MECHANICAL PROPERTIES

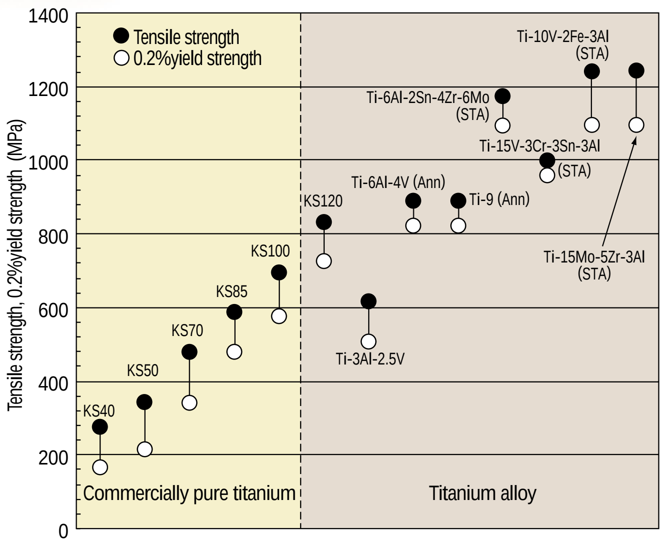


Fig.1: Tensile strength of commercially pure titaniums and various titanium alloys, and 0.2% yield strength(Specified minimum values)

Table 1: Representative characteristics of commercially pure titanium, titanium alloys, and steel base materials (Plate materials)

Material		Tensile direction	Representative values				
			0.2% yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Vickers hardness (Hv)	Erichsen value (mm)
Commercially pure titanium	KS40	T	238	332	45.9	117	11.2
		L	181	337	48.2		
	KS50	T	272	387	41.6	144	10.3
		L	222	391	38.7		
	KS70	T	429	551	26.0	202	6.9
		L	411	545	25.9		
Titanium alloy	Ti-6Al-4V	T	888	957	10.1	320	–
		L	905	959	10.3		
	Ti-3Al-2.5V	T	615	661	23.0	240	–
		L	501	654	20.0		
	Ti-15V-3Cr -3Sn-3Al	T	789	828	19.8	260	7.9
		L	772	823	19.1		
Mild steel		T	169	303	45.0	88	10.1
		L	167	301	46.5		
Stainless steel (SUS 304)		T	263	648	58.0	168	13.0
		L	264	662	55.7		

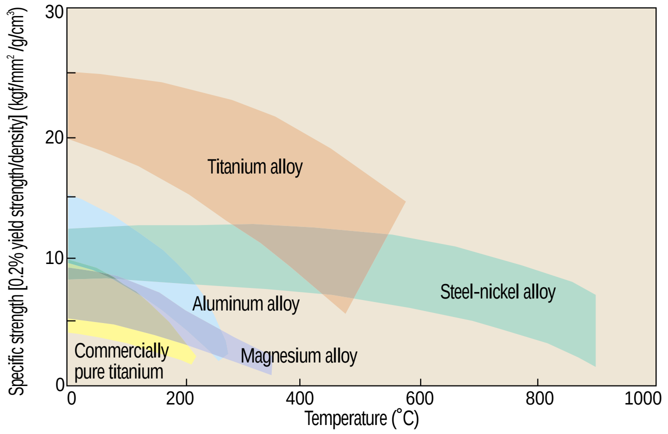


Fig.2: Specific strength of various materials

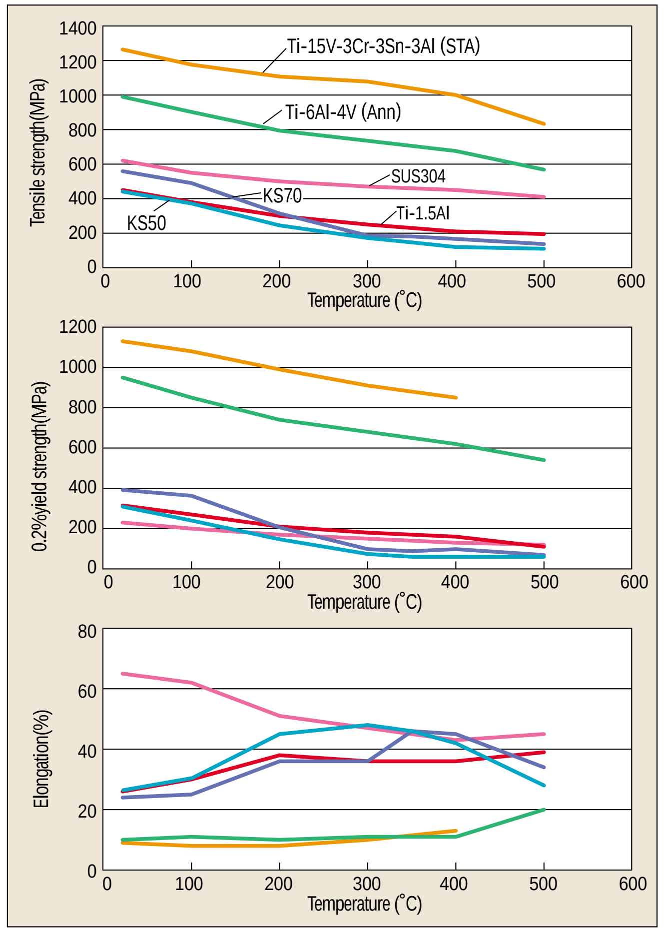


Fig.3: Tensile characteristics of various commercially pure titaniums, various titanium alloys and SUS304 under room temperature and high temperatures

Commercially pure titanium has a tensile strength ranging from 275 to 590 MPa, and this strength is controlled primarily through oxygen content and iron content. The higher the oxygen and iron content, the higher the strength. We are currently producing various titanium alloys from Ti-3A1-2.5V with a tensile strength of 620 MPa, to Ti-15Mo-5Zr-3AI with a tensile strength of 1250 MPa.

(Tensile strengths listed above are KOBELCO's specified minimum values.)

Fig.1 shows the tensile strength and yield strength of commercially pure titanium and various titanium alloys and Table 1 shows the tensile characteristics of commercially pure titanium and representative titanium alloys.

The specific strength of titanium alloy is superior to other metallic materials in the temperature range up to 600˚C. (Fig. 2)

High temperature characteristics

Commercially pure titanium is stable for use in the temperature range up to approximately 300˚C due to its specific strength, creep resistance, and other properties. On the other hand, titanium alloys exhibit high strength in the temperature range up to approximately 500˚C. (Fig. 3)

