# Chapter 1c
# Metallic Biomaterials: Titanium and Titanium Alloys

**H. Breme, V. Biehl, Nina Reger, and Ellen Gawalt**

## 1c.1 Composition

**Table 1c.1** Comparison of international standards for titanium and titanium alloys (Refs. 1, 2[a])

| Alloy | Germany DIN | United Kingdom BS | France AIR | International Organization for Standardization ISO | United States ASTM | Japan JIS |
|---|---|---|---|---|---|---|
| Ti-1 | 17850 | 2TA1 | 9182 T-35 | 5832/II | F67/Grade 1 | H4600 |
| Ti-2 | 17850 | 2TA2 | 9182 T-35 | | F67/Grade 2 | |
| Ti-3 | 17850 | 2TA6 | 9182 T-50 | | F67/Grade 3 | |
| Ti-4 | 17850 | 2TA6, 2AT7<br>2AT8, 2AT9 | 9182 T-60 | | F67/Grade 4 | |
| Ti6Al4V | 17851 | 2TA10, 2TA11 | 9183T-A6V | 5832/III | F136-13 | H4607 |
| | | 2TA13, 2TA28 | | | | |
| | | TA56, TA59 | | | | |
| Ti5Al2.5Fe | 17865 | BS7252–10 | – | 5832/X | – | – |
| Ti6Al7Nb | 17851 | | S94–081 | 5832/XI | Fl295 | – |

[a] Ti-l–Ti-4 = commercially pure unalloyed titanium; others: direct chemical composition

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H. Breme • V. Biehl
Lehrstuhl für Metallische Werkstoffe, Universität des Saarlandes, Saarbrücken, Germany

N. Reger • E. Gawalt (✉)
Department of Chemistry and Biochemistry, Bayer School of Natural and Environmental Sciences, Mellon 337, 600 Forbes Ave., Pittsburgh, PA 15282, USA
e-mail: gawalte@duq.edu

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**Table 1c.2** Chemical composition of commercially pure (cp)-titanium (wt%) (Refs. 1–3)

| cp-Ti | Fe max. | O approx. | N max. | C max. | H max. | Ti |
|---|---|---|---|---|---|---|
| Grade 1 | 0.2 | 0.18 | 0.03 | 0.1 | 0.015 | Balance |
| Grade 2 | 0.3 | 0.25 | 0.03 | 0.08 | 0.015 | Balance |
| Grade 3 | 0.3 | 0.35 | 0.05 | 0.1 | 0.015 | Balance |
| Grade 4 | 0.5 | 0.40 | 0.05 | 0.1 | 0.015 | Balance |

**Table 1c.3** Chemical composition of (α + β)-titanium alloys (wt%) (Ref. 1)

| | | | | | | | | | | Others | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alloy | Al | V | Fe | Nb | Ta | O | N | C | H | Single | Sum | Ti |
| Ti6Al4V | 5.5–6.5 | 3.5–4.5 | 0.25 | – | – | 0.13 | 0.05 | 0.08 | 0.012 | 0.1 | 0.4 | Balance |
| Ti5Al2.5Fe | 4.5–5.5 | – | 2.0–3.0 | – | – | 0.2 | 0.05 | 0.08 | 0.015 | 0.1 | 0.4 | Balance |
| Ti6Al7Nb | 5.5–6.5 | – | 0.25 | 6.5–7.5 | 0.5 | 0.2 | 0.05 | 0.08 | 0.009 | – | – | Balance |

**Table 1c.4** Chemical composition (wt%) of β and near-β titanium alloys (Refs. 4–7)

| Alloy | Al | Mo | Zr | Ta | Nb | Sn | Ti |
|---|---|---|---|---|---|---|---|
| Til5Mo5Zr3Al | 3.8 | 15 | 5 | | | | 77 |
| Til2Mo5Zr5Sn | | 12 | 5 | | | 4.5 | Balance |
| Ti30Nb | | | | | 30 | | 70 |
| Ti30Ta | | | | 29.6 | | | Balance |

## 1c.2 Physical Properties

**Table 1c.5** Physical properties of cp-Ti grade 1 (Refs. 8–11)

| | |
|---|---|
| Young's modulus | 102.7 GPa |
| Density | 4.51 g/cm$^3$ |
| Melting point | 1670 °C |
| Boiling point | 3260 °C |
| Transformation temperature α–β | 890 °C |
| Crystal structure | >882 °C β bcc |
| | <882 °C α cph |
| Magnetic properties | Paramagnetic |
| Heat of transformation | 67 kJ/kg |
| Thermal neutron-capture cross section | $5.8 \times 10^{-22}$ cm$^2$ |
| Specific heat at 15 °C | 0.52 kJ/kg K |
| Heat of fusion | 419 kJ/kg |
| Thermal conductivity at room temperature | 17 W/mK |
| Thermal expansion coefficient between 0 and 315 °C | $9.6 \times 10^{-6}$ °C$^{-1}$ |
| Specific heat resistivity at 20 °C | 0.5 µΩm |

**Table 1c.6** Physical properties of (α+β)-titanium alloys (Refs. 4, 8–9, 12–14)

| Property | Ti6Al4V | Ti5Al2.5Fe | Ti6Al7Nb |
|---|---|---|---|
| Young's modulus (GPa) | 100–110 | 110 | 105 |
| Density (g/cm$^3$) | 4.43 | 4.45 | 4.52 |
| Microstructure | A1–A9 | A1–A9 | A1–A9 |
| Transformation temperature (°C) | 990 ± 15 | 950 ± 15 | 1010 ± 15 |
| Thermal conductivity at room temperature (W/mK) | 6.6 | – | 7 |
| Coefficient of thermal expansion between 30 and 200 °C ($\times 10^{-6}$ K$^{-1}$) | 9.5 | 9.3 | – |
| Specific heat at 20 °C (kJ/kg K) | 0.56 | – | 0.54 |
| Specific electrical resistivity at 20 °C (52 mm$^2$/m) | 1.66 | – | – |

