TANTALUM

Tantalum is not a new material. Its first commercial use at the turn of the century was as filaments in light bulbs. Later, when it became apparent that tantalum was practically inert to attack by most acids, applications in the laboratory and in the chemical and medical industries were developed. The rise of the electronics industry accelerated the development of many new applications.

Much of this growth can be attributed to a broader range of tantalum powders and mill products available from the producers, which have a high melting point, the ability to form a dielectric oxide film, and chemical inertness. With these applications, new reduction, melting, and fabrication techniques have led to higher purities, higher reliabilities, and improved yields to finished products.

Source of Tantalum

The earth's crust is made up of 92 naturally occurring elements, but these elements are not all present in equal amounts. Eight elements—oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium—make up 96.5% of the crust. The remaining 88 elements make up only 3.5%, with tantalum amounting to only 0.0002%.

If the tantalum were equally distributed in the rocks of the earth, it would be uneconomical to recover, and there would be no tantalum industry today. However, the tantalum is concentrated in a few unusual rocks in sufficient quantity to permit economical mining and refining. The most important tantalum minerals, tantalite microlites and wodginite, are found in rock formations known as pegmatites.

Pegmatites are coarse-grained rocks formed when molten rock material was cooled slowly. They range in size from 1 in. to many feet in diameter. Also found in the pegmatites are many rare elements such as tantalum, niobium, tin, lithium, and beryllium.

The only operating mine in North America is located at Bernic Lake in Manitoba, Canada. The other important mine in the Americas is found in Brazil. In the humid tropics, the rocks weather and rot to great depths. Many times, the rocks in which the tantalum minerals were formed have completely weathered and have been carried away by running water. The heavy tantalum minerals tend to be concentrated in deposits called placers. These can be panned or washed with machinery, much as gold was recovered during the gold rush. One important placer-type deposit is found in Greenbushes in western Australia.

Because tin and tantalum are often found together, tantalum is a by-product of the tin industry. Because most of the tantalum deposits are small, hard to find, and very expensive to mine, the result is a high-priced ore and a correspondingly high-priced metal.

Tantalum Manufacture

Ingot Consolidation

The first production route for tantalum was by powder metallurgy. Tantalum powder, produced by one of several reduction techniques, is pressed into suitably sized bars and then sintered in vacuum at temperatures in excess of 3800°F (2100°C). When completed, the pressed and sintered bars are ready for processing into mill shapes. Forging, rolling, swaging, and drawing of tantalum is performed at room temperature on standard metal working equipment with relatively few modifications.

The powder metallurgy route, although still in use and adequate for many applications, has two major limitations: (1) The size of the bar capable of being pressed and sintered to a uniform density limits the size of the finished shape available, and (2) the amount of residual interstitial impurities, such as oxygen, carbon, and nitrogen, remaining after sintering adversely affects weldability.

The use of vacuum melting, either by consumable arc or electron-beam process, overcomes these limitations. Either melting technique is capable of producing ingots that are big enough and high enough in purity to meet most requirements of product size and specifications adequately, provided that starting materials are selected with care.

Quality Description

The greatest volume of tantalum is supplied as powder for the manufacture of solid electrolytic tantalum capacitors.

Because it is necessary to distinguish between capacitor-grade powder and meltinggrade powder, manufacturers of electronic components tend to use the term capacitorgrade when ordering forms such as wire, foil, and sheet to identify end use and desired characteristics.

The term capacitor-grade means that the material should have the ability to form an anodic oxide film of certain characteristics. Capacitor-grade in itself does not mean an inherently higher purity, cleaner surface, or different type of tantalum. It does mean that the material should be tested using carefully standardized procedures for electrical properties. If certain objective standards, such as formation voltage and leakage current, are not available against which to test the material, the use of the phrase capacitor-grade is not definitive.

Metallurgical-grade could be simply defined as non-capacitor-grade.

Properties of Tantalum

Alloys Available

Pure tantalum has a body-centered, cubic crystal lattice. There is no allotropic transformation to the melting point, which means that unalloyed tantalum cannot be hardened by heat treatment. Additions of oxygen, carbon, or nitrogen above normal levels, either purposefully or accidentally, are considered as alloying ingredients no matter what the concentration.

Tantalum–niobium alloys containing more than about 5–10% niobium are much less corrosion resistant than tantalum itself.

Tantalum-tungsten alloys containing more than 18% tungsten are inert to 20% hydrofluoric acid at room temperature. Few data are available on the 90Ta-10W alloy. It

is known to be somewhat more oxidation resistant (e.g., to air at higher temperatures) than tantalum. The indication is that it has about the same corrosion resistance to acids as tantalum itself.

Mechanical Properties

The room-temperature mechanical properties of tantalum are dependent on chemical purity, amount of reduction in cross-sectional area, and temperature of final annealing. Annealing time apparently is not critical. Close control over the many factors that affect mechanical properties is mandatory to ensure reproducible mechanical behavior. Typical mechanical properties for tantalum are shown in Table T.1.

Tantalum can be strengthened only by cold work, with a resulting loss in ductility. Because certain residual impurities have pronounced effects on ductility levels and metallurgical behavior, the purpose of most consolidation techniques is to make the material as pure as possible. Cold-working methods are used almost without exception to preclude the possibility of embrittlement by exposure to oxygen, carbon, nitrogen, and hydrogen at even moderate temperatures. Temperatures in excess of 800°F (425°C) should he avoided. Physical properties are shown in Table T.2.

Modulus of elasticity psi $\times 10^6$	27
Tensile strength psi $\times 10^3$	
Grade VM	30
Grade PM	40
Yield strength 0.2% offset psi $ imes 10^3$	
Grade VM	20
Grade PM	30
Elongation in 2 in., %	30+
Hardness, Rockwell	
Grade VM	B-55
Grade PM	B-65
Density, lb/in. ³	0.6
Specific gravity	16.6
Specific heat, Btu/lb °F	0.036
Thermal conductivity at 68 °F, Btu/h/ft ² /°F/in.	377
Coefficient of thermal expansion in./in./°F $ imes$ 10 ⁻⁶	3.6

 Table T.1
 Mechanical and Physical Properties of Tantalum

Table T.2	Physical	Properties	of	Tantalum
	1	1		

Atomic weight	180.9
Density	16.6 g/cm ³ (0.601 lb/in. ³)
Melting point	2996°C (5432°F)
Vapor pressure at 1727°C	$9.525 \times 10^{-11} \mathrm{mmHg}$

Linear coefficient of expansion	1135K: 5.76×10^{-6} /°C 1641K; 9.53×10^{-6} /°C 2030K: 12.9×10^{-6} /°C
Thermal conductivity	2495K; 16.7×10^{-6} /°C 20°C: 0.130 cal/cm-s°C
	1430°C; 0.174 cal/cm-s°C 1630°C; 0.186 cal/cm-s°C
Specific heat	1830°C; 0.198 cal/cm-s°C 100°C; 0.03364 cal/g
Electrical conductivity Electrical resistivity	13.9% IACS -73°C; 9.0 μΩ/cm 75°C; 12.4 μΩ/cm
	127°C: 18.0 μΩ/cm 1000°C; 54.0 μΩ/cm 1500°C: 71.0 μΩ/cm 2000°C; 87.0 μΩ/cm

 Table T.2
 Physical Properties of Tantalum (Continued)

TANTALUM-BASED ALLOYS

There are certain advantages to the use of tantalum-based alloys:

- **1.** Alloying with a less expensive material reduces the cost of the material while still retaining essentially all of the corrosion-resistant properties.
- 2. The use of light material will reduce the overall weight.
- **3.** Depending upon the alloying ingredient, the physical strength of tantalum may be improved.

Tantalum–Tungsten Alloys

The tantalum-tungsten alloys are probably the most common. The addition of 2– 3% tungsten will raise the strength of the tantalum by 30–50%. By also adding 0.15% niobium, a marked increase in the corrosion resistance to concentrated sulfuric acid at 392°F (200°C) is noted. In the lower temperature ranges, 347°F (175°C) or less, the resistance of the alloy is equal to that of pure tantalum.

When the tungsten concentration is increased to 18% or higher, the alloys exhibit essentially no corrosion rate in 20% hydrofluoric acid. This is a definite advantage over pure tantalum.

Tantalum–Titanium Alloys

The tantalum–titanium alloys are receiving a great deal of study because this series of alloys shows considerable promise of providing a less expensive, lower-weight alloy having a corrosion resistance almost comparable with that of tantalum. Tantalum-titanium alloys show excellent resistance in nitric acid at 374°F (190°C) and at the boiling point.

Tantalum–Molybdenum Alloys

When these alloys are exposed to concentrated sulfuric acid and concentrated hydrochloric acid, they are extremely resistant, and the properties of tantalum are retained as long as the tantalum concentration is higher than 50%.

Corrosion Resistance

Tantalum forms a thin, impervious, passive layer of tantalum oxide on exposure to oxidizing or slightly anodic conditions, even at a temperature as low as 77°F (25°C). Chemicals or conditions that attack tantalum, such as hydrofluoric acid, are those that penetrate or dissolve this oxide film, in the case of fluoride ion by forming the complex TaF₅^{2–}. Once the oxide layer is lost, the metal loses its corrosion resistance dramatically.