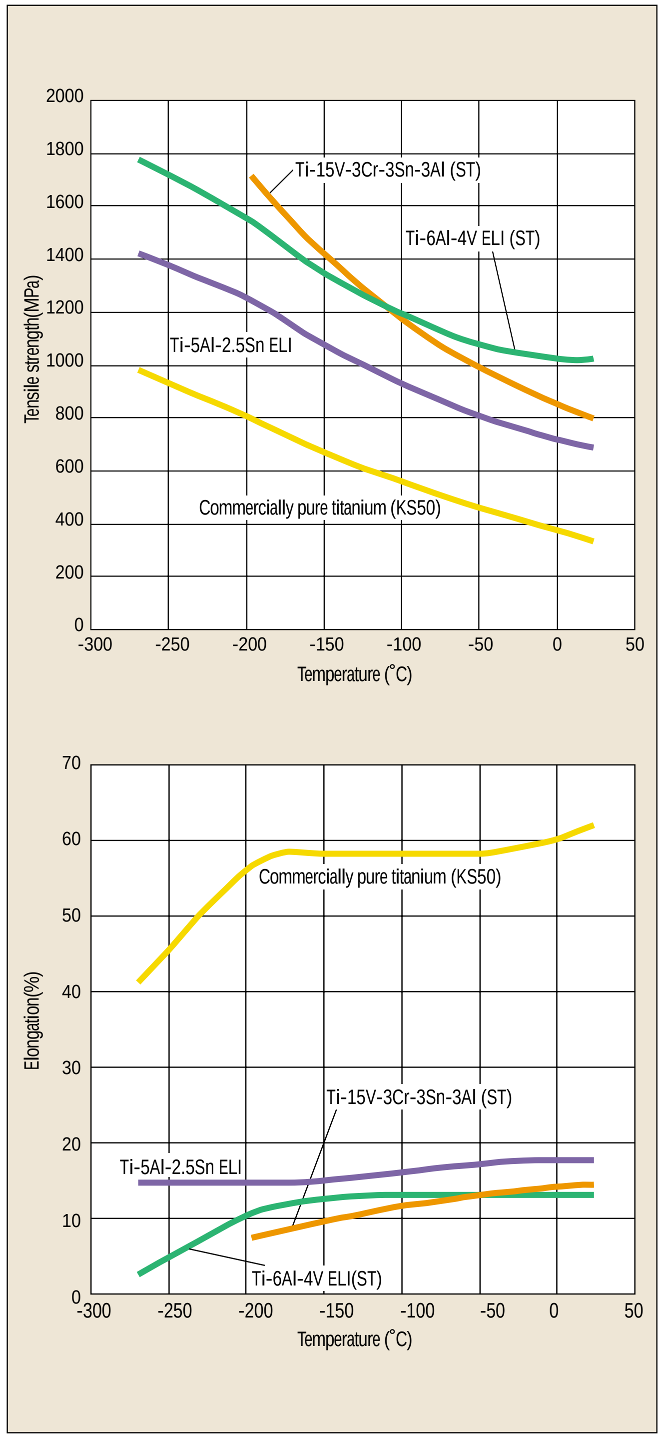


Fig.4: Low temperature tensile properties of commercially pure titanium and various titanium alloys

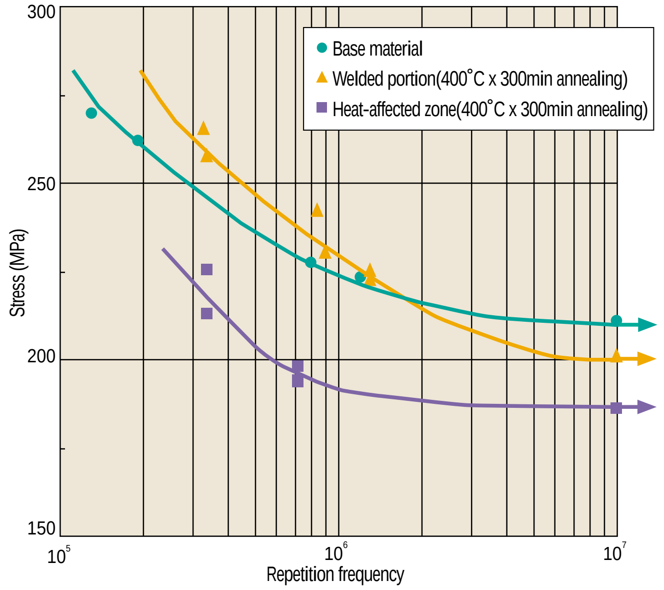


Fig.5: Fatigue characteristics of commercially pure titanium (KS50) base material and welded portion

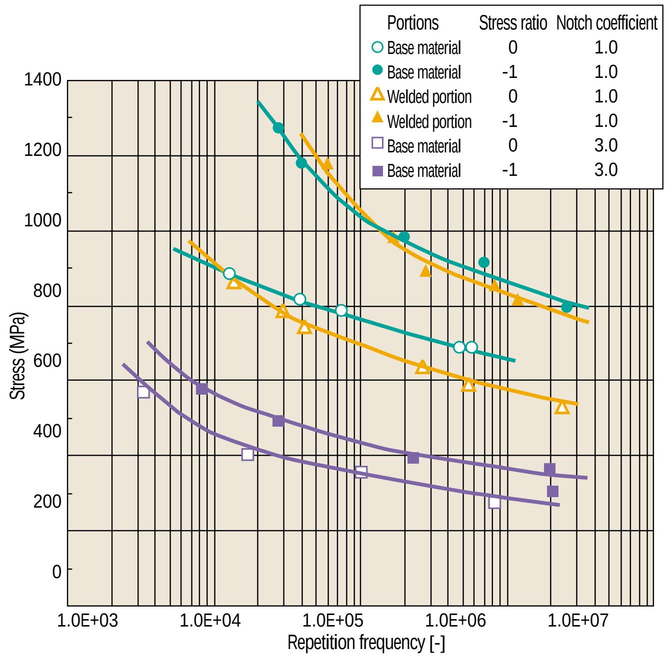


Fig.6: Fatigue characteristics of Ti-6Al-4V base material and welded portion

Low temperature characteristics

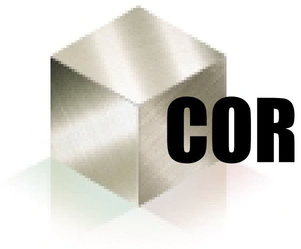
Neither commercially pure titanium nor titanium alloys become brittle even at extremely low temperatures. In particular, commercially pure titanium and Ti-5A1-2.5Sn EL1 can be used even at 4.2 K (-269˚C). (Fig. 4)

Fatigue characteristics

The fatigue strength (10^7 cycles) is roughly equivalent to 50% of the tensile strength, and welding does not cause a significant decline in fatigue strength. (Figs. 5 and 6) In addition, even in seawater, both commercially pure titanium and titanium alloys exhibit almost no decline in fatigue strength.

Toughness

The fracture toughness of titanium alloys range from 28 to 108 $MPa \cdot m^{1/2}$ and is in negative correlation with tensile yield strength. Fracture toughness is dependent on microstructure, and thus fracture toughness is higher in materials with acicular structures.



CORROSION RESISTANCE

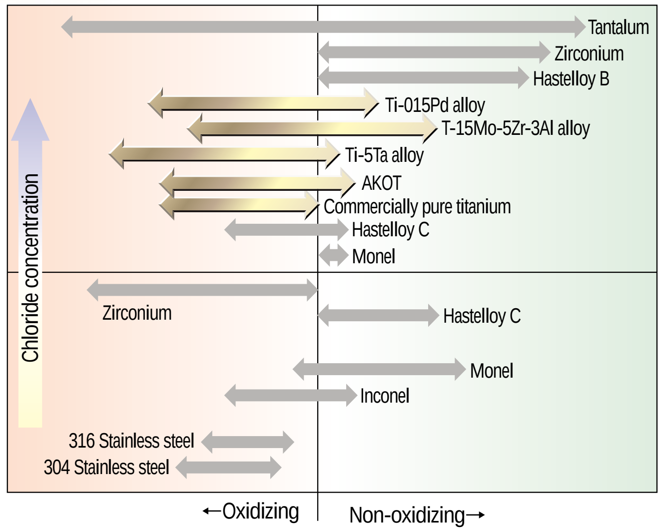


Fig.7: Corrosion resistance range of various metals
(Each metal shows excellent corrosion resistance in the arrow-marked range)

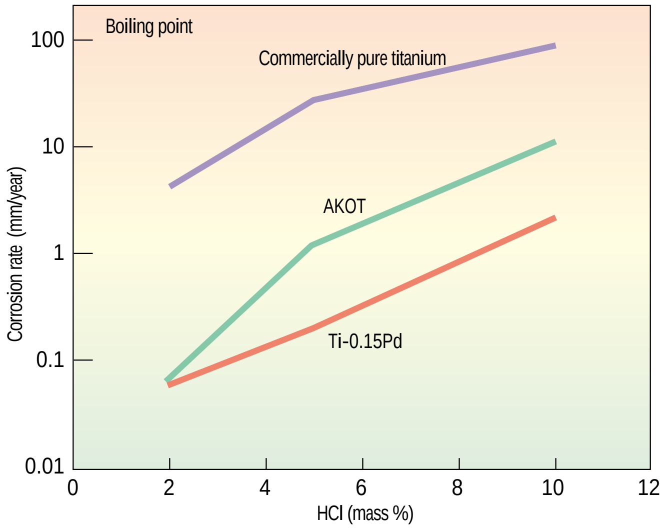


Fig.8: Corrosion resistance of commercially pure titanium and corrosion resistant titanium alloys in hydrochloric acid solution

