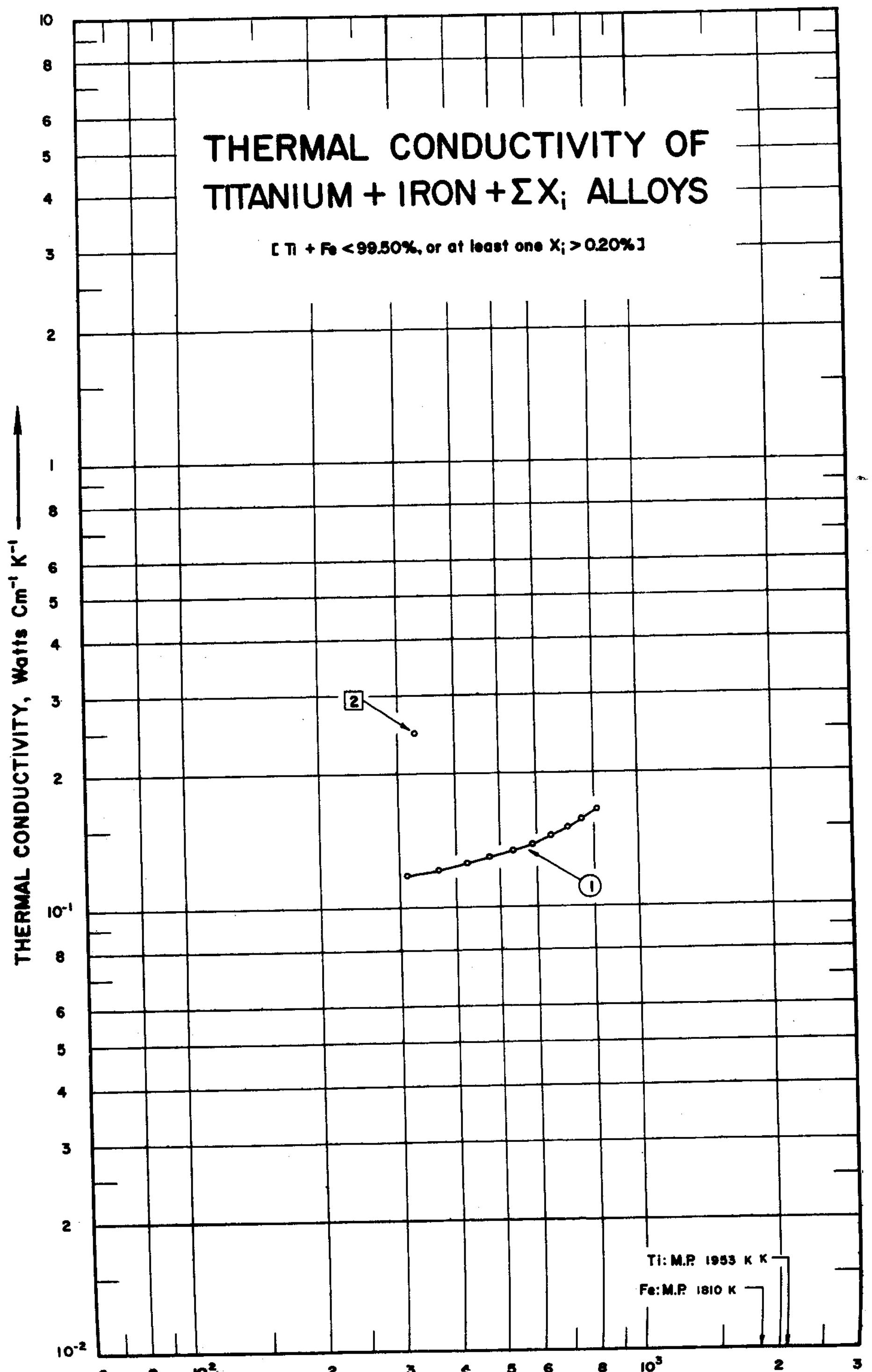

THERMAL CONDUCTIVITY OF
TITANIUM + IRON + ΣX_i ALLOYS
[Ti + Fe < 99.50%, or at least one X_i > 0.20%]
THERMAL CONDUCTIVITY, Watts Cm^{-1} K^{-1}
Ti: M.P. 1953 K K
Fe: M.P. 1810 K
K
1
2