When in contact with most other metals, tantalum becomes cathodic. In galvanic couples in which tantalum becomes the cathode, nascent hydrogen forms and is absorbed by the tantalum, causing hydrogen embrittlement. Caution must be taken to electrically isolate tantalum from other metals or otherwise protect it from becoming cathodic.

Tantalum is inert to practically all organic and inorganic compounds at temperatures under 302°F (150°C). The only exceptions to this are hydrofluoric acid (HF) and fuming sulfuric acid. At temperatures under 302°F (150°C) it is inert to all concentrations of hydrochloric acid, to all concentrations of nitric acid (including fuming), to 98% sulfuric acid, to 85% phosphoric acid, and to aqua regia (refer to Table T.3).

Acetic acid	Calcium hydroxide
Acetic anhydride	Calcium hypochlorite
Acetone	Carbon tetrachloride
Acids. mineral (except HF)	Carbonic acid
Acid salts	Carbon dioxide
Air	Chloric acid
Alcohols	Chlorinated hydrocarbons
Aluminum chloride	Chlorine oxides
Aluminum sulfate	Chlorine water and brine
Amines	Chlorine, wet or dry
Ammonium chloride	Chloroacetic acid
Ammonium hydroxide	Chrome-plating solutions
Ammonium phosphate	Chromic acid
Ammonium sulfate	Citric acid
Amyl acetate	Cleaning solutions
Amyl chloride	Copper salts
Aqua regia	Ethyl sulfate
Barium hydroxide	Ethylene dibromide
Body fluids	Fatty acids
Bromine, wet or dry	Ferric chloride
Butyric acid	Ferrous sulfate
Calcium bisulfate	Foodstuffs
Calcium chloride	Formaldehyde

Table T.3Materials to Which Tantalum Is Completely Inert,up to At Least 150°C (302°F)

-	
Formic acid	Perchloric acid
Fruit products	Petroleum products
Hydriodic acid	Phenols
Hydrobromic acid	Phosphoric acid, < 4 ppm F
Hydrochloric acid	Phosphorus
Hydrogen	Phosphorus chlorides
Hydrogen chloride	Phosphorus oxychloride
Hydrogen iodide	Phthalic anhydride
Hydrogen peroxide	Potassium chloride
Hydrogen sulfide	Potassium dichromate
Hypochlorous acid	Potassium iodide, iodine
Iodine	Potassium nitrate
Lactic acid	Refrigerants
Magnesium chloride	Silver nitrate
Magnesium sulfate	Sodium bisulfate, aqueous
Mercury salts	Sodium bromide
Methyl sulfuric acid	Sodium chlorate
Milk	Sodium chloride
Mineral oils	Sodium hypochlorite
Motor fuels	Sodium nitrate
Nitric acid, industrial fuming	Sodium sulfate
Nitric oxides	Sodium sulfite
Nitrogen	Sugar
Nitrosyl chloride	Sulfamic acid
Nitrous oxides	Sulfur
Organic chlorides	Sulfur dioxide
Oxalic acid	Sulfuric acid, under 98%
Oxygen	Water

 Table T.3
 Materials to Which Tantalum Is Completely Inert, up to At Least 150°C (302°F) (Continued)

Corrosion is first noticed at about 375°F (190°C) for 70% nitric acid, at about 345°F (175°C) for 98% sulfuric acid, and at about 355°F (180°C) for 85% phosphoric acid (refer to Fig.T.1).

Hydrofluoric acid, anhydrous HF, or any acid medium containing fluoride ion will rapidly attack the metal. One exception to fluoride attack appears to be in chromium plating baths. Hot oxalic acid is the only organic acid known to attack tantalum. The corrosion rates of tantalum in various acid media are given in Table T.4.

Referring to Fig. T.1, it will be seen that tantalum shows excellent resistance to reagent-grade phosphoric acid at all concentrations below 85% and temperatures under 374°F (190°C). However, if the acid contains more than a few parts per million of fluoride, as is frequently the case with commercial acid, corrosion of tantalum may take place. Corrosion tests should be run to verify the suitability under these conditions.

Figure T.2 indicates the corrosion resistance of tantalum to hydrochloric acid over the concentration range of 0-37% and temperature to $374^{\circ}F$ (190°C).



Figure T.1 Corrosion rates of tantalum in fuming sulfuric acid, concentrated sulfuric acid, and 85% sulfuric acid. (from Ref. 5).

Table T.4	Corrosion	Rates	of	Tantalum i	n
Selected Med	lia				

	Temp	erature	Corrosion rate
Medium	(°C)	(°F)	(mpy)
Acetic acid	100	212	Nil
AlCl ₃ (10% soln.)	100	212	Nil
NH ₄ CI (10% soln.)	100	212	Nil
HCI 20%	21	70	Nil
	100	212	Nil
Conc.	21	70	Nil
HNO ₃ 20%	100	212	Nil
70%	100	212	Nil
65%	170	338	1
H ₃ PO ₄ 85%	25	76	Nil
-	100	212	Nil
H ₂ SO ₄			
10%	25	76	Nil
40%	25	76	Nil
98%	25	76	Nil
98%	50	122	Nil
98%	100	212	Nil

	Tempe	erature	Corrosion rate
Medium	(°C)	(°F)	(mpy)
98%	200	392	3
98%	250	482	Rapid
H ₂ SO ₄ , fuming (15% SO ₃)	23	73	0.5
	70	158	Rapid
Aqua regia	25	78	Nil
Chlorine, wet	75	167	Nil
H ₂ O			
Cl ₂ sat.	25	76	Nil
Seawater	25	76	Nil
Oxalic acid	21	70	Nil
	96	205	0.1
NaOH 5%	21	70	Nil
	100	212	0.7
10%	100	212	1
40%	80	176	Rapid
HF 40%	25	76	Rapid

Table T.4Corrosion Rates of Tantalum inSelected Media (Continued)



Figure T.2 Corrosion resistance of tantalum in hydrochloric acid at various concentrations (from Ref. 5).

Figure T.3 indicates the corrosion resistance of tantalum to nitric acid in all concentrations and at all temperatures to boiling. The presence of chlorides in the acid does not reduce its corrosion resistance.



Figure T.3 Corrosion resistance of tantalum in nitric acid at various concentrations and temperatures.

Fused sodium and potassium hydroxides and pyrosulfates dissolve tantalum. It is attacked by concentrated alkaline solutions at room temperature; it is fairly resistant to dilute solutions. Tantalum's resistance to oxidation by various gases is very good at low temperatures, but it reacts rapidly at high temperatures. Only HF and SO₃ attack the metal under 212°F (100°C); most gases begin to react with it at 570 to 750°F (300 to 400°C). As the temperature and concentration of such gases as oxygen, nitrogen, chlorine, hydrogen chloride, and ammonia are increased, oxidation becomes more rapid; the usual temperature for rapid failure is 930–1200°F (500–700°C). The conditions under which tantalum is attacked are noted in Table T.5. Refer to Table T.18 for the compatibility of tantalum with selected corrodents.

Medium	State	Remarks
Air	Gas	At temperatures over 300°C (572°F)
Alkaline solutions	Aqueous	At pH > 9, moderate temperature. some corrosion
Ammonia	Gas	Pits at high temperature and pressures
Bromine	Gas	At temperatures over 300°C (572°F)
Chlorine, wet	Gas	At temperatures over 250°C (482°F)
Fluorides, acid media	Aqueous	All temperatures and concentrations
Fluorine	Gas	At all temperatures
HBr 25%	Aqueous	Begins to corrode at temperatures over 190°C (374°F)
Hydrocarbons	Gas	React at temperatures around 1500°C (2732°F)
HCl 25%	Aqueous	Begins to corrode at temperatures over 190°C (374°F)
HF	Aqueous	Corrodes at all temperatures and pressures
Hydrogen	Gas	Causes embrittlement, especially at temperatures over 400°C (752°F)
HBr	Gas	At temperatures over 400°C (752°F)
HCl	Gas	At temperatures over 350°C (662°F)
HF	Gas	At all temperatures

 Table T.5
 Temperatures at which Various Media Attack Tantalum

Medium	State	Remarks
Iodine	Gas	At temperatures over 300°C (572°F)
Nitrogen	Gas	At temperatures over 300°C (572°F)
Oxalic acid, sat. soln.	Aqueous	At temperatures of about 100°C (212°F)
Oxygen	Gas	At temperatures over 350°C (662°F)
H ₃ PO ₄ 85%	Aqueous	Corrodes at temperatures over 180°C (356°F),
		at higher temperatures for lower concentrations
Potassium carbonate	Aqueous	Corrodes at moderate temperatures depending on concentration
Sodium carbonate	Aqueous	Corrodes at moderate temperatures depending on concentration
NaOH 10%	Aqueous	Corrodes at about 100°C (212°F)
NaOH	Molten	Dissolves metal rapidly (over 320°C) (608°F)
Sodium pyrosulfate	Molten	Dissolves metal rapidly (over 400°C) (752°F)
H ₂ SO ₄ 98%	Aqueous	Begins to corrode at temperatures over 175°C (347°F); lower concentrations begin to corrode at higher temperatures
H ₂ SO ₄ (oleum) (over 98% H2SO4)	Fuming	Corrodes at all temperatures
Sulfuric trioxide	Gas	At all temperatures
Water	Aqueous	Corrodes at pH > 9, reacts at high temperatures

Table T.5 Temperatures at which Various Media Attack Tantalum (Continued)

Suggested Applications

Because of its relatively high price, tantalum can be recommended only for use in extremely corrosive media, in areas where no corrosion of the part can be tolerated, or where very high-purity materials are being processed. Although some plastics, and even glass, fulfill these requirements to a large extent, tantalum is a structurally sound material of construction, can take considerable mechanical abuse, and has a much higher heat transfer coefficient. Tantalum should be used as a material of construction in locations and for equipment where hot concentrated hydrochloric, sulfuric, or phosphoric acids will be present. Tantalum is used by the medical profession for instruments and for metal implants in the body. In the manufacture of high-purity chemicals and pharmaceuticals, tantalum ensures that no impurities are introduced from the container or reactor.