**Table 1c.7** Influence of alloying elements and heat treatment on Young's modulus (Refs. 5, 15–18)

| Alloy | Heat treatment | Young's modulus (GPa) |
|---|---|---|
| Ti30Ta | As rolled | 69 |
| | 1 h/1000 °C/$H_2O$ | 63 |
| Ti30Nb | As rolled | 80 |
| Til5Mo5Zr3Al ELI[a] | Solution heat treated at 840 °C | 75 |
| | Solution heat treated at 740 °C | 88 |
| | Solution heat treated at 740 °C + aged at 600 °C | 113 |

[a] ELI = extra-low interstitial

## 1c.3 Processing of cp-Ti and Ti Alloys

Provided that the following characteristics of titanium are taken into consideration, almost all processing procedures are possible:

1. High affinity to oxygen, nitrogen, and hydrogen gases
2. High reactivity to all metals to produce intermetallic compounds
3. Relatively low Young's modulus and therefore backspringing
4. Relatively low thermal conductivity
5. Tendency to stick to tools

### *1c.3.1 Hot Working and Heat Treatment*

Titanium and titanium alloys are fabricated into semifinished products by conventional methods such as forging, rolling, pressing, and drawing. When Ti materials are heated, care must be taken to avoid an excessive adsorption of oxygen, nitrogen, and hydrogen. Therefore, heating and annealing should take place in a neutral or slightly oxidizing atmosphere. During heating in a gas-fired furnace, direct contact with the flame must be avoided because of the risk of hydrogen pickup and local overheating. In a short heating period, oxygen pickup is restricted to the surface area. This surface zone must be removed by chemical or mechanical methods. Hydrogen is able to penetrate the matrix rapidly; therefore, a reducing atmosphere must be avoided. The hot working temperature depends on the alloy composition and should be selected to obtain the best mechanical properties and grain structure (A1–A9 according to ETTC2, Ref. 17). Table 1c.8 summarizes the deformation temperatures for the various Ti materials. Table 1c.9 lists the temperature ranges and recommended annealing times for stress relieving, soft annealing, and solution treating with age hardening. When the cross section is very small, annealing is favorably carried out in a high-vacuum furnace. Prior to this annealing treatment, the oxide film must be removed from the surface to avoid diffusion of oxygen into the material.

## 1c.3.2 *Working of Sheet*

At room temperature cp-Ti grades 1 and 2 can be worked very well, and grades 3 and 4 only moderately well. Titanium alloys, because of their high yield/tensile strength ratio, can be worked only under certain conditions.

**Table 1c.8** Deformation temperatures for various titanium materials (Refs. 19, 20)

| Alloy | Deformation temperature (°C) |
|---|---|
| cp-Ti Grade 1 | 650–870 |
| cp-Ti Grade 2 | 650–870 |
| cp-Ti Grade 3 | 700–900 |
| cp-Ti Grade 4 | 700–930 |
| Ti6Al4V | 700–1100 |

**Table 1c.9** Recommendation for the heat treatment of cp-Ti and Ti alloys (Refs. 2, 8)

| Alloy | Stress relief | Soft annealing | Solution annealing + age hardening |
|---|---|---|---|
| Ti grade 1 | 15 min–4 h at 480–595 °C/air | 6 min–2 h at 650–750 °C/air | – |
| Ti grade 2 | | | |
| Ti grade 3 | | | |
| Ti grade 4 | | | |
| Ti6A14V | 3 min/mm<br>1–4 h at 480–650 °C/air | Min. 1 h<br>max. 4 h at<br>700–850 °C<br>air or furnace cool | 15 min–1 h at<br>955–970 °C/$H_2O$<br>+2 h at 480–595 °C/$H_2O$ |
| Ti5A12.5Fe | 3 min/mm<br>15 min–4 h at 540–650 °C/air | Min. 10 min<br>max. 4 h at<br>720–845 °C<br>air or furnace cool | 15–1 h at 800–920 °C/$H_2O$<br>+2–4 h at 480–600 °C/air |

For deep drawing, special coatings in the form of polymer foils have proved to be effective. At high temperatures colloidal graphite and common hot press greases with graphite or molybdenum disulfide additives have been successful. The Fe-, Ni-, and Cr-contents should be limited to 0.05, 0.1, and 0.33 wt%, respectively, to allow during a short annealing treatment (1–5 min at 750–850 °C) a grain growth producing an average grain size of 50–70 μm. Due to this grain growth a deformation by twinning, with a resulting increased deep drawability, occurs (Ref. 19).

Superplastic forming is a material-saving and cost-reducing process for manufacturing parts of a complicated shape because it can be carried out together with diffusion welding in a single operation. Fine-grained alloys like Ti6Al4V and Ti5Al2.5Fe can be used for superplastic deformation. Other special deformation processes such as stretch forming, spinning, or explosion forming are also possible.

## *1c.3.3 Descaling*

The average thickness of the oxide layer on the surface of cp-Ti as a function of temperature can be found in Table 1c.10 and the composition of the oxide layer on cp-Ti and Ti alloys can be found in Table 1c.11. The oxide layer on the surface of thick-walled pieces generated during deformation and/or heat treatment is removed by sandblasting and/or pickling. The workpiece is treated in an aqueous solution of 20 wt% $HNO_3$ and 2 wt% HF.

Thin-walled pieces are merely pickled in an electrolytic solution or salt bath. It is important that not only the surface layer of oxide but also the underlying oxygen enriched diffusion zone is removed. Otherwise, the machinability and the service life of turning and milling tools would be negatively affected.