FIG 305

SPECIFICATION TABLE NO. 305 THERMAL CONDUCTIVITY OF [TITANIUM + IRON + ΣX_i] ALLOYS

(Ti + Fe < 99.50% or at least one $X_i > 0.20\%$)

[For Data Reported in Figure and Table No. 305]

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	Fe	C	Cr	Mo	Si	Composition (continued), Specifications and Remarks
1	231	C	1958	311-811	< 5	Ti-140A	93.7	2.2		2.1	2.0		Specimen in a mill-annealed condition; measured in vacuum of ~ 2 x 10^{-5} m m Hg; electrical resistivity 78, 86, 95, 103, 111, 119, 125, 132, 138 and 143 μ ohm cm at 311, 366, 422, 477, 533, 589, 644, 700, 755 and 811 K respectively. Lead used as comparative material.
2	204	L	1937	327.4		Russian ferrocarbontitanium	45	34	13.5			7.5	Average composition of analysis.

DATA TABLE NO. 305 THERMAL CONDUCTIVITY OF [TITANIUM + IRON + ΣX_i] ALLOYS

(Ti + Fe < 99.50% or at least one $X_i > 0.20\%$)

[Temperature, T, K; Thermal Conductivity, k, Watts $cm^{-1}K^{-1}$]

T	k
CURVE 1	
311.00	0.119
366.00	0.123
422.00	0.126
477.00	0.130
533.00	0.134
589.00	0.139
644.00	0.145
700.00	0.151
755.00	0.158
811.00	0.166
CURVE 2	
327.4	0.248