See Refs. 1–5.

TARNISH

Tarnish is a surface discoloration of a metal caused by a thin film of corrosion product. This is quite common on silver surfaces.

TECHNOFLON

See "Fluoroelastomers."

TEFLON

See "Polytetrafluoroethylene."

TEFZEL

See "Ethylene-Tetrafluoroethylene."

TEMPERING

Tempering is usually performed after a quenching operation. Quenching produces a hard and strong but brittle phase called martensite. Tempering is performed to promote some carbon diffusion from the martensite, thereby greatly improving the toughness and ductility of the quenched steel.

Tempering is usually done at 1000 to 1300°F (595 to 705°C). Thick sections of many ferritic steels cannot be cooled quickly enough in air to obtain a normalized structure. In order to hasten the cooling rate, the material is quenched. The objective is to produce the same type of microstructure that would be obtained from normalizing a thinner section of the same material. Quenching of very thick sections does not generate the cooling rates necessary to develop martensite. In these cases, tempering is used primarily for stress relief rather than for softening of the martensite.

At times, tempering is done in conjunction with other heat treatments such as normalizing. The purpose is usually to promote carbon diffusion with the intention of softening and/or toughening the steel. Stress relief may be a secondary or even a primary objective.

TEREPHTHALIC POLYESTERS

This family of thermoset resins is based on terephthalic acid, which is a para-isomer of phthalic acids. The properties of cured terephthalic-based polyesters are similar to those of isophthalic polyesters with the terephthalics having higher heat distortion temperatures and being somewhat softer at equal saturation levels.

Corrosion resistance of the polyethylene terephthalates (PETs) is fairly similar to that of the isophthalics. Testing has indicated that the benzene resistance of comparably formulated resins is lower for PET versus isophthalic polyesters. This trend is also followed where retention of flexural modulus is elevated for various terephthalic resins versus the standard corrosion-grade isophthalic resin. The PET's loss of properties in gasoline is greater than the isophthalics at the same level of saturation; however, as the unsaturation increases, the gasoline resistance reverses, with the PET performing better. The trend was seen only at unsaturated acid levels of greater than 50 mol%. This was achieved with a reversal of performance in 10% sodium hydroxide, where the PET with lower unsaturation was better than the isophthalic level. This follows a general trend for thermosets, that as cross-link density increases, solvent resistance increases.

Refer to Table T.6 for the compatibility of terephthalate Polyester with selected corrodents.

	Maxin tem	mum 1p.		Maxin ten	mum 1p.
Chemical	°F	°C	Chemical	°F	°C
Acetic acid 10%	300	149	Cyclohexane	80	27
Acetic acid 50%	300	149	Dichloroethane	х	х
Acetic anhydride	х	x	Ferric chloride	250	121
Acetone	х	х	Ferric nitrate 10–50%	170	77
Acetyl chloride	х	х	Ferrous chloride	250	121
Acrylonitrile	80	26	Hydrobromic acid 20%	250	121
Aluminum chloride,			Hydrobromic acid 50%	250	121
aqueous	170	77	Hydrochloric acid 20%	250	121
Aluminum sulfate	300	149	Hydrochloric acid 30%	х	х
Ammonium chloride, sat.	170	77	Hydrochloric acid 38%	90	32
Ammonium nitrate	140	70	Hydrocyanic acid 10%	80	27
Ammonium persulfate	180	82	Hydrofluoric acid 70%	х	х
Amyl acetate	80	26	Hydrofluoric acid 100%	х	х
Amyl alcohol	250	121	Lactic acid 25%	250	121
Aniline	х	x	Lactic acid, concd.	250	121
Antimony trichloride	250	121	Magnesium chloride	250	121
Aqua regia 3:1	80	26	Methyl ethyl ketone	250	121
Barium carbonate	250	121	Methyl isobutyl ketone	х	х
Barium chloride	250	121	Muriatic acid	90	32
Benzaldehyde	х	х	Nitric acid 5%	150	66
Benzene	х	х	Perchloric acid 10%	х	х
Benzoic acid	250	121	Perchloric acid 70%	х	х
Benzyl alcohol	80	27	Phenol	х	х
Benzyl chloride	250	121	Phosphoric acid 50–80%	250	121
Boric acid	200	93	Sodium carbonate 10%	250	121
Bromine liquid	80	27	Sodium chloride	250	121
Butyl acetate	250	121	Sodium hydroxide 10%	150	66
Butyric acid	250	121	Sodium hydroxide 50%	х	х
Calcium chloride	250	121	Sodium hydroxide, concd	х	х
Calcium hypochlorite	250	121	Sodium hypochlorite 20%	80	27
Carbon tetrachloride	250	121	Sulfuric acid 10%	160	71
Chloroacetic acid 50%	х	х	Sulfuric acid 50%	140	60
Chlorine gas, dry	80	27	Sulfuric acid 70%	х	х
Chlorine gas, wet	80	27	Sulfuric acid 90%	х	х
Chloroform	250	121	Sulfuric acid 98%	х	х
Chromic acid 50%	250	121	Sulfuric acid 100%	х	х
Citric acid 15%	250	121	Sulfuric acid, fuming	х	х
Citric acid, concd.	150	66	Toluene	250	121
Copper chloride	170	77	Trichloroacetic acid	250	121
Copper sulfate	170	77	Zinc chloride	250	121
Cresol	х	х			

 Table T.6
 Compatibility of Polyester Terephthalate (PET) with Selected Corrodents^a

^aThe chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available, Incompatibility is shown by an x. A blank space indicates that data are unavailable.

Source: PA Schweitzer. Corrosion Resistance Tables. 4th ed. Vols. 1-3. New York: Marcel Dekker, 1995.

THERMOPLASTIC ALLOYS

The alloying of several thermoplastic systems often produces better physical properties than any system can produce by itself. These include impact resistance, flame retardancy, and thermal stability. Alloying is generally done with intensive mixing or screw extruders. Polyvinyl chloride and ABS are frequently blended to provide rigidity, toughness, flame retardancy, and chemical resistance. Polycarbonate can be blended with ABS to provide better heat resistance and toughness. Polyurethane improves the abrasion resistance and toughness of ABS while retaining the advantage of reduced cost. The impact strength of polypropylene is increased by alloying with polyisobutylene. Alloying is generally done on a relatively small scale, varying from as low as 0.01% up to as high as 9%.

Also see "Xenoy," "Cycoloy," and "Triax."

THERMOPLASTIC COMPOSITES

See "Composite Laminates."

THERMOPLASTIC ELASTOMERS (TPE), OLEFINIC TYPE

This family of elastomers is based on cross-linked polyolefin alloys compounded with common fillers (pigments), plasticizers, stabilizers, and cross-linking agents. The plasticizers and fillers are used to tailor properties to specific applications. These materials can be injection molded, blow molded, and extruded on conventional thermoplastic equipment. Vulcanization is not required. See Table T.7.

Brittle point -67 to -76°F (-55 to -60°C) Tensile strength, psi -67 to -76°F (-55 to -60°C) at 73°F (23°C) 1700-2150 at 212°F (100°C) 1040-1170 at 277°F (136°C) 730-770 at 302°F (150°C) 640-750 Elongation, at break
Tensile strength, psi at 73°F (23°C) 1700–2150 at 212°F (100°C) 1040–1170 at 277°F (136°C) 730–770 at 302°F (150°C) 640–750 Elongation, at break 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 73°F (23°C) 1700–2150 at 212°F (100°C) 1040–1170 at 277°F (136°C) 730–770 at 302°F (150°C) 640–750 Elongation, at break 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 212°F (100°C) 1040–1170 at 277°F (136°C) 730–770 at 302°F (150°C) 640–750 Elongation, at break 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 277°F (136°C) 730–770 at 302°F (150°C) 640–750 Elongation, at break 210–300 at 73°F (23°C) 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
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Elongation, at break at 73°F (23°C) 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 73°F (23°C) 210–300 at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 212°F (100°C) 290–670 at 277°F (136°C) 380–870
at 277°F (136°C) 380–870
u 2, / 1 (190 C)
at 302°F (150°C) 300–750
Hardness, Shore 92A–54D
Abrasion resistance Good
Maximum temperature, continuous use 277°F (136°C)
Compression set, method A,%
after 22 h at 73°F (23°C) 8–18
after 22 h at 212°F (100°C) 47–48
Tear resistance Good
Resistance to sunlight Good
Resistance to heat Good
Effect of aging Small
Electrical properties Excellent

Table T.7Physical and Mechanical Properties ofThermoplastic Elastomers (TPE), Olefinic Type^a

^aThese are representative values since they may be altered by compounding.