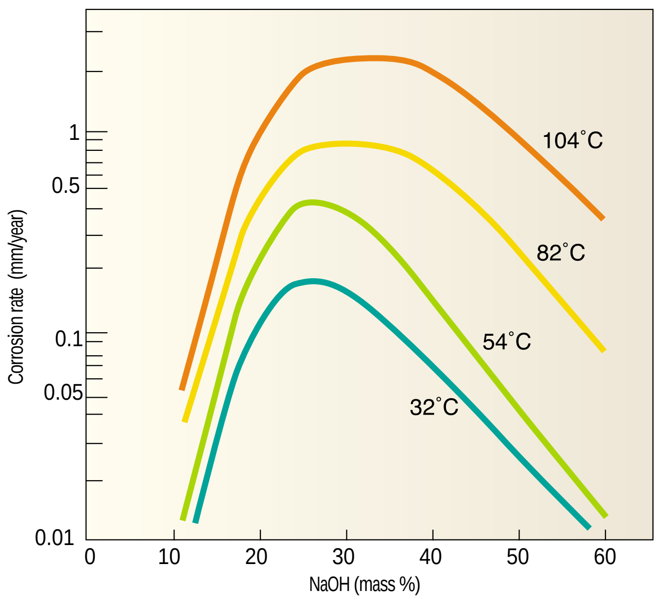


Fig.9: Corrosion rate of commercially pure titanium deaerated NaOH solution

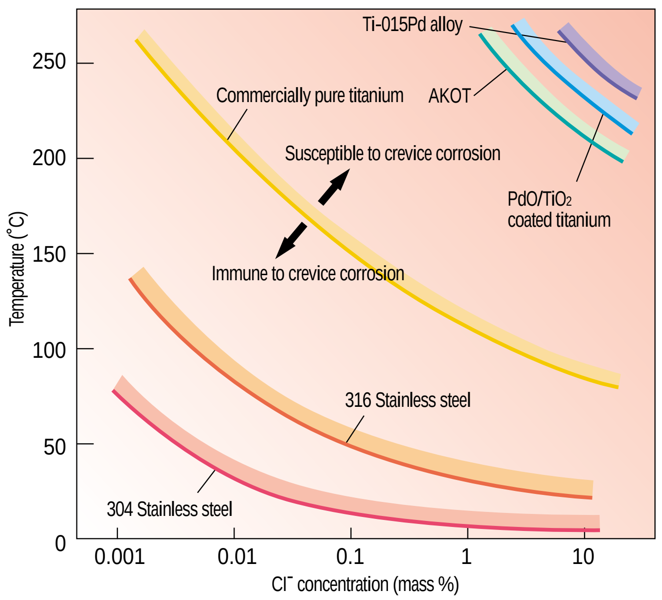


Fig.10: Boundary of crevice corrosion of various titanium materials and stainless steel in chloride solution

(1) General properties

Titanium is normally an active metal, but exhibits extremely high corrosion resistance because a passive film of titanium oxide is generated and is maintained in many environments.

Titanium is optimal in oxidizing environments in which this passive film is formed. (Fig. 7)

The passive film of titanium provides extremely high resistance to seawater because, unlike stainless steel, it is not easily broken down even by chlorine ions.

(2) Corrosion resistance against acid and alkali

Please note that high-concentration non-oxidizing acids such as hydrochloric acid and sulfuric acids at high temperatures can corrode titanium. In such conditions, it is recommended to use corrosion resistant titanium alloys such as Ti-0.15Pd alloy, Ti-Ni-Pd-Ru-Cr alloy (AKOT), etc. (Fig. 8)

Titanium exhibit excellent corrosion resistance against oxidizing acids such as nitric acid, chromic acid, etc.

Please note that titanium is corroded by alkali of high temperature and high concentration. (Fig. 9)

(3) Corrosion resistance against chloride solutions

Unlike stainless steel and copper alloys, titanium is not subject to pitting corrosion or stress corrosion cracking, nor to general corrosion. (Table 2)

However, titanium is subject to crevice corrosion under high-temperature conditions in highly concentrated solutions. In such cases, it is recommended to use corrosion resistant titanium alloys such as Ti-0.15Pd alloy, AKOT, etc. (Fig. 10)

(4) Stress corrosion cracking

Titanium is subject to stress corrosion cracking only in certain special environments. (Table 3)

Table 2: Comparison of corrosion resistance of various heat exchanger materials

Material	Purity of sea water	Corrosion resistance rank				
		General corrosion	Pitting corrosion	Crevice corrosion	Stress corrosion cracking	Erosion
Titanium	Clean	1	1	1	1	2
	Contaminated	1	1	1	1	2
Al brass	Clean	2	2	2	1	3
	Contaminated	2	4	4	4	3
70/30 Cu-Ni	Clean	1	2	2	1	3
	Contaminated	2	4	4	4	3
Stainless steel	Clean	1	1	2	1	2
	Contaminated	1	2	3	2	2

Corrosion resistance rank: 1=Excellent 2=Good 3=Ordinary 4 =Inferior

Table 3: Environment causing titanium stress corrosion cracking

Environment		Susceptible titanium materials
Non-aqueous solution	Methanol containing halogen or acid	Commercially pure titanium
	Fuming red nitric asid	Ti-6Al-4V
Aqueous solution	Brine	High strength titanium alloy
	High temperature and high pressure bromide solution	Commercially pure titanium
High temperature chloride	Molten halogen salt	High strength titanium alloy
Liquid metal	Hg, Cd	High strength titanium alloy

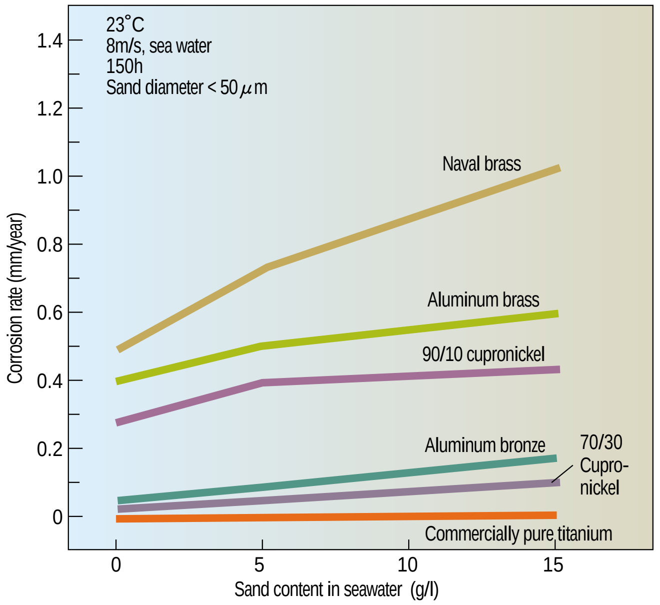
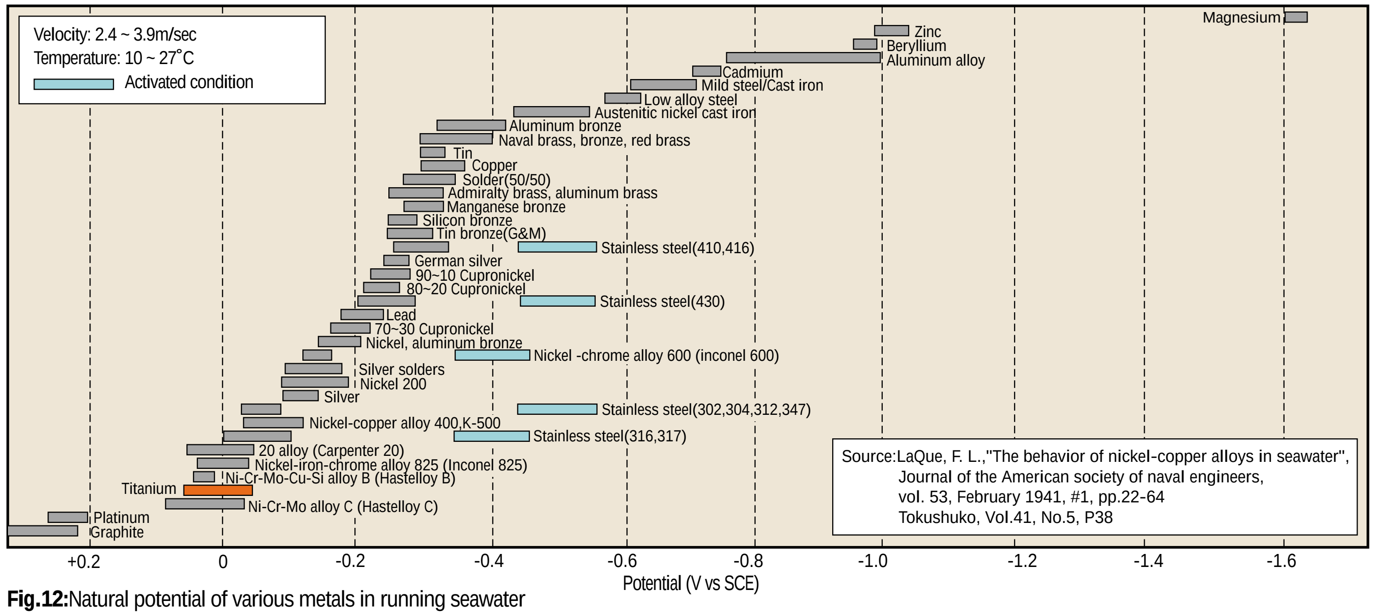