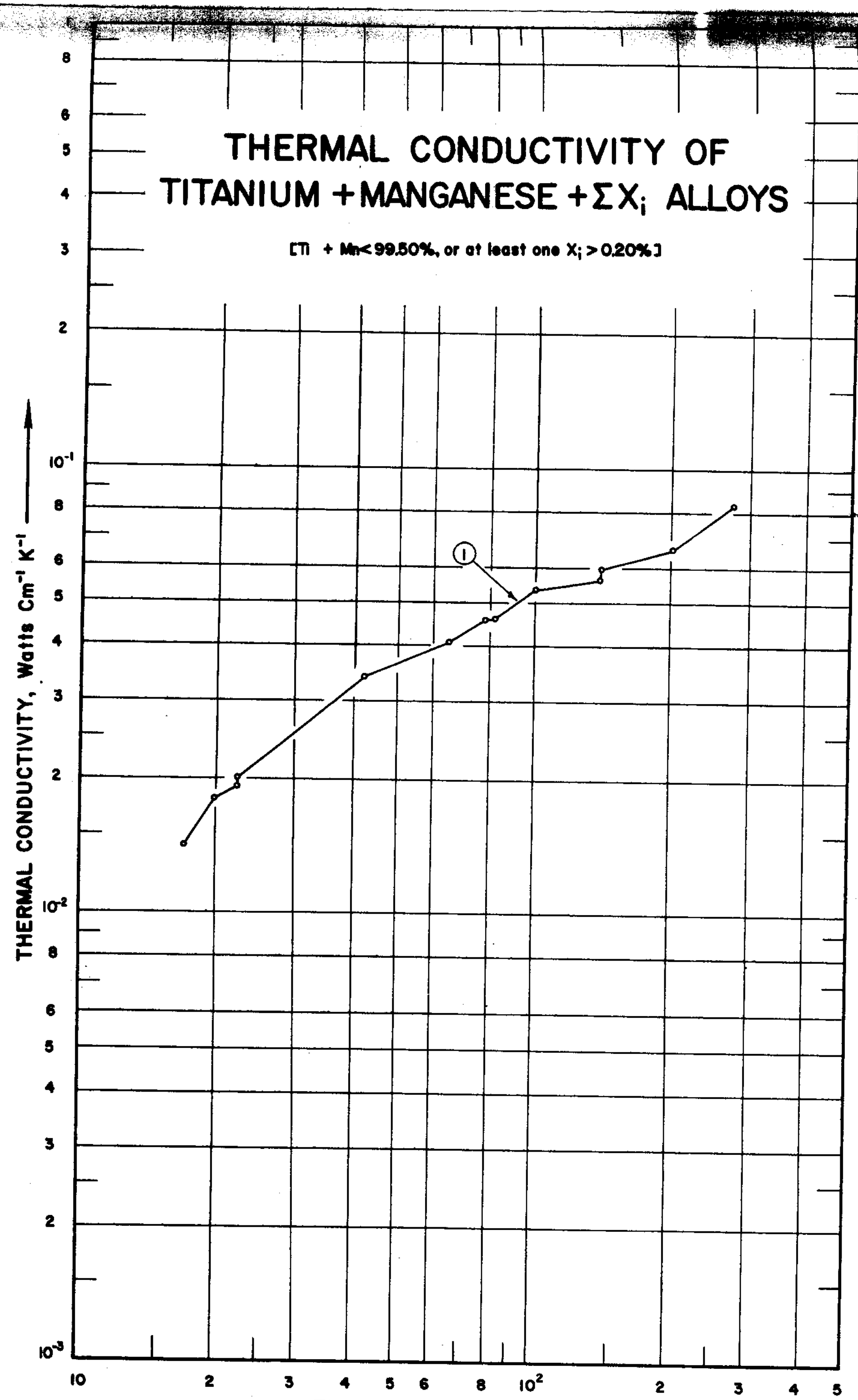

THERMAL CONDUCTIVITY OF
TITANIUM + MANGANESE + ΣX$_i$ ALLOYS
[Ti + Mn < 99.50%, or at least one X$_i$ > 0.20%]
THERMAL CONDUCTIVITY, Watts Cm^{-1} K^{-1}
TEMPERATURE, K
1
10^{-1}
10^{-2}
10^{-3}
10
10^2

FIG 306

SPECIFICATION TABLE NO. 306 THERMAL CONDUCTIVITY OF [TITANIUM + MANGANESE + ΣX_i] ALLOYS

($Ti + Mn < 99.50\%$ or at least one $X_i > 0.20\%$)

[For Data Reported in Figure and Table No. 306]

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	Mn	Al	C	Composition (continued), Specifications and Remarks
1	159	L	1953	17-278	10.0	RC-1308	91.17	4.7	3.99	0.14	

DATA TABLE NO. 306 THERMAL CONDUCTIVITY OF [TITANIUM + MANGANESE + ΣX_i] ALLOYS

(Ti + Mn < 99.50% or at least one X_i > 0.20%)

[Temperature, T, K; Thermal Conductivity, k, Watt $cm^{-1}K^{-1}$]

T	k
CURVE 1	
17.18	0.0142
19.91	0.0180
23.35	0.0193
23.40	0.0201
42.37	0.0339
65.26	0.0406
78.76	0.0456
82.59	0.0460
100.60	0.0536
141.20	0.0561
141.30	0.0598
204.10	0.0661
278.00	0.0837