Resistance to Sun, Weather, and Ozone

The TPEs possess good resistance to sun and ozone and have excellent weatherability. Their water resistance is excellent, showing essentially no property changes after prolonged exposure to water at elevated temperatures.

Chemical Resistance

The thermoplastic elastomers display reasonably good resistance to oils and automotive fluids, comparable to that of neoprene. However, they do not have the outstanding oil resistance of the polyester elastomers. They do have excellent water resistance, even at elevated temperatures.

Applications

These elastomeric compounds are found in a variety of applications including reinforced hose, seals, gaskets and profile extrusions, flexible and supported tubing, automotive trim, functional parts and under-hood components, mechanical goods, and wire and cable jacketing. See Refs. 4 and 6.

See Refs. 4 and 0

THERMOPLASTIC POLYMERS

See "Thermoplasts."

THERMOPLASTS

See also "Polymers" and individual thermoplasts. Thermoplasts are thermoplastic polymers that can be repeatedly re-formed by the application of heat, similar to metallic materials. They are long-chain linear molecules that are easily formed by the application of heat and pressure at temperatures above a critical temperature referred to as the "glass temperature." Because of the ability to be re-formed by heat, these materials can be recycled.

The most common thermoplasts are shown in Table T.8 along with their abbreviations. Table T.9 lists the heat distortion temperatures of the common thermoplasts, while the tensile strengths are given in Table T.10 and the maximum operating temperatures are shown in Table T.11

See Ref. 14.

ABS	Acrylonitrile-butadiene-styrene
CPVC	Chlorinated polyvinyl chloride
ECTFE	Ethylene-chlorotrifluorethylene
FEP	Perfluoroethylenepropylene
HDPE	High-density polyethylene
PEEK	Polyetheretherketone
PES	Polyethersulfone
PFA	Perfluoroalkoxy
PA	Polyamide
PB	Polybutylene
PC	Polycarbonate
PF	Phenol formaldehyde

 Table T.8
 Abbreviations Used for Plastics

PP	Polypropylene
PPS	Polyphenyl sulfide
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PVDC	Polyvinylidene chloride
PVDF	Polyvinylidene fluoride
UHMWPE	Ultra-high molecular weight polyethylene

 Table T.8
 Abbreviations Used for Plastics (Continued)

Table T.9Heat Distortion Temperatureof the Common Plastics (°F/°C)

	Pressure (psi)			
Polymer	66	264	Melt point	
PTFE	250/121	132/56	620/327	
PVC	135/57	140/60	285/141	
LDPE	_	104/40	221/105	
UHMW PE	155/68	110/43	265/129	
PP	225/107	120/49	330/160	
PFA	164/73	118/48	590/310	
FEP	158/70	124/51	554/290	
PVDF	248/148	235/113	352/178	
ECTFE	240/116	170/77	464/240	
ETFE	220/104	165/74	518/270	
PEEK	_	320/160	644/340	
PES	_	410/210	_	
PC	280/138	265/129	_	

Table T.10Tensile strength ofPlastics at 73°F (25°C) at Break

Plastic	Strength (psi)
PVDF	8000
ETFE	6500
PFA	4000-4300
ECTFE	7000
PTFE	2500-6000
FEP	2700-3100
PVC	6000-7500
PE	1200-4550
PP	4500-6000
UHMW PE	5600
PEEK	13,200-23,800
PES	12,200-20,300
PC	10,000

Thermoplast	°F/°C	
PVC	140/160	
CPVC	180/82	
HMW PE	140/60	
UHMW PE	180-220/82-104	
ABS	140/60	
PP	180-220/82-104	
PB	220/104	
ECTFE	300/149	
ETFE	300/149	
FEP	375/190	
PEEK	480/250	
PES	390/200	
PFA	500/260	
PA	212-250/100-121	
PC	210-265/99-128	
PPS	450/230	
PTFE	450/230	
PVDF	320/160	

Table T.11Maximum OperatingTemperature of the Common Thermoplasts

THERMOSET COMPOSITES

Three general types of construction are used to produce thermoset composites to resist corrosion. They are hand-laid-up, filament-winding, and chop-hoop construction.

In hand-laid-up construction, a corrosion barrier of 100 mils (one layer C glass plus two layers of 1½ oz mat) is followed by a structural laminate of alternate layers of rove mat to the desired thickness. This is to provide the optimum in corrosion resistance, but it is not the lowest in cost.

Filament-winding construction starts with a 10-mil corrosion barrier as in hand- laid-up construction, followed by a structural laminate of filament winding to the desired thickness.

With chop-hoop construction, a corrosion barrier of 100 mils is followed by alternate layers of filament winding and chopped glass. The advantage is that the chopped layers provide extra axial strength.

All three methods rely on the corrosion barrier to provide protection for the structural laminate. Only the hand-laid-up construction lends itself to easy repair. When splits occur in the latter two constructions, they invariably follow the wind angle, making field repair difficult, since the corrosion barrier has been breached.

There are several corrosion-resistant laminate surfacing systems that are used. These are shown in the table.

Type of surface layer	Thickness, mils	Description	Specific uses
Gel coat	10–20, at times 60	Unreinforced layer of resin	Commonly used on expoxy piping
Type C glass	10–20	10-mil type C mat	systems Used with reinforcement for
surface mat			chemical plant applications

Type of surface layer	Thickness, mils	Description	Specific uses
Organic veil	10–20	Dacron, acrylic, polypropylene, orlon	Good weathering properties, standard for hydrogen fluoride or caustic applications
Carbon mat	3	0.2 oz/yd^2	Provides high surface electrical conductivity

THERMOSET LAMINATES

See "Thermoset Composites."

THERMOSET POLYMERS

Also see "Polymers."

Once formed, thermoset polymers, unlike the thermoplasts, cannot be heated to change their shape. Consequently, they cannot be recycled. These resins are initially liquid at room temperature and then by adding a catalyst or accelerator they are changed into a rigid product that sets or cures into its final shape. The thermoset resins are highmolecular-weight polymers that are reinforced with glass or other suitable material to provide mechanical strength. The most commonly used resins are the vinyl esters, epoxies, polyesters, and furans.

For reinforcing these polymers, fibrous glass in the F and C grades are the most commonly used. Other reinforcing materials used include boron nitride, carbon fiber, ceramic fibers, graphite jute, Kevlar, metallic wire or sheet, monacrylic fiber, polyester fiber, polypropylene fiber, quartz, sapphire whiskers, and S-grade glass.

The advantages of the thermosets are many. They

- **1.** Are less expensive than the stainless steels.
- 2. Have a wide range of corrosion resistance.
- **3.** Are light in weight.
- **4.** Possess exceptional strength.
- 5. Do not require painting.
- **6.** May be formulated to be fire retardant.

Unreinforced, unfilled thermoset polymers can corrode by several mechanisms. The type of corrosion can be divided into two main categories: physical and chemical.

Physical corrosion is the interaction of a thermoset polymer with its environment so that its properties are altered but no chemical reactions take place. The diffusion of a liquid into the polymer is a typical example. In many cases, physical corrosion is reversible, once the liquid is removed, the original properties are restored.

When a polymer absorbs a liquid or a gas resulting in plasticization or swelling of the thermoset network, physical corrosion has taken place. For a crosslinked thermoset, swelling caused by solvent absorption will be at a maximum when the solvent and polymer solubility parameters are exactly matched.

Chemical corrosion takes place when the bonds in the thermoset are broken by means of a chemical reaction with the polymer's environment. There may be more than one form of chemical corrosion taking place at the same time. Chemical corrosion is usually not reversible. As a result of chemical corrosion, the polymer itself may be affected in one or more ways. For example, the polymer may be embrittled, softened, charred, crazed, delaminated, discolored, dissolved, blistered, or swollen. All thermosets will be attacked in essentially the same manner. However, certain chemically resistant types suffer negligible attack or exhibit significantly lower rates of attack under a wide range of severely corrosive conditions. This is the result of the unequal molecular structure of the resins, including built-in protection of ester groups.

Cure of the resin plays an important part in the chemical resistance of the thermoset. Improper curing will result in a loss of corrosion-resistant properties. Construction of the laminate and the type of reinforcing used also affect the corrosion resistance of the laminate. The degree and nature of the bond between the resin and the reinforcement also plays an important role.

The various modes of attack affect the strength of the laminate in different ways, depending upon the environment, other service conditions, and the mechanisms or combination of mechanisms that are at work.

Some environments may weaken primary and/or secondary polymer linkages with resulting depolymerization. Other environments may cause swelling or microcracking, while still others may hydrolyze ester groupings or linkages. In certain environments, repolymerization can occur, with a resultant change in structure. Other results may be chain scission and decrease in molecular weight or simple solvent action. Attack or absorption at the interface between the reinforcing material and the resin will result in weakening.