Fig.11: Sand erosion resistance of commercially pure titanium and copper alloys in running sea water



Source:LaQue, F. L.,"The behavior of nickel-copper alloys in seawater",
Journal of the American society of naval engineers,
vol. 53, February 1941, #1, pp.22-64
Tokushuko, Vol.41, No.5, P38

Fig.12: Natural potential of various metals in running seawater

(5) Erosion resistance

The erosion resistance of commercially pure titanium is far superior to that of copper alloys. (Fig. 11)

(6) Galvanic corrosion

In comparison with other practical metals, the electric potential of titanium is high. (Fig. 12) Therefore, if titanium comes in contact with other metals of lower potential such as copper alloys and aluminum in an electrically conductive solution, corrosion of such other metals may be accelerated. (Galvanic corrosion)

When austenitic stainless steels such as SUS304 and SUS316 come in contact with titanium under room temperatures, there is generally no problem of galvanic corrosion due to the smaller potential differences between these stainless steels and titanium.

(7) Reactivity to gas

Since titanium has a strong affinity for oxygen, hydrogen, and nitrogen gases, care must be taken with regard to usage conditions such as temperature and pressure.

Titanium exhibits corrosion resistance against moisture-containing chlorine gas, but please note that titanium reacts significantly with dry chlorine gas.

(8) Other

Generally, the corrosion resistance of titanium is not affected by material history including welding, finishing, and heat treatment.

CORROSION RESISTANCE

Table 4: Corrosion resistance of titanium and other metals in various corrosive environments

Classifi-cation	Corrosion medium	Conc. (mass%)	Temperature (˚C)	Corrosion resistance				
				Commercially pure titanium	Ti-0.15Pd	Unalloyed zirconium	304 stainless steel	Hastelloy C
Inorganic acids	Hydrochloric acid (HCl)	1	25	◎	◎	◎	○	◎
			Boiling	×	◎	◎	×	△
		10	25	○	◎	◎	×	△
			Boiling	×	△	◎	×	×
	Sulfuric acid (H_2SO_4)	1	25	◎	◎	◎	◎	◎
			Boiling	×	◎	◎	×	○
		10	25	○	◎	◎	○	◎
			Boiling	×	×	◎	×	○
	Nitric acid (HNO_3)	10	25	◎	◎	◎	◎	◎
			Boiling	◎	◎	◎	◎	○
		65	25	◎	◎	◎	◎	○
			Boiling	◎	◎	◎	○	×
Organic acids	Acetic acid (CH_3COOH)	10	Boiling	◎	◎	◎	◎	◎
		60	Boiling	◎	◎	◎	○	◎
	Formic acid ($HCOOH$)	10	25	◎	◎	◎	△	◎
		30	Boiling	×	◎	◎	×	◎
	Oxalic acid ($(COOH)_2$)	10	25	○	◎	◎	○	○
		25	60	×	No data available	◎	△	○
	Lactic acid ($CH_3CH(OH)COOH$)	10	Boiling	◎	◎	◎	○	○
		85	Boiling	◎	◎	◎	×	○
Alkalis	Caustic soda ($NaOH$)	10	100	◎	◎	◎	◎	◎
		40	Boiling	×	×	○	○	○
	Potassium carbonate (K_2CO_3)	5	Boiling	◎	◎	◎	◎	◎
		20	Boiling	◎	◎	◎	◎	◎
Inorganic chlorides	Sodium chloride ($NaCl$)	25	25	◎	◎	◎	○※	○
			Boiling	◎※	◎	○	○※	○※
	Ammonium chloride (NH_4Cl)	40	25	◎	◎	◎	○※	◎
			Boiling	◎※	◎	◎	△※	◎※
	Zinc chloride ($ZnCl_2$)	20	Boiling	◎※	◎	◎	×	×
		50	Boiling	◎※	◎	◎	×	×
	Magnesium chloride ($MgCl_2$)	42	25	◎	◎	◎	◎※	◎
			Boiling	◎※	◎	◎	◎※	◎※
	Ferric chloride ($FeCl_3$)	30	25	◎	◎	×	×	△
			Boiling	◎※	◎	×	×	×
Inorganic salts	Sodium sulfate (Na_2SO_4)	20	25	◎	◎	◎	◎	◎
			Boiling	◎	◎	◎	◎	◎
	Sodium sulfide (Na_2S)	10	25	◎	◎	◎	◎	◎
			Boiling	◎	◎	◎	○	◎
	Sodium chlorite ($NaOCl$)	5	25	◎	◎	◎	△	△
		15	25	◎	◎	◎	△	△
	Sodium carbonate (Na_2CO_3)	30	25	◎	◎	◎	◎	◎
			Boiling	◎	◎	◎	◎	◎
Organic compounds	Methyl alcohol (CH_3OH)	95	25	◎	◎	◎	◎	◎
	Carbon tetrachloride (CCl_4)	100	Boiling	◎	◎	◎	○	○
	Phenol (C_6H_5OH)	Saturat	25	◎	◎	◎	◎	○
	Formaldehyde ($HCHO$)	37	Boiling	◎	◎	◎	◎	○
Gases	Chlorine (Cl_2)	Dry	25	×	×	◎	◎	◎
		Humid	25	◎※	◎	×	×	×
	Hydrogen sulfide (H_2S)	Dry	25	◎	◎	◎	△	◎
		Humid	25	◎	◎	◎	○	○
	Ammonium (NH_3)	100	40	◎	◎	◎	◎	◎
			100	◎	◎	◎	◎	◎
Others	Seawater	—	25	◎	◎	◎	◎※	◎
			100	◎※	◎	◎	○※	◎※
	Naphtha	—	80	◎	◎	◎	◎※	◎
			180	◎	◎	◎	◎※	◎

〈Degree of corrosion resistance〉 ◎：0.125mm／year or less ○：0.125～0.5mm／year △：0.5～1.25mm／year ×：1.25mm／year or more