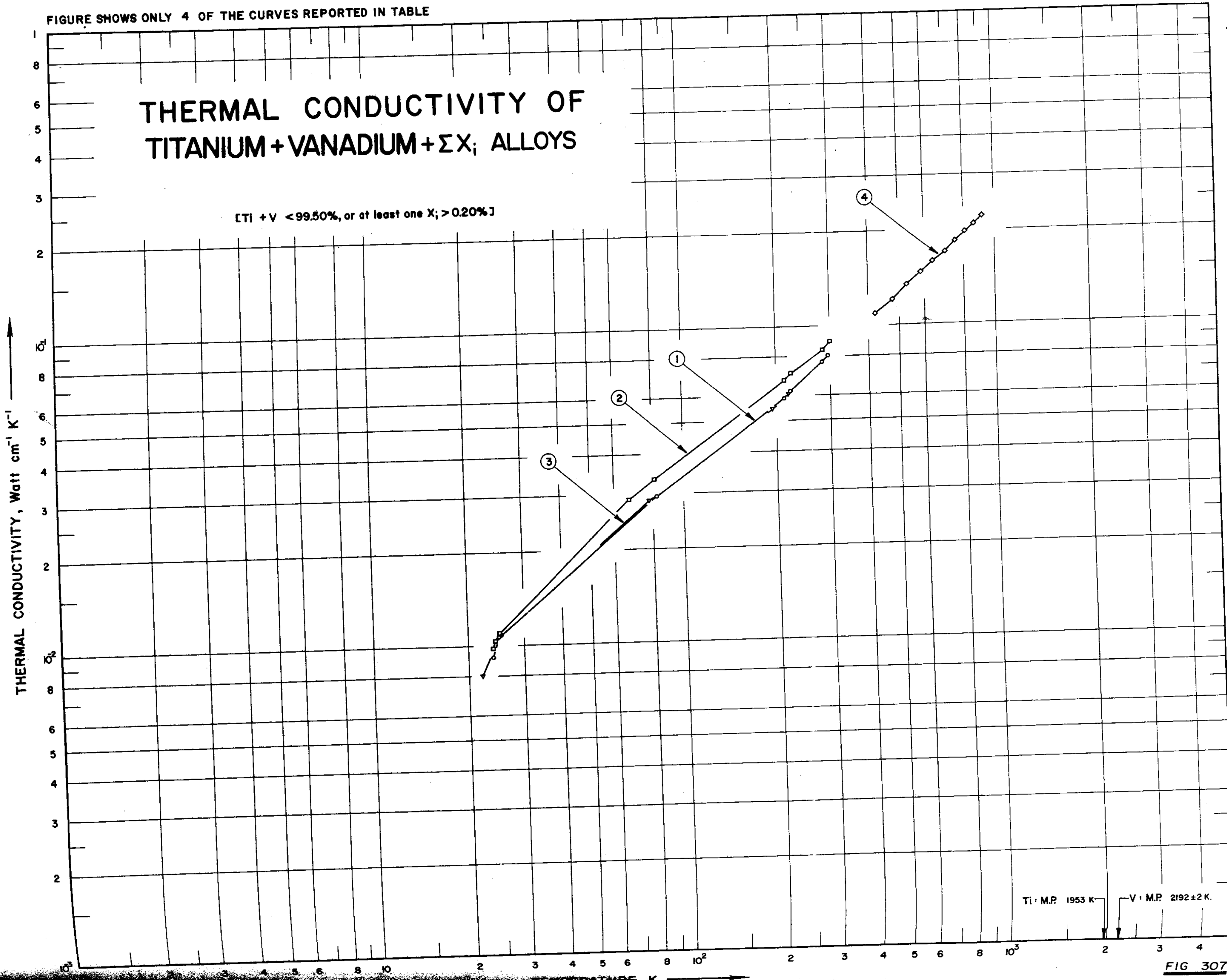


FIGURE SHOWS ONLY 4 OF THE CURVES REPORTED IN TABLE
THERMAL CONDUCTIVITY OF
TITANIUM + VANADIUM + ΣX_i ALLOYS
[Ti + V < 99.50%, or at least one X_i > 0.20%]
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
Ti : M.P. 1953 K
V : M.P. 2192 ± 2 K.
1
2
3
4