In general, chemical attack on thermoset polymers is a go/no-go situation. With an improper environment, attack on the reinforced polyester will occur in a relatively short time. Experience has indicated that if an installation has operated successfully for 12 months, in all probability it will continue to operate satisfactorily for a substantial period of time.

Thermoset polymers are not capable of handling concentrated sulfuric acid (93%) and concentrated nitric acid. Pyrolysis or charring of the resin quickly occurs, so that within a few hours the laminate is destroyed. Polyesters and vinyls can handle 70% sulfuric acid for long periods of time.

The attack of aqueous solutions on reinforced thermosets occurs through hydrolysis, with water degrading bonds in the backbone of the resin molecules. The ester linkage is the most susceptible.

The attack by solvents is of a different nature. The solvent penetrates the resin matrix of the polymer through spaces between the polymer chains. Penetration between the polymer chains causes the laminate surface to swell, soften, and crack.

Organic compounds with carbon–carbon unsaturated double bonds, such as carbon disulfide, are powerful swelling solvents and show greater swelling action than their saturated counterparts. Smaller solvent molecules can penetrate a polymer matrix more effectively. The degree of similarity between solvent and resin is important. Slightly polar resins, such as the polyesters and the vinyl esters, are attacked by mildly polar solvents.

Generally, saturated, long-chain organic molecules, such as the straight-chain hydrocarbons, are handled well by the polyesters.

Orthophthalic, isophthalic, bisphenol, and chlorinated or brominated polyesters exhibit poor resistance to such solvents as acetone, carbon disulfide, toluene, trichloroethylene, trichloroethane, and methyl ethyl ketone. The vinyl esters show improved solvent resistance. Heat-cured epoxies exhibit better solvent resistance. However, the furan resins offer the best all-around solvent resistance.

Stress corrosion is another factor to consider. The failure rate of glass-reinforced composites can be significant. This is particularly true of composites exposed to the combination of acid and stress.

Under stress, an initial fiber fracture occurs, which is a tensile type of failure. If the resin matrix surrounding the failed fiber fractures, the acid is allowed to attack the next available fiber, which subsequently fractures. The process continues until total failure occurs.

See Refs. 7–9 and 14.

THERMOSET REINFORCING MATERIALS

The purpose of adding reinforcing to the thermoset resins is to provide mechanical strength and dimensional stability, which is not possible with the resin alone. Physical and chemical characteristics of the structure can be modified by changing the quantity and/or type of reinforcing. The most widely used reinforcing material for use with thermosetting resins is fibrous glass (fiberglass). Although glass itself is over 3000 years old, fiberglass was not commercialized until 1939 at the New York World's Fair. Other reinforcing materials that also find application are the following:

Boron carbide Silicon carbide Carbon fiber Ceramic fibers Graphite Polyester fibers Aramid fibers Polypropylene fibers Acrylic fibers

Most composite materials manufactured use fiberglass for reinforcing. One of the main advantages in their use is that the fibers remain largely intact. The resin in liquid form can be made to flow around the fibers at room temperature and pressure. Any desired size or shape can be produced by building up layer by layer. Glass retains its strength only to a temperature of 752°F (400°C). Above this temperature, it is necessary to use another type of reinforcing material, such as boron, carbon, or silicon carbide. The dangers of asbestos (mesothelioma, etc.) have eliminated the use of asbestos as a reinforcing material, although it was widely used during the 1960s and 1970s.

Properties of Reinforcing Materials

As mentioned previously, there is a relatively wide choice of materials that can be used for reinforcing. Of these materials, glass is the most often used where corrosion resistance is required. It is available in several grades.

E-Glass

This is a boroaluminosilicate glass with excellent water resistance, strength, low elongation, and reasonable cost. Practically all glass mat, continuous filaments, and woven rovings come from this source.

C-Glass

C-glass is a calcium aluminosilicate glass used for surfacing mats, flakes, or flake glass linings and for acid-resistant cloths. It has poor water resistance and carries a premium cost. Until the development of synthetic veils, 10-mil C-glass surfacing mats were widely used. It is available in 10, 15, 20, and 30 mil thicknesses.

S-Glass

S-glass has excellent resistance to acids and water with exceptional strength, comparable to an aramid fiber. Because of its cost, which is several times greater than that of E-glass, it is not used in the corrosion industry.

Boron Carbide

Boron carbide is used for applications at elevated temperatures or for those requiring high strength. It is used with epoxy resin to produce helicopter rotor blades that turn at high speed.

Silicon Carbide

Silicon carbide is used as a reinforcing material for applications above 752°F (400°C). It is resistant to hydrochloric, sulfuric, hydrofluoric, and nitric acids but will be attacked by mixtures of hydrofluoric and nitric acids.

Carbon Fibers

Carbon fibers are inert to most chemicals. Their use also imparts surface conductivity to FRP laminates. It is also used at temperatures above 752°F (400°C) to impart strength. Carbon fibers in epoxy resin provide compressor blades in lightweight jet engines.

In-depth grounding systems and static control in hazardous areas where static sparks may result in fires or explosions are provided when carbon fiber mat, either alone or in conjunction with graphite or ground carbon, is used for reinforcing.

Graphite Fibers

Graphite fibers, like carbon fibers, are inert to most chemicals and produce an inert conductive pathway. Applications are the same as for carbon fibers.

Polyester Fibers

Polyester is used primarily as a surfacing mat for the resin-rich inner surfaces of filamentwound or contact-molded structures. The nexus veil (registered trademark of Burlington Industries) possesses a relatively high degree of elongation that makes it compatible with the higher elongation resin and reduces the potential for checking, crazing, and cracking in temperature-cycling applications.

Nexus veiling exhibits excellent resistance to alcohols, bleaching agents, water, hydrocarbons, and aqueous solutions of most weak acids at boiling. It is not resistant to strong acids, such as 93% sulfuric acid.

Aramid Fibers

The most popular aramid fiber is Kevlar (trademark of E.I. DuPont de Nemours). It is a high-strength fiber. As such, it is used in the manufacture of bulletproof vests, canoe and boat construction, and other areas where its high strength is required in the laminate. It is available both as a surfacing mat and in cloth form. Kevlar cloth is used occasionally as

Τ

reinforcement for high-stress areas in the corrosion industry, such as the vertical corners of rectangular tanks.

Polypropylene Fibers

Polypropylene fibers do not develop the strength of glass, but they do have a relatively wide range of corrosion resistance and are less expensive.

See Refs. 7 and 10.

TIN COATINGS (TIN PLATE)

Tin plate is produced mainly by the electroplating process. Alkaline and acid baths are used in the production line. The acid baths are classified as either ferrostan or halogen baths.

A thermal treatment above the melting point of tin follows the electrolytic deposition. The intermetallic compound $FeSn_2$ forms at the interface between the iron and tin during this thermal processing. The corrosion behavior of the tin plate is determined by the quality of the $FeSn_2$ formed, particularly when the amount of the free tin is small. The best performing tin plate is that in which the $FeSn_2$ uniformly covers the steel so that the area of exposed iron is very small in case the tin should dissolve. Good coverage requires good and uniform nucleation of $FeSn_2$. Many nuclei form when electrodeposition of tin is carried out from the alkaline stannate bath.

Compared with either iron or tin, FeSn₂ is chemically inert to all but the strongest oxidizing environments.

Most of the tin plate (tin coating on steel) produced is used for the manufacture of food containers (tin cans). The nontoxic nature of tin salts makes tin an ideal material for the handling of food and beverages.

An inspection of the galvanic series will indicate that tin is more noble than steel and, consequently, the steel would corrode at the base of the pores. On the outside of a tinned container, this is what happens; the tin is cathodic to the steel. However, on the inside of the container, there is a reversal of polarity because of the complexing of the stannous ions by many food products. This greatly reduces the activity of the stannous ions, resulting in a change in the potential of tin in the active direction.

This change in polarity is absolutely necessary because most tin coatings are thin and therefore porous. To avoid perforation of the can, the tin must act as a sacrificial coating. Figure T.4 illustrates the reversal of activity between the outside and inside of the can.

The environment inside a hermetically sealed can varies depending upon the contents, which could include general foods, beverages, oils, aerosol products, liquid gases, etc. For example, pH values vary for different contents as shown below:

Acidic beverage	2.4-4.5
Beer and wine	3.5–4.5
Meat, fish, marine products, and vegetables	4.1-7.4
Fruit juices, fruit products	3.1-4.3
Nonfood products	1.2–1.5

The interior of a can is subject to general corrosion, localized corrosion, and discoloring. The coating system for tin plate consists of tin oxide, metallic tin, and alloy. The dissolution of the tin layer in acidic fruit products is caused by acids such as citric acid. In acidic



Figure T.4 Tin acting as both a noble and a sacrificial coating on a "tin" can.

fruit products, the potential reversal occurs between the tin layer and the steel substrate, as shown in Fig. T.5. The potential reversal of a tin layer for steel substrate occurs at a pH range <3.8 in a citric acid solution. This phenomenon results from the potential shift of the tin layer to a more negative direction. Namely, the activity of the stannous ion, Sn^{2+} , is reduced by the formation of double complexes, and thereby the corrosion potential of the tin layer becomes more negative than that of steel. Thus, the tin layer acts as a sacrificial anode for steel so that the thickness and density of the pores in the tin layer are important factors affecting the service life of the coating. A thicker tin layer prolongs the service life of a tin can. The function of the alloy layer (FeSn) is to reduce the active area of steel substrate are exposed, the corrosion of the tin layer is accelerated by galvanic coupling with the steel. The corrosion potential of the alloy layer is between that of the tin layer and that of the steel. A less defective layer exhibits potential closer to that of the tin layer. Therefore, the covering with alloy layer is important to decrease the dissolution of the tin layer.