※：Local corrosion such as pitting and crevice corrosion resistance

MACHINING

Table 5: Difficulties in cutting and shearing titanium and countermeasures

Difficulties	Causes	Countermeasures
Seizure occurs, then causing a cutting tool to wear earlier.	• Heat build-up accumulates easily due to less heat capacity in addition to less thermal conductivity. • Titanium itself reacts easily to cutting tools because of it's active material.	• Slower cutting speed (ex. to 1/3 or less of steel cutting speed) and re-set the cutting feed to a fairly coarse pitch, for exothermal control. • Use a coolant as much as possible for cooling down the titanium and cutting tool (Generally a non-soluble oil coolant is used for low-speed heavy-duty cutting and shearing and a soluble cutting coolant is used for high speed cutting/shearing. • Replace a cutting tool earlier than usual. If ceramic-, TiC- and TiN-coated tools are used for cutting/shearing titanium, their lives get shorter. In general, hard steel tools are used (for cutting/shearing large quanties of titanium by machines with sufficient rigidity and high power capacity) and high-speed carbide tool are used (for cutting/shearing small quanties of titanium by machine with low power capacity.
Chattering (Vibration arising from titanium cutting/shearing is about 10 times as much as that from steel cutting/shearing.)	• The cutting power fluctuates due to chips of saw-tooth form. (This is caused by cutting heat concentrating to the cutting section and local deformation of titanium.)	• Fully cool down the tool and titanium, in addition to exothermic control by the above recommended conditions. • Use a cutting/shearing machine with enough rigidity, power and an adjustable broad cutting speed range.
Chips burning	Titanium reacts rapidly to oxygen, because of its active metal. (Formed titanium work never burns, but cutting chips and polishing compound could ignite from welding and grinding sparks or strong impact.)	Clean the cutting and shearing machines periodically to prevent chips from being deposited. Use dry sand, common dry salt, graphite powder and metal extinguisher as fire extinguishing agents /extinguishers.

Table 6: Tool materials recommended for titanium machining

Tool material	JIS tool material codes	
Tungsten carbide	Class-K	K01, K05, K10※, K20※, K30, K40
	Class-M	M10, M20, M30※, M40※
High-speed steel	V-based	SKH10※, SKH57, SKH54
	Mo-based	SKH7, SKH9, SKH52, SKH53, SKH55, SKH56※
	Powdered high-speed steel	KHA※
Diamond		Man-made diamond, natural diamond

※*Material types used frequently*

(1) Cutting

The properties of machinability of titanium are similar to those of stainless steel, though slightly inferior. However, the application of easy-to-machine conditions enables trouble-free lathe turning, milling, drilling, threading, etc. Of course, the machinability of titanium differs according to the material quality. For example, commercially pure titanium and α titanium alloys offer excellent machinability, while β titanium alloy is the most inferior in machinability. α - β alloy is an intermediate material between the former two alloys.

The main difficulties experienced with titanium cutting are shown in Table 5. The tool materials recommended for titanium cutting are shown in Table 6.

(2) Shearing

Burr often occur when shearing titanium, and therefore a key point is to slightly reduce the upper blade - lower blade clearance. 5% of plate thickness is a guideline (with stainless steel it is 10%). The shear resistance of titanium is approximately 80% of its tensile strength. It is possible to shear titanium with a shearing machine, provided that the machine is capable of shearing materials with tensile strength equal to that of titanium. Of course, titanium cutting is possible by means other than a shear machine. Please contact us for details.

FORMING

Due to its potential for cold bending and press-forming, titanium is generally used as a material for press-formed products. Titanium alloys are mainly classified into α, α - β and β alloys, and the formability differs according to the type of titanium alloy. Warm and hot formings are used with α and α - β alloys because of their insufficient cold formability and large spring-back. (Fig. 13)
The forming methods applied are mainly press-forming methods such as bending, deep drawing, stretch forming, and spinning, the same as those used with stainless steel. In the solution-treated condition, β titanium alloy can be cold formed. Aging treatment can be applied to post-formed β titanium alloy, thereby achieving strength ranging from 1300 to 1500 MPa.

The key points in bending and press-forming are described below.

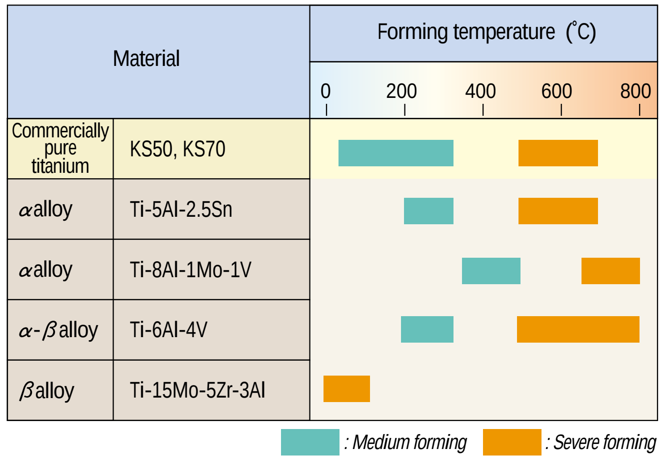


Fig.13: Forming temperature ranges for commercially pure titanium and titanium alloys

(1) Bending

The spring-back of both commercially pure titanium and titanium alloys tends to be greater than that of other metals. Of the commercially pure titanium materials, the soft materials KS40S and KS40 exhibit the same level of spring-back as SUS304, but the higher the strength of the material, the greater the spring-back. An effective method of reducing spring-back is to bend the material at a bending angle allowing for the spring-back value, or to use a die set matching the sheet thickness and pressing the material until it is in perfect contact with the die set.

For commercially pure titanium, cold (room temperature) bending is possible up to KS40S to KS70. KS40S and KS40 will respond to most bending angles, although it depends on the sheet thickness. Materials of higher strength require a larger bending radius. Hot bending is effective in bending high-strength materials (ex. KS85m, KS100, etc.) exceeding KS70. Caution must be used with KS40 and KS50 because hot bending may deteriorate the bendability characteristics.

The bendability of commercially pure titanium is generally better for T-bending than for L-bending. (Fig. 14) Therefore, care must be exercised in sheet cutting. On the other hand, the sheet cutting direction does not generally need to be considered when cutting β titanium alloy because of less anisotropy in the bending plane.

In some cases, the bending properties of titanium may deteriorate depending on the surface roughness of the bending surface. In such cases, the surface may be effectively smoothed by buffing, but it is important to buff perpendicularly to the bending axis. Furthermore, it is much more effective to remove buffing traces by pickling.

Tables 7〜10 show the bending properties of commercially pure titanium and titanium alloys.

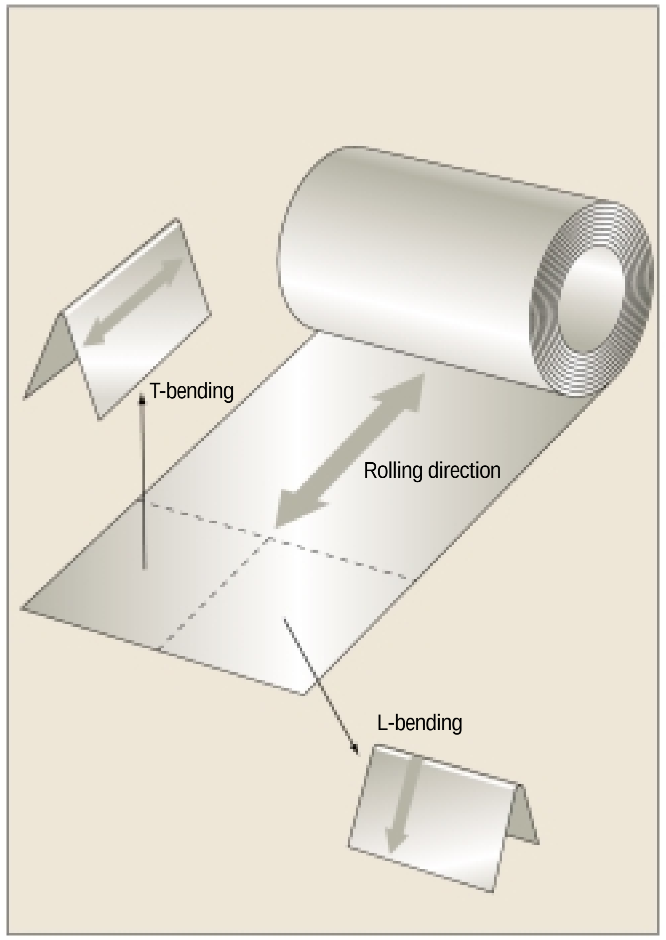


Fig.14: Definition of bending direction

Table 7: Bending properties of commercially pure titanium sheets - 1 (4^t, U-shaped bending)