**Table 1c.10** Thickness of oxide formed on the surface of cp-Ti as a function of temperature (Ref. 2)

| Temperature (°C) | Measurable thickness (mm) |
|---|---|
| 315 | None |
| 425 | None |
| 540 | None |
| 650 | <0.005 |
| 705 | 0.005 |
| 760 | 0.008 |
| 815 | <0.025 |
| 870 | <0.025 |
| 925 | <0.05 |
| 980 | 0.05 |
| 1040 | 0.10 |
| 1095 | 0.36 |

**Table 1c.11** Nature of oxides formed on cp-Ti and titanium alloys (Ref. 22)

| Alloy | Oxide | | | | |
|---|---|---|---|---|---|
| | $TiO_2$ | $Al_2O_3$ | $Nb_2O_5$ | $MoO_3/MoO_2$ | $ZrO_2$ |
| cp-Ti | × | | | | |
| Ti6Al4V | × | × | | | |
| Ti5Al2.5Fe | × | × | | | |
| Ti6Al7Nb | × | × | × | | |
| Ti15Mo5Zr3Al | × | × | | × | × |

## *1c.3.4 Machining*

The machining of titanium materials presents no difficulties provided that the following properties are taken into account:

1. Relatively low thermal conductivity which may cause high thermal stresses at the cutting edge of the tool
2. Low Young's modulus which applies pressure to the tool
3. Tendency to stick to the tool

Titanium materials must be machined at low cutting speeds, at a relatively high feed rate, and with an ample supply of coolant (sulfur-containing oil; mixture of tetrachloride carbon, molybdenum sulfide, and graphite; 5 % aqueous solution of sodium nitrite, 5–10 % aqueous solution of water-soluble oil or sulfurized chlorinated oil). The cutting tools should be sharp and mounted as rigidly as possible. Recommended parameters for turning and milling are given in Table 1c.12. Since titanium dust and chips can easily catch fire, safety precautions must be taken. Threads should be cut on a lathe, as thread-cutting discs are subject to seizure.

Sawing causes no difficulties if a high blade pressure is used and the coolant supply is sufficient. Coarse-toothed blades (4 teeth per inch) are recommended.

For grinding, aluminum oxide (5–10 m/s) and silicon carbide (20–30 m/s) can be used.

## *1c.3.5 Soldering and Brazing*

Immediately before soldering and brazing, the oxide layer present on the surface of titanium material must be removed. For direct applications using a torch, aluminum–zinc and tin–zinc solders are suitable. The higher temperatures required for brazing present the difficulty of avoiding the formation of intermetallic phases. As with almost all metals, titanium forms brittle intermetallic phases in the fusion zone. The only exception is silver, so that this metal forms one of the main constituents of brazers. The sources of heat used for brazing and soldering are the acetylene torch, high-frequency induction coils, infrared radiation, an inert-gas-shielded arc with graphite or tungsten electrodes, furnaces with an argon atmosphere (min. 99.99 %

**Table 1c.12** Recommendations for the cutting and milling of cp-Ti and Ti alloys (Ref. 8)

| Alloy | Cutting speed (m/min) | Feed (mm/rev) | Depth of cut (mm) | Cutting angle | Relief angle |
|---|---|---|---|---|---|
| *Rough cutting* | | | | | |
| cp-Ti TC | 30–75 | 0.2–0.4 | | 0–6° | 6–8° |
| HSS | 7.5–4.0 | 0.1–1.25 | | 6–15° | 5–7° |
| | | | >2.5 | | |
| Ti alloys TC | 15–25 | 0.2–0.4 | | 0–6° | 6–8° |
| HSS | 3–15 | 0.1–0.4 | | 6–15° | 5–7° |
| *Forecutting* | | | | | |
| cp-Ti TC | 60–100 | 0.1–0.4 | | 6–6° | 6–8° |
| HSS | 18–50 | 0.075–0.2 | | 6–15° | 5–7° |
| | | | 0.75–2.5 | | |
| Ti alloys TC | 20–50 | 0.1–0.4 | | 6–6° | 6–8° |
| HSS | 5–15 | 0.075–0.2 | | 6–15° | 5–7° |
| *Finish cutting* | | | | | |
| cp-Ti TC | 60–100 | 0.075–0.3 | | 0–15° | 6–8° |
| HSS | 20–50 | 0.05–0.1 | | 5–6° | 5–7° |
| | | | 0.1–0.75 | | |
| Ti alloys TC | 20–70 | 0.075–0.3 | | 0–15° | 6–8° |
| HSS | 9–15 | 0.05–0.1 | | 5–6° | 5–7° |
| *Milling* | | | | | |
| cp-Ti TC | 25–30 | 0.07–0.15 | | | |
| HSS | 50–60 | 0.1–0.2 | >1.25 face cutter | – | – |
| Ti alloys TC | 7.5–20 | 0.07–0.2 | >2.5 gear cutter | | |
| HSS | 15–30 | 0.1–0.2 | | | |

*TC* hard metal (tungsten carbide)
*HSS* high-speed steel

and/or a dew point below −50 °C), and high-vacuum furnaces. If brazing is not performed under vacuum or in a controlled atmosphere, fluxes are necessary to dissolve the oxide layers and prevent a pickup of gases.

## *1c.3.6 Welding*

The inert-gas-shielded arc processes (TIG and MIG) are mainly used for fusion welding. In special cases resistance, ultrasonic, electron beam, diffusion, and laser welding are applied. With the cp-Ti grades the weld attains mechanical properties approximating those of the base metal. A slight decrease in ductility may occur with high tensile grades. Under passivating conditions, titanium welds have the same corrosion resistance as the base metal. On the contrary, in reducing media the weld may be subjected to a more severe corrosive attack than the base metal. During the welding operation, the weld, the heat-affected zone, and the underside of the weld are shielded from the atmosphere. The filler rod used is an uncoated wire of the same grade or of a grade with a lower hardness than the base metal. Careful preparation of the joint is necessary; that is, surface impurities must be removed by grinding or pickling in order to avoid porosity. Even fingermarks can produce a hardening of the weld. A single layer can weld sheets up to 2.5 mm thick. In order to avoid local oxygen concentrations oxidation products, such as those found at the tip of the electrode, must be cut off. The effectiveness of the inert gas is responsible for the welding rate. The optimum argon flow rate has proved to be about 6–8 l/mm. After welding, the appearance of a dark blue or gray oxide layer indicates an insufficient inert gas shielding and an embrittlement of the weld due to oxygen and/or nitrogen pickup. The hardness of a good weld may exceed that of the fully recrystallized base metal by a maximum of 50 VHN. If, after a slight grinding of the surface, a hardness test should give a higher value, the weld must be completely removed because of embrittlement.

Electron beam welding is particularly suitable for titanium materials. It offers many advantages such as very narrow seams and small heat-affected zones, weldability of thick diameters, high welding speed, and reproducibility of even complex welds.