In carbonated beverages, the potential reversal does not take place; therefore, the steel dissolves preferentially at the defects in the tin layer. Under such conditions, pitting corrosion sometimes results in perforation. Consequently, except for fruit cans, almost all tin plate cans are lacquered.

When tin plate is to be used for structural purposes, such as roofs, an alloy of 12–25 parts of tin to 88–75 parts of lead is frequently used. This is called terneplate. It is less expensive and more resistant to weather than a pure tin coating.

Terneplate exhibits excellent corrosion resistance, especially under wet conditions, with only small amounts of corrosion products forming. A thin nickel deposit can be applied as an undercoat for the terne layer. Nickel reacts rapidly with the tin–lead alloy to form a nickel–tin alloy layer. This layer provides good corrosion resistance and inhibits localized corrosion.



Figure T.5 Potential reversal in tin plate.

Terneplate is used for fuel tanks of automobiles and is also used in the manufacture of fuel lines, brake lines, and radiators in automobiles.

See Refs. 11 and 12.

TITANIUM

Titanium is the ninth most abundant element on earth and the fourth most abundant metal. It is more plentiful than chromium, copper, or nickel, which are commonly employed as alloys to resist corrosion. Titanium and its alloys are noted for their high strength-to-weight ratios and excellent corrosion resistance. Although the needs of the aerospace industry for better strength-to-weight ratio structured materials was recognized, little use was made of titanium until the commercialization of the Kroll process, which made titanium sponge available in about 1950.

Although it has the advantages of being highly corrosion resistant in oxidizing environments, a low density (specific gravity 4.5, approximately 60% that of steel), and a high tensile strength (60,000 psi), its widespread use has been limited somewhat by cost. However, as consumption has increased and new technologies have been developed to reduce the high cost, usage has increased and will probably continue to increase further. At the present time, it is competitive with nickel-base alloys. Thinner sections, coupled with decreased maintenance requirements and longer life expectancy in many applications, permit titanium equipment installations to be cost effective despite a higher initial cost. Increasing usage has been found in automotive applications, chemical processing equipment, pulp and paper industry, marine vehicles, medical prostheses, and sporting goods. Applications for some of the more popular alloys are shown in Table T.12.

Alloy	Applications
ASTM grade 12	
UNS R53400	Chemical process industries. Used in hot brines, heat exchangers, and chlorine cells.
ASTM grade 9	
UNS R56320	Chemical processing and handling equipment. Has high degree of immunity to attack by most mineral acids and chlorides, boiling seawater, and organic compounds.
UNS R54210	Cryogenic applications.
UNS R56210	Marine vehicle hulls. Has high fracture toughness.
TI 6211 and	Aerospace industry, medical prostheses, marine equipment, chemical pumps, high
UNS R56400	performance automotive components.
ASTM grade 5	
UNS R56400	Golf club heads, auto parts, working tools.
UNS R58030	Aircraft fasteners, springs, orthodontic appliances.
UNS R54810	Airframe and turbines.

Table T.12 Applications of Titanium Alloys

The titanium alloys, unlike other nonferrous alloys, are not separated into wrought and cast categories. Most of the widely used casting alloys are based on the traditional wrought compositions.

Metallurgists have separated titanium alloys into categories according to the phases present:

- 1. Commercially pure or modified titanium
- 2. Alpha and near-alpha alloys
- 3. Alpha-beta alloys
- 4. Beta alloys

TITANIUM ALLOYS

These alloys have strengths comparable to alloy steels, while the weight is only 60% that of steel. In addition, the corrosion resistance of titanium alloys is superior to aluminum and stainless steels under most conditions. Titanium's low magnetic permeability is also notable.

The chemical composition of unalloyed titanium grades and titanium alloys are covered by ASTM specifications. Table T.13 lists the compositions of representative grades. These alloys are all available in various product forms covered by ASTM specifications as shown in Table T.14.

Element	Ti-50A ^a (ASTM grade 2)	Ti-6Al-V ^a (ASTM grade 5)	Ti-Pd (ASTM grade 7)	Ti-Code 12 ^a (ASTM grade 12)
Nitrogen, max.	0.03	0.05	0.03	0.03
Carbon, max.	0.10	0.10	0.10	0.08
Hydrogen, max.	0.015	0.015	0.015	0.015
Iron, max.	0.30	0.40	0.30	0.30
Oxygen, max.	0.25	0.20	0.25	0.25
Aluminum	_	5.5-6.75	_	_

 Table T.13
 Chemical Composition of Titanium Alloys

Element	Ti-50A ^a (ASTM grade 2)	Ti-6Al-V ^a (ASTM grade 5)	Ti-Pd (ASTM grade 7)	Ti-Code 12 ^a (ASTM grade 12)
-	(10 1111 grade 2)	(10 I III grade))	(no min grade /)	(101111 gruue 12)
Vanadium	—	3.5-4.5	—	
Palladium	_	_	0.12-0.25	_
Molybdenum	_	_	_	0.2-0.4
Nickel	_	_	_	0.6-0.9
Titanium	Remainder	Remainder	Remainder	Remainder

 Table T.13
 Chemical Composition of Titanium Alloys (Continued)

^aTimet designation.

 Table T.14
 ASTM Titanium Specifications

ASTM B 265-76	Titanium and titanium alloy strip, sheet, and plate
ASTM B 337-76	Seamless and welded titanium and titanium alloy pipe
ASTM B 338-76	Seamless and welded titanium and titanium alloy tubes for condensers and heat exchangers
ASTM B 348-76	Titanium and titanium alloy bars and billets
ASTM B 363-76	Seamless and welded unalloyed titanium welding fittings
ASTM B 367-69	(1974) Titanium and titanium alloy castings
ASTM B 381-76	Titanium and titanium alloy forgings

ASTM grades 1, 2, 3, and 4 cover unalloyed titanium. Grade 2 is most often used for corrosion resistance. Grade 1 possesses better ductility but lower strength; grades 3 and 4 possess higher strength.

Grade 7 alloy, compared with unalloyed titanium, possesses an improved corrosion resistance. This alloy, as grade 11, is used for improved formability.

Grade 12 is a lower-cost alternative to grades 7 and 11 and is suitable for some applications. The palladium of alloys 7 and 11 has been replaced with 0.8% nickel and 0.3% molybdenum.

Grade 5 is an alloy having high strength and toughness and is a general-purpose alloy finding numerous applications in the aerospace industry. Its corrosion resistance is inferior to the unalloyed grades.

The general properties of titanium alloys are shown in Table T.15.

ASTM grade	UNS no.	Properties		
1 (CP)	R50250	Ductility, lower strength		
2 (CP)	R50400	Good balance of moderate strength and ductility		
3 (CP)	R50550	Moderate strength		
7 and 11	R52400	Improved resistance to reducing acids and		
	R52250	superior crevice corrosion resistance		
16	_	Resistance similar to grade 7, but at lower cost		
12	R53400	Reasonable strength and improved crevice corrosion resistance; lower cost		
9	R56320	Medium strength and superior pressure code design allowances		
18	_	Same as grade 9 but with improved resistance to reducing acids and crevice corrosion		
5	R56400	High strength and toughness		

 Table T.15
 General Properties of Titanium Alloys

CP = chemically pure.

Modulus of elasticity psi $ imes 10^6$	14.9
Tensile strength psi \times 10 ³	50
Yield strength 0.2% offset psi $ imes 10^3$	40
Elongation in 2 in., %	20
Density, lb/in. ³	0.163
Specific gravity	4.48
Specific heat at 75°F, Btu/lb °F	0.125
Thermal conductivity at 75°F, Btu/ft ² /h/°F/in.	114
Coefficient of thermal expansion at 32–600°F, in./in. °F $\times 10^{-6}$	5.1

Table T.16Mechanical and Physical Properties of Titanium (Grade 2)

Physical and Mechanical Properties

Titanium is a light metal with a density slightly over half that of iron- or copper-based alloys. The modulus of elasticity is also approximately half that of steel, while its specific heat and thermal conductivity are similar to those of stainless steel. Titanium has a low expansion coefficient, and a relatively high electrical resistivity.

The mechanical and physical properties are shown in Table T.16.