Material	Bending direction	Bending radius (R/t)			
		2.5	2.0	1.0	Tight contact
KS40	T-bending	OK	OK	OK	NG
KS50		OK	OK	OK	NG
KS60		OK	OK	NG	NG
KS70		OK	NG	NG	NG

Table 8: Bending properties of commercially pure titanium sheets - 2 (0.5^t, knife edge and tight-contact bending)

Material	Bending direction	90degree knife edge	135degree knife edge	Tight contact
KS40	T	OK	OK	OK
	L	OK	OK	OK
KS50	T	OK	OK	NG
	L	OK	OK	NG

Table 9: In-plane anisotropy in bending of commercially pure titanium sheets

Material	Thickness (mm)	Bending properties		Bending method
		T-bending	L-bending	
KS40	4	OK	NG	135degree knife edge→closely contact
kS50	4	OK	NG	135degree knife edge
KS60	3	OK	NG	90degree knife edge
KS70	4	OK	NG	R=2t, U-shaped bending

Table 10: Bending properties of Ti-15V-3Cr-3Sn-3Al alloy sheets

Thickness (mm)	Bending direction	105degree R=2t	90degree knife edge	135degree knife edge	Tight contact
0.5	T	OK	OK	OK	NG
	L	OK	OK	OK	NG
1.0	T	OK	OK	NG	NG
	L	OK	OK	OK	NG

** The datum of Tables 7 ~10 were all taken from pages 77, 78 and 81 of "Titanium Machining Technology" edited by Japan Titanium Association and issued by NIKKAN KOGYO SHIMBUN.LTD.*

(2) Press-forming

Press-forming is mainly applied to commercially pure titanium, and is usually performed at room temperature. The formability of β titanium alloy is comparable to that of commercially pure titanium KS50 〜 KS70, but be aware that high spring-back will cause difficulty in forming and achieving dimensional accuracy.

The main deformation conditions in press forming are stretch forming and deep drawing, but the deep drawing properties of commercially pure titanium are better than its stretch forming properties. Thus it is important to consider deep drawing factors when selecting an appropriate press-forming condition and designing a forming die set.

Of the commercially pure titanium metals, the softest, KS40S, is suited to press-forming subjected to many stretch forming factors.
In contrast, KS40 and KS50 are also suitable for press-forming subjected to many deep-drawing factors.
Table 11 shows the stretch formability of various materials.

Titanium galls easily to die sets, so lubrication is required to suit the press-forming conditions. For example, lubricants such as grease and oil, or wax-based lubricants and graphite grease are used in press-forming at room temperature.
It is also effective to affix a polyethylene sheet to the blank.

Table 11: Stretch formability of commercially pure titanium, titanium alloy and steel material

Material		Thickness (mm)	Erichsen value (mm)	Stretch forming height (mm)
Commercially pure titanium	KS40S	1.0	12.1	36.2
	KS40		11.2	35.4
	KS50		10.3	33.7
	KS60		7.5	26.3
	KS70		6.9	23.1
Ti-15V-3Cr-3Sn-3Al			7.9	27.6
SUS304			13.0	40.5
SUS430		0.6	8.8	29.7
Mild steel			10.1	37.2

Taken from:page 84 of "Titanium Press-forming Technology" edited by Japan Titanium Association and issued by the NIKKAN KOGYO SHIMBUN.LTD. and KOBE STEEL's internal technical data

JOINING

Various joining techniques such as welding, brazing, pressure-welding, diffusion bonding, and mechanical joining (e.g. bolting, etc.) may be used to join titanium plates. (Fig. 15)

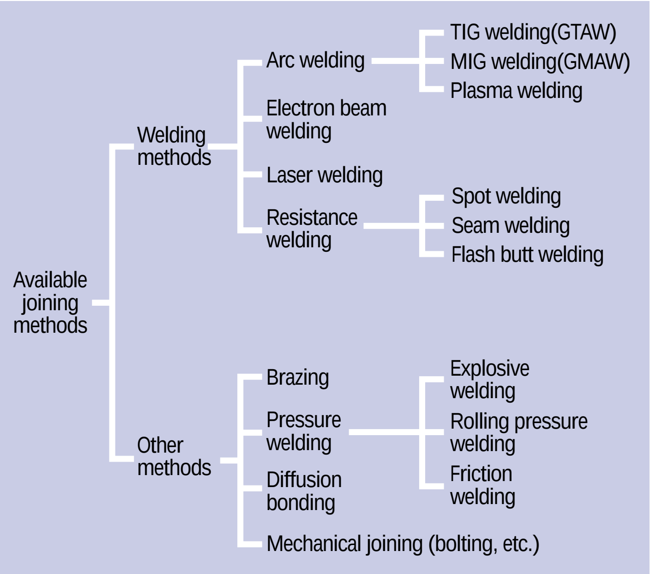


Fig.15: Titanium jointing methods

Table 12: Mechanical properties of titanium thick plate to plate welded joint

Material	Thickness (mm)	Base metal		Weld	
		Tensile strength (MPa)	Hv hardness (10kg)	Tensile strength (MPa)	Hv hardness (10kg)
Commercially pure titanium (JIS Class-2)	9	375	145	419	155
Commercially pure titanium (JIS Class-3)	20	530	185	562	218
Ti-0.15Pd (JIS Class-12)	5	401	153	405	178

Welding method: TIG welding
Electrode: same material as base metal (ϕ 2mm)

(1) Welding

Titanium has excellent properties of weldability, and there is little change in the mechanical properties or corrosion resistance of the welded area. (Table 12, Fig. 16)
However, at high temperatures titanium has a high affinity for oxygen gas and nitrogen gas, and reaction with these gases may result in hardening and embrittlement which could cause a decline in ductility and the occurrence of blowholes in the welded area. Hence, welding of titanium must be performed in an inert gas or vacuum. In addition, the welding material and electrode, and the welding environment must be cleaned thoroughly before welding.

Of all titanium materials, commercially pure titanium and α titanium alloy have the best properties of weldability.

Of the welding methods shown in Fig. 15, TIG welding is the generally used. As shown in Fig. 17, a welding torch with a gas shield jig is used for TIG welding. A Reaction of the welded portion to oxygen, etc. is prevented by putting it under an argon gas atmosphere.

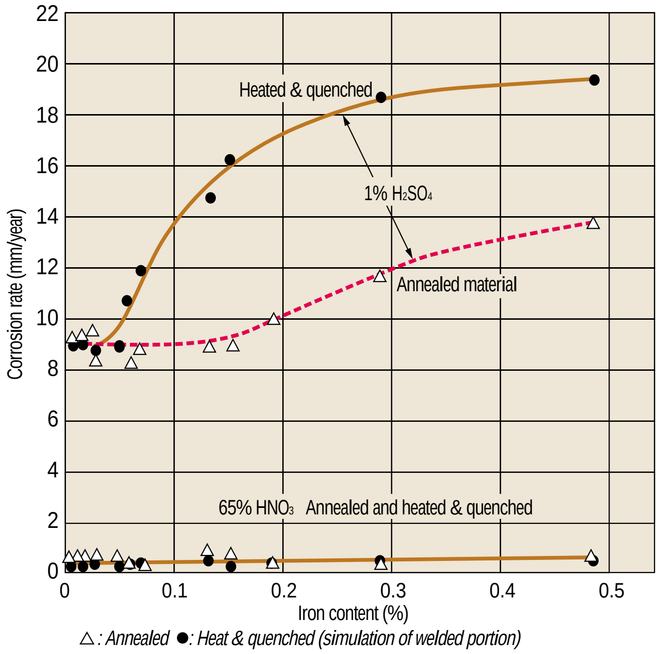


Fig.16: Effects of welding on corrosion rate of commercially pure titanium

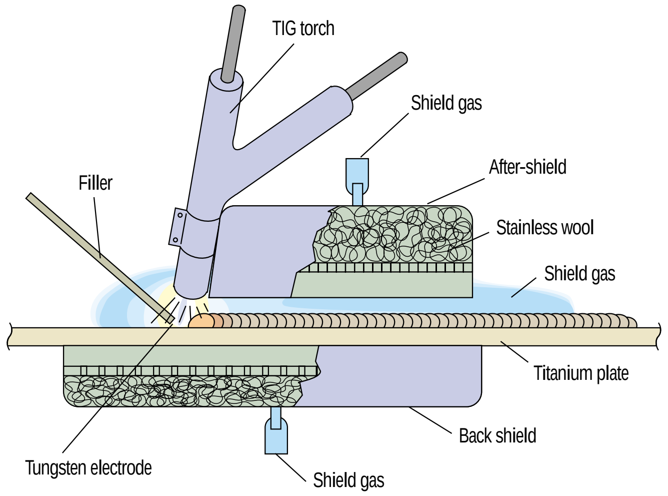


Fig.17:TIG welding torch and shield jig for titanium plate

If the welded portion reacts to gas, the result is discoloration as shown in Fig. 18. This phenomenon allows us to determine the weld quality, to some extent, by an inspection of its appearance.