Titanium materials can be spot welded without any particular preparation under similar conditions to those of stainless steel. Using flat-tipped electrodes, spot welding can be performed without inert gas. A hardening of the zone by up to 50 VHN compared with the base metal is regarded as normal and does not diminish the strength of the joint. Seam and flashbutt welding are also possible if an argon atmosphere is used.

Diffusion welding is of particular importance for titanium materials because these materials are more amenable to a homogeneous band in the solid state than other metals. After welding, the joint zone shows a higher temperature under high vacuum or, in an inert atmosphere, a microstructure very similar to that of the base metal.

## 1c.4 Mechanical Properties

**Table 1c.13** Mechanical properties of commercially pure titanium (Ref. 3, 21)

| Titanium[a] | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/ tensile strength | Elongation at fracture[b] (%) | Reduction of area[b] (%) | Brinell hardness | Bend radius (105°) for sheet thickness (*T*) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | <1.8 mm | >1.8–4.75 mm |
| Grade 1 | 170 | 240 | 0.71 | 24 | 30 | 110–170 | 3T | 4T |
| Grade 2 | 275 | 345 | 0.80 | 20 | 30 | 140–200 | 4T | 5T |
| Grade 3 | 380 | 450 | 0.84 | 18 | 30 | 140–200 | 4T | 5T |
| Grade 4 | 483 | 550 | 0.88 | 15 | 25 | 200–275 | 5T | 6T |

[a] Condition: Sheet, as rolled

[b] Minimum values

**Table 1c.14** Influence of a cold deformation on the mechanical properties of commercially pure titanium (Ref. 23)

| cp-Titanium | Condition (%) | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/ tensile strength | Elongation at fracture (%) |
|---|---|---|---|---|---|
| Ti grade 1 | 30 | 555 | 635 | 0.87 | 18 |
| | 40 | 560 | 645 | 0.87 | 16 |
| | 55 | 605 | 710 | 0.85 | 15 |
| | 60 | 620 | 725 | 0.86 | 14 |
| | 65 | 640 | 730 | 0.88 | 14.5 |
| Ti grade 2 | 30 | 605 | 680 | 0.89 | 18 |
| | 40 | 645 | 740 | 0.87 | 17 |
| | 50 | 680 | 780 | 0.87 | 16 |
| | 60 | 685 | 795 | 0.86 | 16 |
| | 65 | 692 | 810 | 0.85 | 16.5 |

**Table 1c.15** Mechanical properties of β and near-β-titanium alloys (experimental alloys) (Refs. 6, 15, 24–26)

| Alloy | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/ tensile strength | Elongation at fracture (%) | Reduction of area (%) |
|---|---|---|---|---|---|
| Ti15Mo5Zr3Al | 838 | 852 | 0.98 | 25 | 48 |
| Ti30Nb | 500 | 700 | 0.71 | 20 | 60 |
| Ti30Ta | 590 | 740 | 0.80 | 28 | 58 |

**Table 1c.16** Influence of heat treatment on the mechanical properties of β- and near-β-titanium alloys (Refs. 6, 15)

| Alloy | Condition | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/ tensile strength | Elongation at fracture (%) | Reduction of area (%) |
|---|---|---|---|---|---|---|
| Ti15Mo5Zr3Al | SHT at 840 °C | 870 | 882 | 0.99 | 20 | 83.2 |
| | SHT at 740 °C | 968 | 975 | 0.99 | 16.9 | 64.5 |
| | SHT at 740 °C | 1087 | 1099 | 0.99 | 15.3 | 57.5 |
| | + aged at 600 °C | | | | | |
| | 45 % cold worked | 1284 | 1312 | 0.98 | 11.3 | 43.8 |
| | + aged at 600 °C | | | | | |
| Ti30Ta | Annealed at 1100 °C | 650 | 800 | 0.81 | 8 | 42 |
| | Annealed at 1200 °C | 660 | 800 | 0.83 | 8 | 38 |
| | Annealed at 1300 °C | 665 | 800 | 0.83 | 8 | 30 |
| | Annealed at 1400 °C | 680 | 800 | 0.83 | 6 | 18 |

*SHT* solution heat treatment

**Table 1c.17** Mechanical properties of (α + β)-titanium alloys (Refs. 2, 27–29)

| Alloy | Condition sheet as rolled thickness (mm) | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/ tensile strength | Elongation at fracture (%) | Reduction of area (%) | Hardness | Bend radius (105°) for sheet thickness (*T*) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | <2 mm | <2–5 mm |
| Ti6A14V | –6 | 834 | 937 | 0.92 | 19 | 46 | 310 | 9T | 10T |
| | 6–100 | 951 | 1117 | 0.90 | 17 | 60 | 310 | | |
| Ti5A12.5Fe | –6 | 780 | 860 | 0.91 | 8 | 25 | 310 | 9T | 10T |
| Ti6A17Nb | Extruded | 811– | 869– | 0.93– | 7–13 | 24–44 | | | |
| | hot | 952 | 1008 | 0.94 | | | | | |
| | rolled | 943– | 1016– | 0.93 | 11–16 | 40–55 | | | |
| | + hot | 1008 | 1086 | | | | | | |
| | forged | | | | | | | | |

**Table 1c.18** Influence of a solution treating and ageing on the mechanical properties of Ti6Al4V

| Condition | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/tensile strength | Elongation at fracture (%) | Reduction of area (%) |
|---|---|---|---|---|---|
| Sheet ≤ 12.5 mm 15–60 min at 800–920 °C/$H_2O$ + 2–4 h 480–600 °C/air | 1070 | 1140 | 0.94 | 8 | 20 |

**Table 1c.19** Influence of a plasma nitriding (PVD) on the mechanical properties of Ti6Al4V (Ref. 30)

| Treatment | Tensile yield strength (0.2 %) (MPa) | Ultimate tensile strength (MPa) | Ratio yield/tensile strength | Elongation at fracture (%) |
|---|---|---|---|---|
| Untreated | 809 | 894 | 0.90 | 20 |
| Vacuum annealed | 815 | 924 | 0.88 | 21 |
| 20 h/850 °C | | | | |
| Plasma nitrided[a] | 805 | 914 | 0.88 | 20 |
| 20 h/850 °C/$N_2$ | | | | |
| Plasma nitrided[a] | 880 | 984 | 0.89 | 20 |
| 20 h/850 °C/$NH_3$ | | | | |