Types of Corrosion

Titanium, like any other metal, is subject to corrosion in certain environments. The corrosion resistance of titanium is the result of a stable, protective, strongly adherent oxide film. This film forms instantly when a fresh surface is exposed to air or moisture. Additions of alloying elements to titanium affect the corrosion resistance because these elements alter the composition of the oxide film

The oxide film of titanium is very stable, though relatively thin, and is attacked by only a few substances, most notable of which is hydrofluoric acid. Because of its strong affinity for oxygen, titanium is capable of healing ruptures in this film almost instantly in any environment where a trace of moisture or oxygen is present.

Anhydrous conditions, in the absence of a source of oxygen, should be avoided because the protective film may not he regenerated if damaged. The protective oxide film of most metals is subject to being swept away above a critical water velocity. Once this takes place, accelerated corrosion attack occurs. This is known as erosion corrosion. For some metals, this can occur at velocities as low as 2 to 3 ft/s. The critical velocity for titanium in seawater is in excess of 90 ft/s. Numerous corrosion resion tests have been conducted, and all have shown that titanium has outstanding resistance to this form of corrosion.

General Corrosion

This form of corrosion is characterized by a uniform attack over the entire exposed surface of the metal. The severity of this kind of attack can be expressed by a corrosion rate. With titanium, this type of corrosion is most frequently encountered in hot reducing acid solutions. In environments where titanium would be subject to this type of corrosion, oxidizing agents and certain multivalent metal ions have the ability to passivate the titanium. Many process streams, particularly sulfuric and hydrochloric acid solutions, contain enough impurities in the form of ferric or cupric ions, etc., to passivate titanium and give trouble-free service.

Galvanic Corrosion

The coupling of titanium with dissimilar metals usually does not accelerate the corrosion of titanium. The exception is in reducing environments where titanium does not passivate. Under these conditions, titanium has a potential similar to aluminum and will undergo accelerated corrosion when coupled to more noble metals.

For most environments, titanium will be the cathodic member of any galvanic couple. It may accelerate the corrosion of the other member of the couple but in most cases the titanium will be unaffected. As a result of this, hydrogen will be evolved on the surface of the titanium proportional to the galvanic current flow. This may result in the formation of surface hydride films that are generally stable and cause no problems. However, if the temperature exceeds 170°F (77°C), hydriding can cause embrittlement.

The surest way to avoid problems with galvanic corrosion is to construct equipment of a single metal. If this is not practical, select two metals that are close in the galvanic series. If contact of dissimilar metals with titanium is necessary, the critical parts should be constructed of titanium, since this is not usually attacked.

Hydrogen Embrittlement

The oxide film on titanium in most cases acts as an effective barrier to penetration by hydrogen. However, embrittlement can occur under conditions that allow hydrogen to enter titanium and exceed the concentration needed to form a hydride phase (about 100 to 150 ppm). Hydrogen absorption has been observed in alkaline solutions at temperatures above the boiling point. Acidic conditions that cause the oxide films to be unstable may also result in embrittlement under conditions in which hydrogen is generated on the titanium surface. In any event, it appears that embrittlement occurs only if the temperature is sufficiently high above 170°F (75°C) to allow hydrogen to diffuse into the titanium. Otherwise, if surface hydride films do form, they are not detrimental.

Gaseous hydrogen has had no embrittlement effects on titanium. The presence of as little as 2% moisture effectively prevents the absorption of molecular hydrogen up to a temperature as high as 600°F (315°C). This may reduce the ability of the titanium to resist erosion, resulting in a higher corrosion rate.

Crevice Corrosion

Crevice corrosion of titanium is most often observed in hot chloride solutions. However, it has also been observed in bromide, iodide, and sulfate solutions.

Dissolved oxygen or other oxidizing species present in the solution are depleted in the restricted volume of solution in the crevice. These species are consumed faster than they can be replenished by diffusion from the bulk solution. As a result, the potential of the metal in the crevice becomes more negative than the metal exposed to the bulk solution. This establishes an electrolytic cell with the metal in the crevice acting as the anode and the metal outside the crevice acting as the cathode. Metal dissolves at the anode under the influence of the resulting current, Titanium chlorides formed in the crevice are unstable and tend to hydrolyze, forming small amounts of hydrochloric acid. This reaction is very slow at first, but in the very restricted volume of the crevice it can reduce the pH of the solution to a value as low as 1. This reduces the potential still further until corrosion becomes quite severe.

Alloying with elements such as nickel, molybdenum, or palladium improves the crevice corrosion resistance of titanium. Consequently, Ti-Code 12 and the titanium–palladium alloys are much more resistant to crevice corrosion than unalloyed titanium.

TITANIUM ALLOYS

Stress Corrosion Cracking (SCC)

Unalloyed titanium with an oxygen content of less than 0.2% (ASTM grades 1 and 2) is susceptible to cracking only in absolute methanol and higher alcohols, certain liquid metals such as cadmium and possibly mercury, red fuming nitric acid, and nitrogen tetraoxide. The presence of halides in the alcohols accelerates cracking tendencies. The presence of water (>2%) tends to inhibit stress cracking in alcohols and red fuming nitric acid. Titanium is not recommended for use in these environments under anhydrous conditions.

Corrosion Resistance

In general, titanium offers excellent resistance in oxidizing environments and poor resistance in reducing environments. It has excellent resistance to moist chlorine gas, chlorinated brines, and hypochlorites. Some corrosion rates for titanium in hypochlorite solutions are given in Table T.17. Titanium is not resistant to dry chlorine gas. It is attacked rapidly and can ignite and burn if the moisture content is sufficiently low. Approximately 1% water is required under static conditions at room temperature. Somewhat less is required if the chlorine is flowing. Approximately 1.5% water is required at 392°F (200°C).

Titanium is immune to all forms of corrosive attack in seawater and chloride salt solutions at ambient temperatures. It is also very resistant to attack in most chloride solutions at elevated temperatures.

Titanium offers excellent resistance to oxidizing acids such as nitric and chromic acids. It is not recommended for use in red fuming nitric acid, particularly if the water content is below 1.5% and the nitrogen dioxide content is above 2.5%. Pyrophoric reactions have occurred in this environment.

Titanium will be attacked by reducing acids such as hydrochloric, sulfuric, and phosphoric acids.

It is also quite resistant to organic acids that are oxidizing. Only a few organic acids are known to attack titanium; these are hot, nonaerated formic acid, hot oxalic acid, concentrated trichloracetic acid, and solutions of sulfamic acid.

Titanium is resistant to acetic acid, teraphthalic acid, and adipic acids. It also exhibits good resistance to citric, tartaric, carbolic, stearic, lactic, and tannic acids. Good corrosion resistance is also shown to organic compounds. In anhydrous environments when the temperature is high enough to cause dissociation of the organic compound, hydrogen embrittlement of the titanium is a consideration.

The compatibility of titanium with selected corrodents is given in Table T.18. See Refs. 4 and 13.

Environment	Temperature (°F)	Test duration (days)	Corrosion rate (mpy)	Pitting
17% hypochlorous acid, with free chlorine and				
chlorine monoxide	50	203	< 0.1	_
16% sodium hypochlorite	70	170	< 0.1	None
18–20% calcium hypochlorite	70–75	204	Nil	None
1.5–4% sodium hypochlorite, 12–15% sodium				
chloride, 1% sodium hydroxide	150-200	72	0.1	None

 Table T.17
 Corrosion of Titanium in Hypochlorite Solutions

	Ma	ximum temperature	(°F/°C)
Chemical	Titanium	Zirconium	Tantalum
Acetaldehyde	300/104	250/121	90/32
Acetamide			
Acetic acid 10%	260/127	220/104	302/150
Acetic acid 50%	260/127	230/110	302/150
Acetic acid 80%	260/127	230/110	302/150
Acetic acid, glacial	260/127	230/110	302/150
Acetic anhydride	280/138	250/121	302/150
Acetone	290/88	190/88	302/150
Acetyl chloride		80/27	80/27
Acrylic acid			
Acrylonitrile	210/93	210/93	210/93
Adipic acid	450/232		210/93
Allyl alcohol	200/93	200/93	300/149
Allyl chloride		200/93	
Alum	200/93	210/99	90/32
Aluminum acetate			
Aluminum chloride, aqueous	10%	40%	302/150
	310/154	200/93	
Aluminum chloride, dry		37%	
	200/93	210/99	302/150
Aluminum fluoride	80/27	x	x
Aluminum hydroxide	190/88	200/93	100/38
Aluminum nitrate	200/93		80/27
Aluminum oxychloride			
Aluminum sulfate	210/99	210/99	302/150
Ammonia gas		200/38	
Ammonium bifluoride			
Ammonium carbonate	200/93		200/93
Ammonium chloride 10%	210/99	210/99	302/150
Ammonium chloride 50%	190/88	220/104	302/150
Ammonium chloride, sat.	203/93		302/150
Ammonium fluoride 10%	90/32	х	x
Ammonium fluoride 25%	80/27	х	х
Ammonium hydroxide 25%	80/27	210/99	302/150
Ammonium hydroxide, sat.	210/99	210/99	302/150
Ammonium nitrate	210/99	210/99	210/99
Ammonium persulfate	80/27	220/104	90/32
Ammonium phosphate 10%	210/99	210/99	302/150
Ammonium sulfate 10–40%	210/99	210/99	302/150
Ammonium sulfide			90/32
Ammonium sulfite			210/99
Amyl acetate	210/99	210/99	302/150
Amyl alcohol	200/93	200/93	320/160
Amyl chloride		210/99	302/150
Aniline	210/99	210/99	210/99
Antimony trichloride	110/43		210/99
Aqua regia 3:1	80/27	x	302/150
Barium carbonate	80/27	210/99	90/32