FIG 307

TEMPERATURE, K ⟶

SPECIFICATION TABLE NO. 307 THERMAL CONDUCTIVITY OF [TITANIUM + VANADIUM + ΣX_i] ALLOYS

($Ti + V + \Sigma X_i < 99.50\%$ or at least one $X_i > 0.20\%$)

[For Data Reported in Figure and Table No. 307]

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent) Ti	V	Al	Cr	Fe	C	N_2	H	Composition (continued), Specifications and Remarks
1	831	L	1963	24-297	±5	13V-11Cr-3Al	Bal	13.9	3.5	10.4	0.25	0.04	0.025	0.0114	Solution heat-treated at 1061 K for 20 min, air-cooled; aged at 755.4 K for 60 hrs, air-cooled; measurements done in high vacuum ($<10^{-5}$ mm Hg); specimen produced by Crucible Steel Co.
2	831	L	1963	24-301	±5	2.5Al-16V	Bal	14.95	2.75		0.21	0.03	0.015	0.0066	Solution heat-treated at 1038.7 K for 30 min; aged at 805.4 K for 4 hrs; measurements done in high vacuum ($<10^{-5}$ mm Hg); specimen produced by Mallory-Sharon Metals Corporation.
3	939	L	1962	22-294		120VCA		13.9	3.5	10.4	0.25	0.04	0.025		Specimen 4 x 0.375 x 0.125 in.; supplied by Crucible Steel Co. of America; solution heat-treated at 1061 K for 20 min and aged at 755 K for 60 hrs; density 4.82 g cm^{-3}.
4	939	L	1962	422-922		120VCA		13.9	3.5	10.4	0.25	0.04	0.025		Specimen 10 x 0.5 x 0.125 in.; supplied by Crucible Steel Co. of America; solution heat-treated at 1061 K for 20 min and aged at 755 K for 60 hrs; density 4.82 g cm^{-3}.
5	939	L	1962	22-294		2.5Al-16V		14.95	2.75		0.21	0.3	0.015		Specimen 4 x 0.375 x 0.125 in.; supplied by Reactive Metals, Inc.; solution heat-treated at 1039 K for 30 min and aged at 805 K for 4 hrs; density 4.65 g cm^{-3}.
6	939	L	1962	422-922		2.5Al-16V		14.95	2.75		0.21	0.3	0.015		Specimen 10 x 0.5 x 0.125 in.; supplied by Reactive Metals, Inc.; solution heat-treated at 1039 K for 30 min and aged at 805 K for 4 hrs; density 4.65 g cm^{-3}.

DATA TABLE NO. 307 THERMAL CONDUCTIVITY OF [TITANIUM + VANADIUM + ΣX_i] ALLOYS

(Ti + V <99.50% or at least one X_i >0.20%)

[Temperature, T, K; Thermal Conductivity, k, Watt $cm^{-1} K^{-1}$]

T	k	T	k
CURVE 1		**CURVE 4**	
23.89	0.0092	422	0.109
23.91	0.0092*	478	0.121
24.96	0.0108	533	0.135
24.96	0.0109*	589	0.147
25.34	0.0109	644	0.159
25.37	0.0111*	700	0.171
82.06	0.0294	755	0.185
212.78	0.0590	811	0.197
223.90	0.0623	867	0.209
283.96	0.0767	922	0.221
296.65	0.0802		
		CURVE 5*	
CURVE 2		22	0.0085
		25	0.0107
23.90	0.0098	78	0.0320
23.92	0.0099*	194	0.0633
24.38	0.0104	219	0.0696
24.41	0.0104*	294	0.0869
25.02	0.0109*		
25.08	0.0110	**CURVE 6***	
25.37	0.0108*		
25.40	0.0108*	422	0.109
67.33	0.0281*	478	0.121
81.59	0.0327*	533	0.135
81.65	0.0332	589	0.147
212.70	0.0673	644	0.159
224.02	0.0707	700	0.171
284.61	0.0839	755	0.185
301.12	0.0889*	811	0.197
301.13	0.0891	867	0.209
		922	0.221
CURVE 3			
22	0.0080		
25	0.0107*		
78	0.0286		
194	0.0545		
219	0.0606		
294	0.0796*		