[a] Plasma nitriding at 20–40 kW

**Table 1c.20** Fracture toughness of Ti-alloys (Refs. 6, 31)

| Alloy | Condition | Fracture toughness $K_{IC}$ ($N/mm^{3/2}$) |
|---|---|---|
| Ti6Al4V | Annealed | 1740 |
| | Solution treated + annealed | 2020 |
| Ti5Al2.5Fe | Annealed (2 h/700 °C/air) | 1225 |
| | Solution treated + annealed | 1785 |
| | (1 h/900 °C/$H_2O$/2 h/700 °C/air) | |
| Ti15Mo5Zr3Al | Solution treated at 740 °C | 4580 |
| | Solution treated at 740 °C | 2430 |
| | + annealed at 600 °C | |
| | 40 % cold worked | 980 |
| | + annealed at 600 °C | |

## 1c.5 Fatigue

**Table 1c.21** High cycle fatigue strength $\sigma_B$ and rotating fatigue strength $\sigma_R$ of pure titanium and titanium alloys (Wöhler curves) (Refs. 15, 32–37)

| Alloy | *R* | $\sigma_B$ (MPa) | *R* | $\sigma_R$ (MPa) |
|---|---|---|---|---|
| cp-Ti | −1 | 230–280 | −1 | 200 |
| Ti6Al4V | −1 | 610–625 | −1 | 500–660 |
| Ti5Al2.5Fe | −1 | 580 | −1 | 450–550 |
| Ti6Al7Nb | −1 | 500–600 | −1 | 450–600 |
| cp-Nb | −1 | 270 | −1 | 150 |
| cp-Ta | −1 | 410 | −1 | 200 |
| Ti30Ta | −1 | – | −1 | 400 |

**Table 1c.22** Rotating bending fatigue tests of unnotched and notched titanium alloys (Ref. 31)

| Alloy | *R* | Condition | Stress concentration factor | Fatigue strength for alternating tensile stresses (>$10^7$ cycles) (MPa) |
|---|---|---|---|---|
| Ti6Al4V | −1 | | 1.0 | 725 |
| Ti5Al12.5Fe | −1 | Wrought + annealed | 1.0 | 725 |
| | −1 | Wrought + solution | 3.6 | 300 |
| | −1 | Treated + annealed | | |
| | −1 | Cast + HIP | 3.6 | 300 |
| | −1 | Cast + HIP | 1.0 | 450 |

**Table 1c.23** High cycle fatigue strength of hip endoprostheses of titanium alloys, measured in 0.9 % NaCl solution at 37 °C. Testing conditions similar to DIN 58840 (simulated loosened shaft, 50 mm) (Refs. 34, 36, 38)

| Alloy | Maximum load in $2 \times 10^7$ cycles (kN) 0.9 % NaCl (*f* = 2 Hz) |
|---|---|
| Hot wrought Ti6Al4V | 6.5–8.0 |
| Wrought Ti5Al2.5Fe | 8 |
| Ti6Al7Nb | 3.5–6.0 |

**Table 1c.24** Influence of the mean stress $S_m$ on the fatigue strength of Ti6Al4V (Ref. 39)

| $S_m$ (MPa) | *R* | Notch factor $K_f$ | Fatigue strength (MPa) at $10^7$ cycles |
|---|---|---|---|
| 0 | −1 | 1 | 400 |
| | | 2.82 | 250 |
| 250 | −0.1 | 1 | 300 |
| | 0.33 | 2.82 | 125 |
| 500 | 0.33 | 1 | 250 |
| | 0.66 | 2.82 | 100 |
| 750 | 0.7 | 1 | 125 |
| | 0.81 | 2.82 | 80 |

**Table 1c.25** Influence of the notch factor on the fatigue strength of Ti6Al4V (Refs. 40–43)

| Notch factor $K_f$ | Stress ratio $R$ | Fatigue strength (MPa) |
|---|---|---|
| 1 | −1 | 400 |
| 1.7 | −1 | 300 |
| 3.7 | −1 | 150 |
| 6.0 | −1 | 100 |

**Table 1c.26** Influence of interstitial elements on the rotating bending strength of Ti6Al4V (Ref. 44)

| Chemical composition of the base alloy (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Al | V | Fe | C | N | O | H | Ti |
| 6.03 | 3.96 | 0.10 | 0.02 | 0.009 | 0.1 | 0.005 | balance |

| | | Notch factor | Fatigue strength | |
|---|---|---|---|---|
| Composition | Heat treatment | $K_f$ | $R$ | (MPa) |
| Base alloy | 1 h 815 °C/furnace | 1 | –1 | 610 |
| | 600 °C air | 3 | –1 | 210 |
| Base alloy | 1 h 855 °C/furnace | 1 | –1 | 510 |
| +0.07 % N | 600 °C air | 3 | –1 | 180 |
| Base alloy | 1 h 870 °C/furnace | 1 | –1 | 550 |
| +0.2 % O | 600 °C air | 3 | –1 | 210 |
| Base alloy | 1 h 840 °C/furnace | 1 | –1 | 560 |
| +9.2 % C | 600 °C air | 3 | –1 | 230 |
| Base alloy | 1 h 930 °C/furnace | 1 | –1 | 580 |
| +0.07 % N | 600 °C air | 3 | –1 | 240 |
| +0.2 % O | | | | |
| +0.2 % C | | | | |

**Table 1c.27** Influence of texture and test directions on the rotating bending fatigue strength of Ti6Al4V (fine equiaxed microstructure in rolled plates) (Ref. 45)

| Type of texture and method of production | $R$ | Text direction | Fatigue strength (MPa) test direction at $10^7$ cycles |
|---|---|---|---|
| Basal (0002 tilted out of the rolling plane by about 30°) cross rolling in lower (α + β)-field | –1 | Rolling direction | 625 |
| Transverse (0002 aligned parallel to the rolling direction) unidirectional in the higher (α + β)-field, 950 °C | –1 | Rolling direction<br>Transverse direction | 630<br>590 |
| Basal/transverse (both are present)<br>Unidirectional roll at about 930 °C | –1 | Rolling direction<br>Transverse direction | 720<br>690 |