The welding of titanium to steel materials had previously been considered difficult, but the technology developed by KOBE STEEL for welding heterogeneous metals has enabled techniques such as the direct lining of titanium to steel plate. (Please refer to "Steel Pipe Piles for Wharf" on page 6.)

(2) Brazing

Brazing is applied when titanium cannot be welded to other metals or when welding is difficult due to complex structures. Brazing to titanium is performed under a vacuum or inert gas atmosphere. The use of the brazing materials listed in Table 13 is recommended.

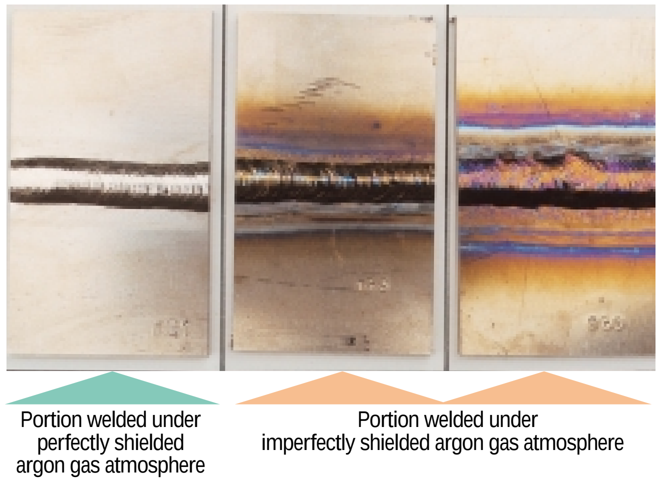


Fig.18: Appearance of TIG-welded portion of titanium

Table 13: Representative brazing materials and brazing temperatures

Brazing material	Brazing temperature (˚C)
Ag-3Li	800
Ag-7.5Cu-0.2Li	920
Ag-28Cu-0.2Li	830
Ag-20Cu-2Ni-0.2Li	920
Ag-20Cu-2Ni-0.4Li	920
Ag-9Ga-9Pd	900
Ag-27Cu-5Ti	840
Ti-15Cu-15Ni	930
Ti-20Zr-20Cu-20Ni	890
Ti-25Zr-50Cu	890

HEAT TREATMENT

Strain relief annealing is applied to commercially pure titanium and titanium alloys after hot and cold working. Annealing is also applied to recover or re-crystallize the deformed microstructure. Thus, annealing is effective for stabilizing the microstructure and dimensions of the treated product, and to improve the cutting properties and mechanical properties.

Heat treatments such as solution treatment & aging (STA), and double solution treatment & aging (STSTA) are applied to titanium alloys to improve strength, toughness, and fatigue properties. Titanium alloys of more β phase exhibit better heat-treatment properties. With β titanium alloy, after solution treatment it is possible to achieve tensile strength of around 1600 MPa by a two-stepped aging process of low-temperature aging and high-temperature aging.

An electric furnace with a fan agitation function is preferable for temperature control in the heat-treatment of titanium (Fig. 19). Furthermore, when using an annealing furnace, in order to prevent hydrogen absorption, it is necessary to increase the air ratio and make the furnace atmosphere one of weak oxidation, and to contain the product to be treated in a muffle to protect the product from direct contact with flame.

Table 14 shows typical conditions for the heat treatment of titanium materials.

Table 14: Representative heat treatment conditions for titanium materials

Material		Available heat treatment methods			
		Stress relief	Annealing	Solution treatment	Aging
Commercially pure titanium		480-595˚C 15-240min	650-815˚C 15-120min	—	—
α - β titanium alloy	Ti-3Al-2.5V	370-595˚C 15-240min	650-790˚C 30-120min	—	—
	Ti-6Al-4V	480-650˚C 60-240min	705-870˚C 15-60min	900-970˚C 2-90min	480-690˚C 2-8hr
β titanium alloy	Ti-15V-3Cr-3Sn-3Al	790-895˚C 30-60min	760-815˚C 3-30min	760-815˚C 2-30min	480-675˚C 2-24hr

Taken from: AMS-H-81200 Product shapes: thin plates, thick plates

Fig.19: Furnace for titanium products

SURFACE TREATMENT

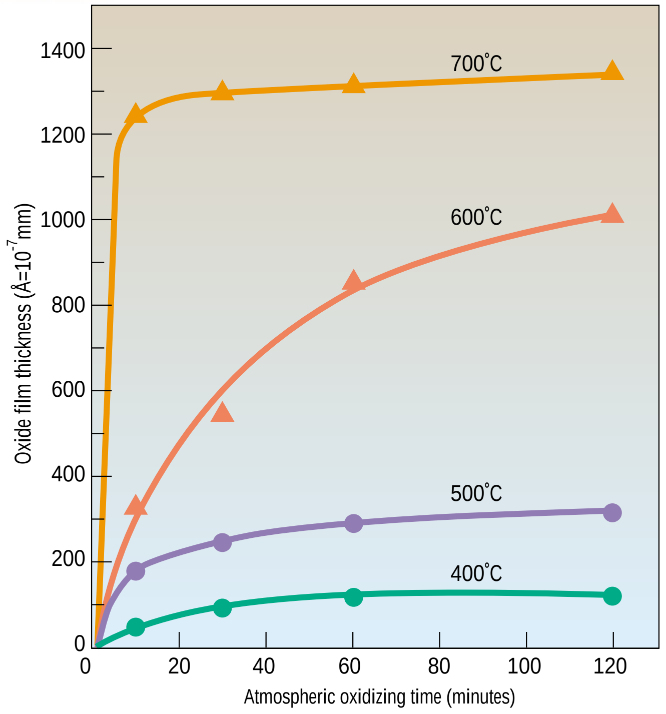


Fig.20: Relationship between atmospheric oxidizing time and oxide film thickness

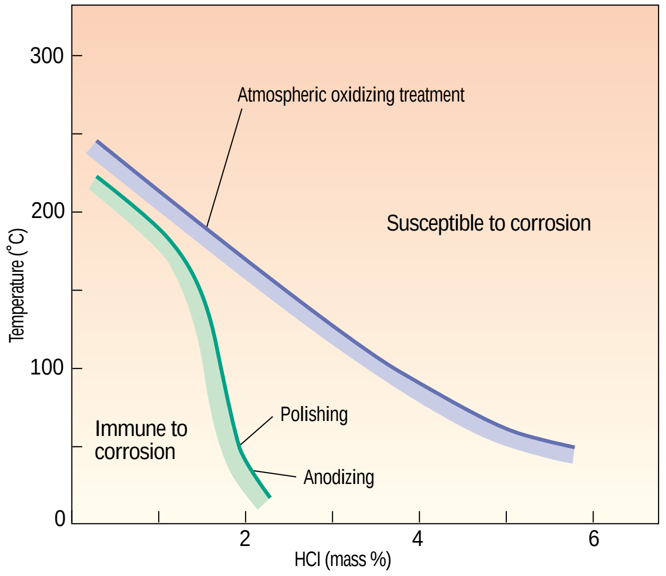


Fig.22: Boundary of active area to passive area of surface treated titanium materials in hydrochloric acid solution

(1) Surface treatment for corrosion resistance

- Atmospheric oxidizing treatment

The excellent corrosion resistance of titanium is due to a thin film of titanium oxide on the surface that is no more than a few dozen angstrom in thickness. Hence, the corrosion resistance can be further improved by investing the titanium with additional oxide film through atmospheric oxidizing treatment of its surface.
(Fig. 20〜22) Furthermore, atmospheric oxidizing treatment greatly inhibits hydrogen absorption.