* Not shown on plot

SPECIFICATION TABLE NO. 308 THERMAL CONDUCTIVITY OF [TITANIUM + ΣX_i] ALLOYS Ti + ΣX_i

Curve No.	Ref. No.	Method Used	Year	Temp. Range, K	Reported Error, %	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	340	L	1956	418-927	10.0	Ti 150A(1)	Composition unknown.

DATA TABLE NO. 308 THERMAL CONDUCTIVITY OF [TITANIUM + ΣX_i] ALLOYS Ti + ΣX_i

[Temperature, T, K; Thermal Conductivity, k, Watt $cm^{-1} K^{-1}$]

T	k	T	k
CURVE 1*		CURVE 1 (cont.)*	
418.44	0.166	815.7	0.163
421.2	0.169	917.9	0.169
493.4	0.171	926.8	0.174
497.1	0.169		
516.5	0.161		
524.8	0.163		
535.9	0.177		
610.1	0.164		
621.2	0.168		
653.4	0.156		
663.7	0.162		
731.8	0.170		
746.2	0.175		
801.8	0.166		

*No graphical presentation

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Compositions and Properties

Commercial and semicommercial grades and alloys of titanium

Designation	Tensile strength (min) MPa	Tensile strength (min) ksi	0.2% yield strength (min) MPa	0.2% yield strength (min) ksi	Impurity limits, wt % max N	C	H	Fe	O	Nominal composition, wt % Al	Sn	Zr	Mo	Other
Unalloyed grades														
ASTM Grade 1	240	35	170	25	0.03	0.10	0.015	0.20	0.18	...	...	...	...	...
ASTM Grade 2	340	50	280	40	0.03	0.10	0.015	0.30	0.25	...	...	...	...	...
ASTM Grade 3	450	65	380	55	0.05	0.10	0.015	0.30	0.35	...	...	...	...	...
ASTM Grade 4	550	80	480	70	0.05	0.10	0.015	0.50	0.40	...	...	...	...	...
ASTM Grade 7	340	50	280	40	0.03	0.10	0.015	0.30	0.25	...	...	...	...	0.2Pd
Alpha and near-alpha alloys														
Ti Code 12	480	70	380	55	0.03	0.10	0.015	0.30	0.25	...	...	...	0.3	0.8Ni
Ti-5Al-2.5Sn	790	115	760	110	0.05	0.08	0.02	0.50	0.20	5	2.5	...	...	...
Ti-5Al-2.5Sn-ELI	690	100	620	90	0.07	0.08	0.0125	0.25	0.12	5	2.5	...	...	...
Ti-8Al-1Mo-1V	900	130	830	120	0.05	0.08	0.015	0.30	0.12	8	...	...	1	1V
Ti-6Al-2Sn-4Zr-2Mo	900	130	830	120	0.05	0.05	0.0125	0.25	0.15	6	2	4	2	...
Ti-6Al-2Nb-1Ta-0.8Mo	790	115	690	100	0.02	0.03	0.0125	0.12	0.10	6	...	...	1	2Nb, 1Ta
Ti-2.25Al-11Sn-5Zr-1Mo	1000	145	900	130	0.04	0.04	0.008	0.12	0.17	2.25	11.0	5.0	1.0	0.2Si
Ti-5Al-5Sn-2Zr-2Mo(a)	900	130	830	120	0.03	0.05	0.0125	0.15	0.13	5	5	2	2	0.25Si
Alpha-beta alloys														
Ti-6Al-4V(b)	900	130	830	120	0.05	0.10	0.0125	0.30	0.20	6.0	...	...	...	4.0V
Ti-6Al-4V-ELI(b)	830	120	760	110	0.05	0.08	0.0125	0.25	0.13	6.0	...	...	...	4.0V
Ti-6Al-6V-2Sn(b)	1030	150	970	140	0.04	0.05	0.015	1.0	0.20	6.0	2.0	...	...	0.75Cu, 6.0V
Ti-8Mn(b)	860	125	760	110	0.05	0.08	0.015	0.50	0.20	...	...	...	...	8.0Mn
Ti-7Al-4Mo(b)	1030	150	970	140	0.05	0.10	0.013	0.30	0.20	7.0	...	...	4.0	...
Ti-6Al-2Sn-4Zr-6Mo(c)	1170	170	1100	160	0.04	0.04	0.0125	0.15	0.15	6.0	2.0	4.0	6.0	...
Ti-5Al-2Sn-2Zr-4Mo-4Cr(a)(c)	1125	163	1055	153	0.04	0.05	0.0125	0.30	0.13	5.0	2.0	2.0	4.0	4.0Cr
Ti-6Al-2Sn-2Zr-2Mo-2Cr(a)(b)	1030	150	970	140	0.03	0.05	0.0125	0.25	0.14	5.7	2.0	2.0	2.0	2.0Cr, 0.25Si
Ti-10V-2Fe-3Al(a)(c)	1170	170	1100	160	0.05	0.05	0.015	2.5	0.16	3.0	...	...	...	10.0 V
Ti-3Al-2.5V(d)	620	90	520	75	0.015	0.05	0.015	0.30	0.12	3.0	...	...	...	2.5V
Beta alloys														
Ti-13V-11Cr-3Al(c)	1170	170	1100	160	0.05	0.05	0.025	0.35	0.17	3.0	...	...	...	11.0Cr, 13.0V
Ti-8Mo-8V-2Fe-3Al(a)(c)	1170	170	1100	160	0.05	0.05	0.015	2.5	0.17	3.0	...	...	8.0	8.0V
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(b)	900	130	830	120	0.03	0.05	0.020	0.25	0.12	3.0	...	4.0	4.0	6.0Cr, 8.0V
Ti-11.5Mo-6Zr-4.5Sn(b)	690	100	620	90	0.05	0.10	0.020	0.35	0.18	...	4.5	6.0	11.5	...