**Table 1c.28** Influence of heat treatment (annealing and precipitation hardening, respectively) on the fatigue strength of Ti6Al4V (Ref. 43, 46)

| Condition | Yield strength (MPa) | | | Tensile strength (MPa) |
|---|---|---|---|---|
| As annealed | 900 | | | 955 |
| As hardened | 1100 | | | 1195 |
| | | | | Fatigue strength (MPa) |
| Condition | $s_m$ | $K_f$ | $R$ | at $10^7$ cycles |
| As annealed | 0 | 1 | –1 | 510 |
| | 0 | 3.3 | –1 | 300 |
| As hardened | 0 | 1 | –1 | 600 |
| | 0 | 3.3 | –1 | 280 |
| As annealed | 200 | 1 | –0.3 | 425 |
| | 200 | 3.3 | –0.01 | 200 |
| As hardened | 200 | 1 | –0.5 | 600 |
| | 200 | 3.3 | 0 | 200 |
| As annealed | 300 | 1 | 0.14 | 400 |
| | 300 | 3.3 | 0.23 | 165 |
| As hardened | 300 | 1 | –0.22 | 550 |
| | 300 | 3.3 | –0.2 | 190 |

**Table 1c.29** Influence of the beta field heat treatment on the fatigue strength of Ti6Al4V (Ref. 47)

| Heat treatment | $R$ | Fatigue strength (MPa) at $10^7$ cycles |
|---|---|---|
| 0.5 h 1010 °C/AC + 2 h 700 °C/AC | 0 | 525 |
| 5 h 1000 °C/AC + 2 h 700 °C/AC | 0 | 620 |
| 0.5 h 1010 °C/$H_2O$ + 2 h 700 °C/AC | 0 | 750 |
| 5 h 1010 °C/$H_2O$ + 2 h 700 °C/$AC_2$ | 0 | 650 |

**Table 1c.30** Influence of the surface treatment on the rotating bending fatigue (fine lamellar microstructure, produced by annealing in 15 min/1050 °C/$H_2O$ + 1 h/800 °C/$H_2O$) (Ref. 48)

| Surface treatment | $R$ | Fatigue strength (MPa) at $10^7$ cycles |
|---|---|---|
| Electrically polished | –1 | 680 |
| Mechanically polished (7 μm) | –1 | 750 |
| Mechanically polished (80 μm) | –1 | 605 |
| Mechanically polished (80 μm) + 1 h 500 °C | –1 | 550 |
| Mechanically polished (180 μm) | –1 | 600 |
| Mechanically polished (80 μm) + 1 h 800 °C | –1 | 450 |

**Table 1c.31** Influence of the surface treatment on the rotating bending fatigue of Ti6Al4V (fine equiaxed microstructure produced by rolling at 800 °C/$H_2O$ + 1 h/800 °C (HP)) (Ref. 48)

| Surface treatment | $R$ | Fatigue strength (MPa) |
|---|---|---|
| Electrically polished | –1 | 610 |
| Shot peened | –1 | 710 |
| Shot peened + 1 h 500 °C | –1 | 390 |
| Shot peened + 1 h 500 °C | –1 | 800 |
| 20 μm surface removed | | |
| Shot peened + 20 μm surface removed | –1 | 820 |

**Table 1c.32** Influence of surface working on the rotating bending of Ti6Al4V (Ref. 40, 49)

| Surface working | Notch factor ($K_f$) | $R$ | Fatigue strength (MPa) |
|---|---|---|---|
| Mechanically polished | 1 | –1 | 620 |
| Mechanically polished | 1 | –1 | 660 |
| + cold roll bent | | | |
| Ground | 1 | –1 | 540 |
| Mechanically polished | 2.02 | –1 | 330 |

**Table 1c.33** Influence of plasma nitriding (PVD) on the rotating bending fatigue of Ti6Al4V (Ref. 30)

| Treatment | $R$ | Maximum bending stress at $10^7$ cycles (MPa) |
|---|---|---|
| Untreated | –1 | 600 |
| Vacuum annealed 20 h/850 °C | –1 | 370 |
| Plasma nitrided[a] 20 h/850 °C/$N_2$ | –1 | 470 |
| Plasma nitrided[a] 20 h/700 °C/$NH_3$ | –1 | 550 |
| Solution treated 1 h/940 °C/vac. | –1 | 530 |
| + Ar cooled | | |
| Solution treated 1 h/940 °C/vac. | –1 | 500 |
| + Ar cooled + plasma nitrided[a] | | |
| at 20 h/770 °C/$N_2$ | | |

[a] Plasma nitriding at 20–40 kW

## 1c.6 Corrosion and Wear

**Table 1c.34** Electrochemical data for titanium and titanium alloys in 0.1 M NaCl under different conditions (Refs. 24, 50–54)

| | Corrosion potential | Passive current density breakdown potential | |
|---|---|---|---|
| Alloy | $E_{corr}$ (mV) | $I_p$ (μA/cm$^2$) | $E_b$ (mV) |
| cp-Ti | | | |
| pH 7 | −628 | 2.5 | |
| pH 2 | −459 | 5–10 | >1500 |
| Ti5Al2.5Fe | | | |
| pH 7 | −529 | 0.68 | |
| pH 2 | −567 | 0.71 | >1500 |
| Ti6Al4V | | | |
| pH 7 | −510 | 0.92 | |
| pH 2 | −699 | 0.69 | >1500 |
| Ti6Al7Nb | | | |
| pH 7 | −368 | 0.53 | >1000 |
| Ti30Ta | | | |
| pH 7 | −419 | 0.3 | >1500 |