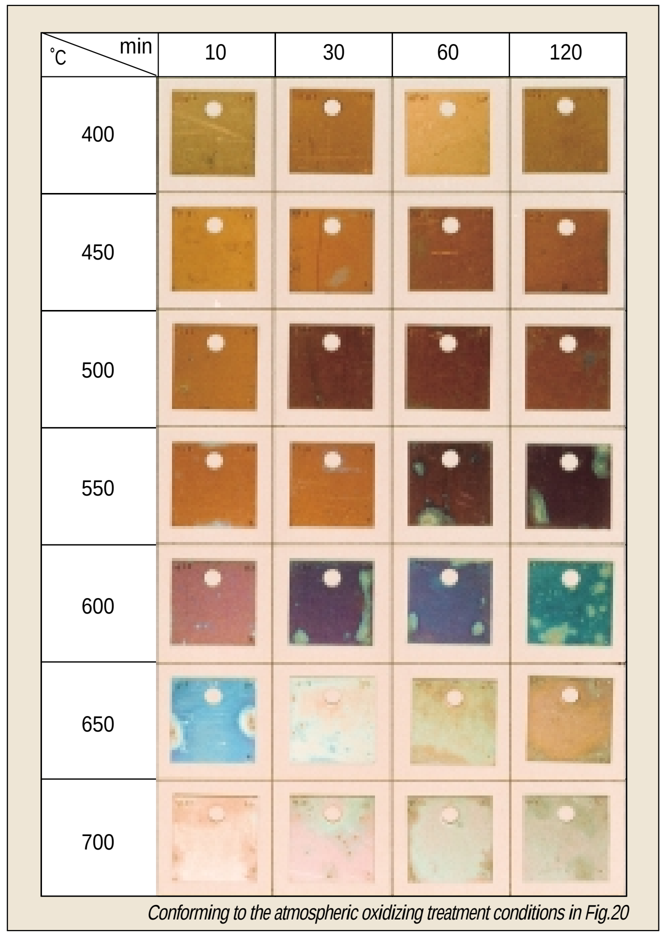


Fig.21: Appearance of commercially pure titanium specimens after atmospheric oxidation

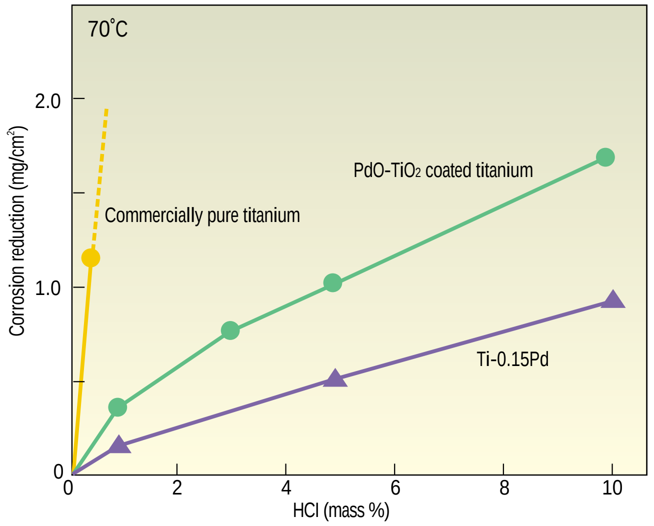


Fig.23: Corrosion resistance of PdO-TiO$_2$ coated titanium, commercially pure titanium and Ti-0.15Pd alloy in hydrochloric acid

- Noble metal coating

The general corrosion resistance and crevice corrosion resistance of titanium can be further improved by coating the surface with a film incorporating PdO-TiO$_2$. (Fig. 23)

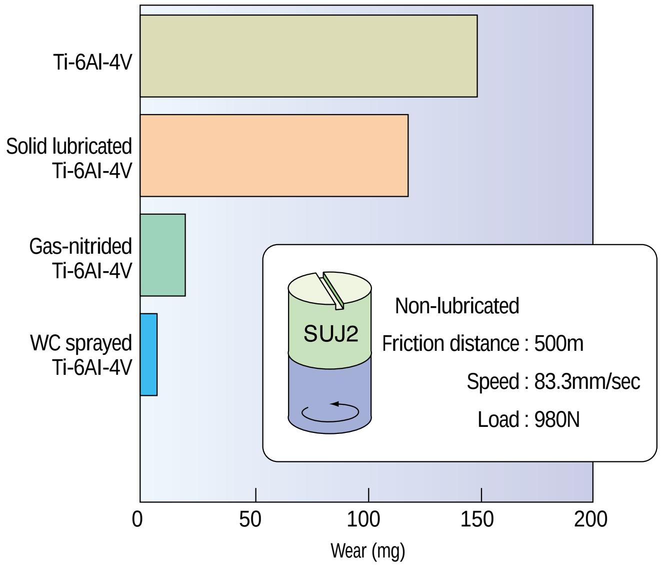


Fig.24: Sliding wear test results of Ti-6Al-4V alloys to which various surface treatments were applied

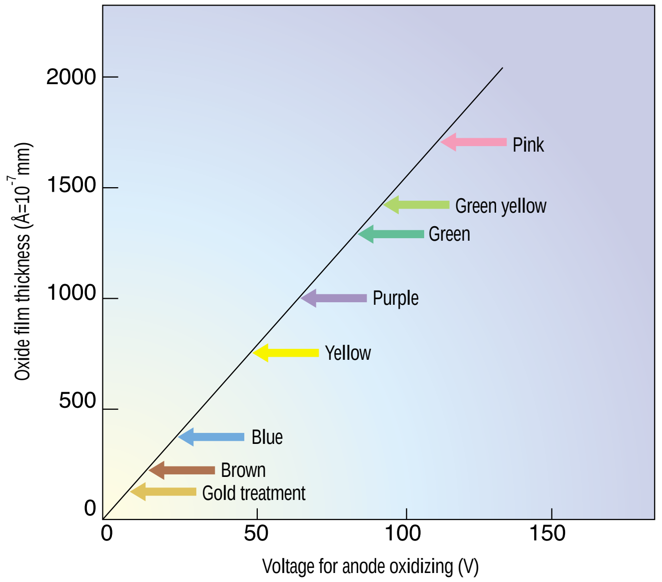


Fig.26: Relationship of anode oxidizing treatment voltage vs titanium oxide film thickness

(2) Surface treatment for surface design

By forming an oxide film on the titanium surface using the anodizing, light interference allows us to achieve beautiful color tones of high saturation, according to the film thickness. (Figs.25〜27)

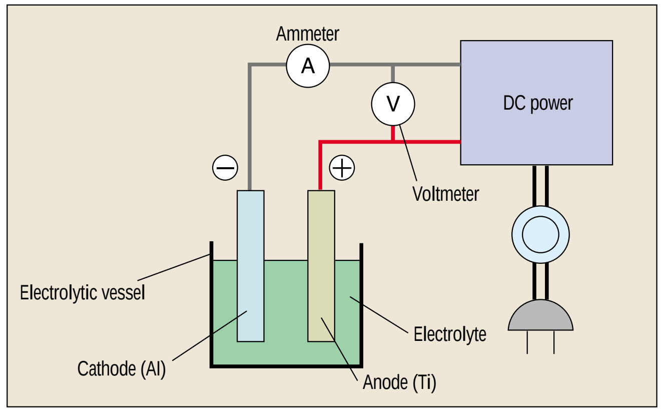


Fig.25: Schematic diagram of anodizing method

Fig.27: Appearance of anodized titanium
(The numerals show the applied anodizing voltages)

(3) Surface finishing

Various surface finishes are available including mirror, Scotch-Brite, hairline, vibration, blast, dull, and embossed.