(a) Semicommercial alloy; mechanical properties and composition limits subject to negotiation with suppliers. (b) Mechanical properties given for annealed condition; may be solution treated and aged to increase strength. (c) Mechanical properties given for solution treated and aged condition; alloy not normally applied in annealed condition. Properties may be sensitive to section size and processing. (d) Primarily a tubing alloy; may be cold drawn to increase strength

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MATERIALS SCIENCE AND ENGINEERING HANDBOOK

THIRD EDITION

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Table 102. THERMAL CONDUCTIVITY OF TIN, TITANIUM, ZINC AND THEIR ALLOYS

Metal or alloy	Designation	Thermal Conductivity near room temperature (cal / cm^2 • cm • s • °C)
Tin and Tin Alloys	Pure tin	0.15
	Soft solder (63Sn–37Pb)	0.12
	Tin foil (92Sn–8Zn)	0.14
Titanium and Titanium Alloys	Titanium(99.0%)	0.043
	Ti–5Al–2.5Sn	0.019
	Ti–2Fe-2Cr–2Mo	0.028
	Ti–8Mn	0.026
Zinc and Zinc Alloys	Pure zinc	0.27
	AG40A alloy	0.27
	AC41A alloy	0.26
	Commercial rolled zinc 0.08 Pb	0.257
	Commercial rolled zinc 0.06 Pb, 0.06 Cd	0.257
	Rolled zinc alloy (1 CU, 0.010 Mg)	0.25
	Zn-Cu–Ti alloy (0.8 Cu, 0.15 Ti)	0.25

Data from *ASM Metals Reference Book, Third Edition*, Michael Bauccio, Ed., ASM International, Materials Park, OH, p156, (1993).