**Table 1c.35** Polarization current ($i$) and polarization resistance ($R_c$) of titanium and titanium alloys in pure saline at 37 °C (Ref. 50) and in 0.9 % NaCl with a stable redox system $[Fe(CN)_6^{4}VFe(CN)_6^{3}]$ (Ref. 55)

| | | $R_c$ (kΩ cm$^2$) | |
|---|---|---|---|
| Material | $i$ (μA/cm$^2$) | Pure saline | Saline + redox |
| cp-Ti | 0.010 | 1000 | 714 |
| Ti6Al4V | 0.008 | 1250 | 455 |

**Table 1c.36** Repassivation time in 0.9 % NaCl and breakdown potential in Hanks' solution of cp-Ti and Ti alloys (Refs. 24, 32, 56, 57)

| Alloy | Breakdown potential (mV) vs. calomel electrode | Repassivation −500 mV | Time (ms) +500 mV |
|---|---|---|---|
| cp-Ti | 2400 | 43 | 44.4 |
| cp-Ta | 2250 | – | – |
| Ti30Ta | >1500 | 41.7 | 47.5 |
| Ti40Nb | >1500 | 44.6 | 43.4 |
| Ti6Al4V | >2000 | 37 | 41 |
| Ti5Al2.5Fe | | 110–130 | 120–160 |

**Table 1c.37** Electrochemical data for anodic titanium and Ti6Al4V at 37 °C in different solutions (de-aired) versus standard calomel electrode (SCE) (Ref. 58)

| Alloy | Corrosion potential vs. SCE $E_p$ (mV) | Passive current density $I_b$ (μA/c$^{-2}$) | Breakdown potential $E$ (mV) | Solution[a] |
|---|---|---|---|---|
| cp-Ti | –440 to 490 | 1.0–3.0 | 1300 | 1 |
| | –94 to 140 | 0–1.0 | 1750 | 2 |
| | –94 | 5.0–9.0 | 1950 | 3 |
| Ti6Al4V | –200 to 250 | 0.9–1.0 | 1155–1240 | 1 |
| | –240 to 300 | 0.8–1.5 | 1900 | 2 |
| | –180 to 250 | 0.9–2.0 | 1550 | 3 |

[a] 1 = Ringer's solution; 2 = Hanks' solution; 3 = 0.17 M NaCl solution

**Table 1c.38** Electrochemical data for cp-Ti and Ti alloys after 7 days in artificial saliva (Ref. 59)

| Alloy | Corrosion potential (mV) | Current densities | |
|---|---|---|---|
| | | $I_{corr}$ (nA/cm$^2$) | $I_{pass}$ (μA/cm$^2$) |
| cp-Ti | –260 | 21 | 9.5 |
| Ti6Al4V | –230 | 31 | 10 |
| Ti6Al7Nb | –220 | 32 | 9 |
| Ti5Al2.5Fe | –180 | 30 | 6 |

**Table 1c.39** Repassivation time of titanium and titanium alloys in contact with different metallic materials (Ref. 60)

| NaCl pH = 7.4 (shortcut alloy) | HCl pH = 3 (activated alloy) | Repassivation time $t_c$ (ms) |
|---|---|---|
| cp-Ti | cp-Ti | – |
| | Ti30Ta | 37.7 |
| | Ti6Al4V | 41.8 |
| | cp-Nb | 480.0 |
| | Co30Cr6.5Mo | 38.7 |
| | Co28Cr5Mo | 38.4 |
| | X3CrNiMol812 | 1000.0 |
| Ti30Ta | cp-Ti | 43.0 |
| | Ti30Ta | 48.6 |
| | Ti6Al4V | 39.0 |
| | cp-Nb | 1080.0 |
| | Co30Cr6.5Mo | 44.1 |
| | Co28Cr5Mo | (4200) |
| | X3CrNiMol812 | 1000.0 |
| Ti6Al4V | cp-Ti | 44.0 |
| | Ti30Ta | 34.2 |

**Table 1c.40** Influence of the surface treatment on the fretting corrosion behavior of Ti6Al4V (Ref. 61)

| Material combination | Total weight loss (μg) | Ti (μg) | V (μg) |
|---|---|---|---|
| Untreated–untreated | 2423 | 3925 | 78.5 |
| Untreated–nitrogen ion implanted | 1295 | 1260 | 31.2 |
| Untreated–PVD coated with TiN | 1002 | 902 | 15.0 |
| Untreated–plasma ion nitrided | 807 | 716 | 6.4 |
| PVD-PVD | 713 | 470 | 8.5 |
| Plasma ion nitrided–plasma ion nitrided | 273 | 87 | 0.5 |

Testing conditions: plate screw system (micromotion = 100), 14 days in calf serum solution (1 Hz for 1,200,000 cycles)

**Table 1c.41** Influence of the surface treatment on the wear behavior of Ti6Al7Nb as a result of a pin-on-disk test (Ref. 62)

| Property | PVD coated with 3 μm TiN layer | Oxygen diffusion hardened (ODH) (30 μm hardened surface) |
|---|---|---|
| Wear factor ($10^{-7}$ mm$^3$/Nm) | 2.111 | 1.353 |
| Coefficient of friction | 0.078 | 0.051 |
| Surface roughness $R_z$ (μm) | 0.159 | 0.330 |
| Wetting angle (°) | 47 | 49 |

**Table 1c.42** Volumetric wear rate of Ti6Al4V and Ti6Al7Nb under different sliding speeds and normal load (Ref. 63)

| Sliding speed | Load (N) | Volumetric wear (mm$^3$ N/mm) | |
|---|---|---|---|
| | | Ti6Al4V | Ti6Al7Nb |
| 1 mm/s | 3 | $4.45 \times 10^{-3}$ | $5.48 \times 10^{-3}$ |
| | 6 | $4.24 \times 10^{-3}$ | $9.64 \times 10^{-3}$ |
| | 10 | $11.08 \times 10^{-3}$ | $13.12 \times 10^{-3}$ |
| 15 mm/s | 3 | $20.35 \times 10^{-3}$ | $22.06 \times 10^{-3}$ |
| | 6 | $37.98 \times 10^{-3}$ | $38.10 \times 10^{-3}$ |
| | 10 | $51.55 \times 10^{-3}$ | $57.35 \times 10^{-3}$ |
| 25 mm/s | 3 | $27.32 \times 10^{-3}$ | $31.38 \times 10^{-3}$ |
| | 6 | $42.15 \times 10^{-3}$ | $45.28 \times 10^{-3}$ |
| | 10 | $54.21 \times 10^{-3}$ | $57.62 \times 10^{-3}$ |