Table T.18Compatibility of Titanium, Zirconium, and Tantalum withSelected Corrodents^a

	Ma	Maximum temperature (°F/°C)		
Chemical	Titanium	Zirconium	Tantalum	
Barium chloride 25%	210/99	210/99	210/99	
Barium hydroxide	210/99	200/93	302/150	
Barium sulfate	210/99	210/99	210/99	
Barium sulfide	90/32	90/32	90/32	
Benzaldehyde	100/38	210/99	210/99	
Benzene	230/110	230/110	230/110	
Benzene sulfonic acid 10%		210/99	210/99	
Benzoic acid	400/204	400/204	210/99	
Benzyl alcohol	210/99	210/99	210/99	
Benzyl chloride			230/110	
Borax	190/88		x	
Boric acid	210/99	210/99	300/149	
Bromine gas, dry	X	x	302/150	
Bromine gas, moist	190/88	60/16	302/150	
Bromine liquid	x	60/16	570/299	
Butadiene		00,10	80/27	
Butyl acetate	210/99	210/99	80/27	
Butyl alcohol	200/93	200/93	80/27	
<i>n</i> -Butylamine	210/99	2007/5	00/2/	
Butyl phthalate	210/99	210/99	210/99	
Butyric acid	210/99	210/99	302/150	
Calcium bisulfide	210())	210,777	502/190	
Calcium bisulfite	210/99	90/32	80/27	
Calcium carbonate	230/110	230/110	230/110	
Calcium chlorate	140/60	250/110	210/99	
Calcium chloride	310/154	210/99	302/150	
Calcium hydroxide 10%	210/99	210/99	302/150	
Calcium hydroxide, sat.	230/110	210/99	302/150	
Calcium hypochlorite	200/93	200/93	302/150	
Calcium nitrate	210/99	2001/5	80/27	
Calcium oxide	210///		00,2,	
Calcium sulfate	210/99	210/99	210/99	
Caprylic acid	210/99	210/99	300/149	
Carbon bisulfide	210/99	210()))	210/99	
Carbon dioxide dry	90/32	410/210	310/154	
Carbon dioxide, wet	80/27	110,210	300/149	
Carbon disulfide	210/99		210/99	
Carbon monoxide	300/149		210()))	
Carbon tetrachloride	50011)		302/150	
Carbonic acid	210/99	210/99	300/149	
Cellosolve	210/99	210/99	210/99	
Chloracetic acid. 50% water	210/99	210/99	210/99	
Chloracetic acid	210/99	210/99	302/150	
Chlorine gas, dry	x	90/32	460/238	
Chlorine gas, wet	390/199	y v	570/299	
Chlorine, liquid	5/011//	Y	300/149	
Chlorobenzene	200/93	200/93	300/149	
Chloroform	210/99	210/99	210/99	
Chiefoldini				

 Table T.18
 Compatibility of Titanium, Zirconium, and Tantalum with

 Selected Corrodents^a (Continued)

	Ma	ximum temperature	: (°F/°C)
Chemical	Titanium	Zirconium	Tantalum
Chlorosulfonic acid	210/99		210/99
Chromic acid 10%	210/99	210/99	302/150
Chromic acid 50%	210/99	210/99	302/150
Chromyl chloride	60/16		210/99
Citric acid 15%	210/99	210/99	302/150
Citric acid, concentrated	180/82	180/82	302/150
Copper acetate		200/93	300/149
Copper carbonate	80/27		300/149
Copper chloride	200/93	х	300/149
Copper cyanide	90/32	х	300/149
Copper sulfate	210/99	210/99	300/149
Cresol	210/99		
Cupric chloride 5%	210/99	х	300/149
Cupric chloride 50%	210/99	190/88	90/32
Cyclohexane			
Cyclohexanol			
Dichloroacetic acid	280/138	350/177	260/127
Dichloroethane			
Ethylene glycol	210/99	210/99	90/32
Ferric chloride	300/149	х	302/150
Ferric chloride 50% in water	210/99	х	302/150
Ferric nitrate 10–50%	90/32		210/99
Ferrous chloride	210/99	210/99	210/99
Ferrous nitrate			
Fluorine gas, dry	x	х	х
Fluorine gas, moist	х	х	x
Hydrobromic acid, dilute	90/32	80/27	302/150
Hydrobromic acid 20%	200/93	х	302/150
Hydrobromic acid 50%	200/93	х	302/150
Hydrochloric acid 20%	x	300/149	302/150
Hydrochloric acid 38%	х	140/60	302/150
Hydrocyanic acid 10%			
Hydrofluoric acid 30%	x	х	x
Hydrofluoric acid 70%	х	х	х
Hydrofluoric acid 100%	x	х	x
Hypochlorous acid	100/38		302/150
Iodine solution 10%	90/32		
Ketones, general	90/32		
Lactic acid 25%	210/99	300/149	302/150
Lactic acid, concentrated	300/149	300/149	300/149
Magnesium chloride	300/149		302/150
Malic acid	210/99	210/99	210/99
Manganese chloride 5–20%	210/99	210/99	210/99
Methyl chloride	210/99		210/99
Methyl ethyl ketone	210/99	210/99	210/99
Methyl isobutyl ketone	200/93	200/93	210/99
Muriatic acid	x		302/150

360/182

500/260

302/150

 Table T.18
 Compatibility of Titanium, Zirconium, and Tantalum with
 Selected Corrodents^a (Continued)

Nitric acid 5%

	Maximum temperature (°F/°C)		
Chemical	Titanium	Zirconium	Tantalum
Nitric acid 20%	400/204	500/260	302/150
Nitric acid 70%	390/199	500/260	302/150
Nitric acid, anhydrous	210/99	90/32	302/150
Nitrous acid, concentrated			300/149
Oleum			х
Perchloric acid 10%	x		302/150
Perchloric acid 70%	x	210/99	302/150
Phenol	90/32	210/99	302/150
Phosphoric acid 50-80%	x	180/82	302/150
Picric acid	90/32		200/93
Potassium bromide 30%	200/93	200/93	90/32
Salicylic acid	90/32		210/99
Silver bromide 10%			90/32
Sodium carbonate	210/99	210/99	210/99
Sodium chloride	210/99	250/121	302/150
Sodium hydroxide 10%	210/99	210/99	х
Sodium hydroxide 50%	200/93	200/93	х
Sodium hydroxide, concentrated	200/93	210/99	х
Sodium hypochlorite 20%	200/93	100/38	302/150
Sodium hypochlorite, concentrated			302/150
Sodium sulfide to 10%	210/99	х	210/99
Stannic chloride 20%	210/99	210/99	300/149
Stannous chloride	90/32		210/99
Sulfuric acid 10%	x	300/149	302/150
Sulfuric acid 50%	x	300/149	302/150
Sulfuric acid 70%	х	210/99	302/150
Sulfuric acid 90%			302/150
Sulfuric acid 98%	x	х	302/150
Sulfuric acid 100%	х	х	300/149
Sulfuric acid, fuming	х		х
Sulfurous acid	170/77	370/188	300/149
Thionyl chloride			300/149
Toluene	210/99	80/27	300/149
Trichloroacetic acid	х	х	300/149
White liquor		250/121	
Zinc chloride			210/99

Table T.18Compatibility of Titanium, Zirconium, and Tantalum withSelected Corrodents^a (Continued)

^aThe chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, corrosion rate is <20 mpy. *Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

TRANSGRANULAR CORROSION

Transgranular corrosion is a form of localized corrosion in the form of subsurface attack where a narrow path is corroded at random across the grain structure of a metal, disregarding the grain boundaries.

Property	Value	Units
Specific gravity	1.06-1.07	
Water absorption (immersion at 73°F (25°C) 24 h)	1.1–1.5	%
Tensile stress at yield	4.3-6.3	psi $ imes 10^3$
Tensile elongation at break	1.4–3.6	$psi \times 10^3$
Tensile stress at break	6.3–5.8	$psi \times 10^3$
Tensile modulus	245-295	psi $ imes 10^3$
Flexural modulus	1.7-3.00	psi $ imes 10^2$
Impact strength, notched		
Izod, 0.125 in. thickness at 73°F (25°C)	15-20	ft-lb/in.
Deflection temperature		
0.125 in. thickness, 264 psi	207-210	ft-lb/in.
0.125 in. thickness, 66 psi	183–144	ft-lb/in.

Table T.19Range of Physical and Mechanical Properties ofTriax Based on Formulation

TRIAX

Triax is the trademark for Bayer's polyamide/acrylonitrile-butadiene-styrene thermoplastic alloy. It has high impact strength, excellent abrasion characteristics, good chemical resistance, and good fatigue performance. The range of physical and mechanical properties that can be achieved through formulation are shown in Table T.19. See "Polyamides" and "Acrylonitrile-Butadiene-Styrene."

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