**Table 1c.43** Influence of ion implantation of nitrogen on the wear properties of commercial cp-Ti and Ti6A14V (Ref. 64)

| Material | Friction couple | Total wear (mg) | Friction coefficient |
|---|---|---|---|
| cp-Ti[a] | Untreated–untreated | 632.3 | 0.48 |
| | Nitrided–nitrided | 54.3 | 0.10 |
| | 4 h/940 °C/$N_2$:$H_2$ = 2:1 | | |
| Ti6A14V[b] | Untreated–untreated | 600.0 | 0.46 |
| | Nitrided–nitrided | 40.1 | 0.10 |
| | 4 h/940 ° C/$N_2$: $H_2$ = 2:1 | | |
| | Nitrided–nitrided | 92.3 | 0.12 |
| | 6 h/800 °C/$N_2$:$H_2$ = 1:1 | | |

[a] Friction distance = 1257 m
[b] Friction distance = 1885 m

**Table 1c.44** Rate of formation of corrosion products for cp-Ti in Hanks' solution during current-time-tests (Ref. 65)

| Polishing method | Metal converted into compound (ng/$cm^2$ h) |
|---|---|
| Mechanically polished | 4.1 |
| Chemically polished | 3.5 |

## 1c.7 Biological Properties

**Table 1c.45** Biocompatibility of cp-Ti and Ti alloys, survival rate of L132 cells incubated with powders (Ref. 66)

| Alloy | Powder concentration (mg/L) | Survival rate of cells |
|---|---|---|
| cp-Ti | >400 | |
| Ti6Al4V | >400 | |
| Ti5Al2.5Fe | >400 | >80 % |
| Ti30Ta | >400 | |
| Ti30Nb | >400 | |

**Table 1c.46** Influence of the implantation time (in vivo) on the surface roughness and peak-to-valley (P–V) height of Ti6A14V femoral heads (Ref. 67)

| Implantation time | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Position | Before implantation | | 85 months | | 110 months | | 124 months | |
| | $R_a$ (nm) | P–V | $R_a$ (nm) | P–V | $R_a$ (nm) | P–V | $R_a$ (nm) | P–V |
| Anterior | 43 ± 10 | 370 ± 72 | 58 ± 50 | 746 ± 509 | 250 ± 147 | 2044 ± 1178 | 86 ± 81 | 812 ± 763 |
| Posterior | 41 ± 6 | 591 ± 333 | 150 ± 125 | 2281 ± 1842 | 114 ± 96 | 1175 ± 778 | 142 ± 131 | 1045 ± 890 |
| Medial | 51 ± 14 | 411 ± 159 | 44 ± 29 | 649 ± 259 | 118 ± 69 | 1224 ± 731 | 412 ± 11 | 401 ± 125 |
| Lateral | 52 ± 9 | 364 ± 68 | 71 + 55 | 722 ± 474 | 117 ± 106 | 1195 ± 1009 | 40 ± 16 | 527 ± 156 |

## 1c.8 Nitinol: Shape Memory

**Table 1c.47** Properties of Nitinol (shape memory, Ni45Ti) alloy (Refs. 50, 68–71)

| | Above (=austenitic) | | Below (= martensitic) |
|---|---|---|---|
| | Transition temperature (–200 to 110 °C) | | |
| Density (g/cm$^3$) | | 6.45 | |
| Melting point (°C) | | 1310 | |
| Young's modulus (GPa) | 83 | | 28–41 |
| Tensile yield strength (0.2 %) (MPa) | 195–690 | | 70–140 |
| Ultimate tensile strength (MPa) | 640–1380 | | 103–862 |
| Ratio yield/tensile strength | 0.75–0.68 | | 0.33–0.16 |
| Elongation at fracture (%) | 1–15 | | up to 60 |
| Thermal expansion coefficient (°C$^{-1}$) | $1.1\times10^{-7}$ | | $6.6\times10^{-6}$ |
| Specific heat (Cal/g °C) | | 0.20 | |
| Electrical conductivity (S/m) | | 1–1.5 | |
| Corrosion potential (mV) | | | |
| in 0.1 M NaCl pH 7 | | –431 | |
| pH 2 | | –518 | |
| Passive current density (A/cm$^2$) | | | |
| in 0.1 M NaCl pH 7 | | 0.44 | |
| pH 2 | | 0.61 | |
| Breakdown potential (mV) | | | |
| in 0.1 M NaCl pH 7 | | 890 | |
| pH 2 | | 960 | |

**Table 1c.48** Resulting oxide layer thickness on Nitinol stents using different preparation techniques (Ref. 72)

| Surface treatment | Oxide layer thickness (Å) |
|---|---|
| Electropolished | 34 ± 14 |
| Passivated in 10 % $HNO_3$ | 30 ± 1 |
| Air aged at 450 °C | 240 ± 70 |
| Heat treated in a $NO_2^-/NO_3^-$ solution 500 °C | 911 ± 270 |

**Table 1c.49** Ion release from Nitinol incubated with L132 cell culture (Ref. 73)

| | Ni (ppm) | | Ti (ppm) | |
|---|---|---|---|---|
| | 3 days | 6 days | 3 days | 6 days |
| hp-Ni | 6.599 ± 0.037 | 11.364 ± 0.034 | n.m. | n.m. |
| cp-Ti | n.m. | n.m. | 0.001 | 0.002 |
| NiTi | 0.081 ± 0.006 | 0.176 ± 0.008 | 0.004 | 0.006 |

*hp-Ni* high-purity nickel, *n.m.* not measured

**Table 1c.50** Survival rate of L132 cells incubated with Nitinol powder (Ref. 74)

| Metal | Powder concentration (μg/mL) | Survival rate of cells |
|---|---|---|
| Nitinol | 400 | 71.2 % |

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