Processing of Titanium Materials

Technical Guidelines for Machining, Forming, Cutting, Welding and Heat Treatment

Titanium and titanium alloys can be processed reliably using established manufacturing methods. Compared with conventional steels, however, several material-specific characteristics must be taken into account. These include low thermal conductivity, a comparatively low modulus of elasticity, a tendency to gall and adhere during machining, and the high reactivity of titanium at elevated temperatures.

This technical information consolidates the content of the previous Form & Technik documentation in a streamlined and newly structured edition. Repeated material has been combined; historical individual values and test results are identified as reference data where they cannot be generalized without qualification.

Important note: Specific process parameters must always be matched to the material condition, machine, tool, component geometry, and current occupational-safety and manufacturer specifications. Information on highly hazardous process chemicals contained in the older documentation is not reproduced here as a working recipe.

Contents

1. Fundamentals of Titanium Processing

Material-specific characteristics

Processing titanium materials differs in several respects from machining conventional steels. Commercially pure titanium is generally readily formable, while titanium alloys can be considerably more demanding because of their higher strength and narrower plastic deformation range.

During machining, the cutting edge is exposed to high thermal loads. Titanium dissipates machining heat relatively poorly. At the same time, the material can deflect elastically under cutting pressure and, when locally heated, tends to adhere or weld to the tool.

- **Tools:** select sharp, stable tools suitable for the load.
- **Feed:** maintain a uniform and sufficiently high feed to limit rubbing and work hardening.
- **Cooling:** ensure effective heat removal.
- **Clamping:** clamp workpiece and tool as rigidly and vibration-free as possible.
- **Surface condition:** hard oxide or scale layers can significantly increase tool wear.

Reactivity at elevated temperatures

Heated titanium has a high affinity for oxygen, nitrogen and hydrogen. This is particularly important during welding and heat treatment. Uncontrolled gas absorption can adversely affect toughness and near-surface material properties.

> The older documentation contains numerous specific values from tests and earlier manufacturing recommendations. These values should be treated as technical reference data and validated against current tooling, equipment and material data before use in modern series production.

2. Chipless Forming and Deformation

Commercially pure titanium

The softest commercially pure titanium grade, 3.7025 (Grade 1), is particularly suitable for cold deep drawing. Harder commercially pure grades require larger radii and higher forces for bending, edging, spinning, flanging and folding. Greater springback must also be expected.

For more demanding forming operations, the previous documentation describes combined cold/warm forming in a range of approximately 250 to 400 °C. Uniform heating is more important than local temperature peaks. Material condition, wall thickness, bend radius and required geometry must be considered together when defining the process.

Titanium alloys

At room temperature, titanium alloys often have a comparatively limited plastic deformation range. Depending on alloy and geometry, cold forming may therefore be restricted. For demanding geometries, the source documentation recommends warm forming at approximately 500 to 800 °C, or cold forming followed by warm pressing.

For precision components, controlled warm forming can improve dimensional accuracy and reduce scrap. In all thermally assisted forming processes, the reactivity of the titanium surface must be taken into account.

Forging

The older documentation cites temperatures around 700 °C under a protective-gas atmosphere for forging titanium. In practice, suitable forging temperatures depend strongly on alloy, microstructural condition and degree of deformation.

3. Machining: Turning and Milling

Basic principles

Titanium and titanium alloys can be machined in a manner comparable to austenitic steels when their particular thermal and mechanical characteristics are considered. Low to moderate cutting speeds, sufficiently high and uniform feed, effective cooling, and rigid, vibration-resistant clamping have proven beneficial.

Turning

The previous documentation lists high-cobalt high-speed steels, carbides and Stellite as possible cutting materials. For carbide tools it particularly describes tungsten-carbide grades with cobalt bonding. Historical tool geometries in the document cite rake angles of approximately -6° to +6° for roughing and pre-turning and 0° to 15° for finish turning. These values should be regarded as starting points and checked against current tool-manufacturer data.

Milling

Because titanium tends to adhere to the tool, climb milling is preferred over conventional milling in the source documentation. This can reduce built-up edge formation and chip adhesion. For milling cutters, the older document gives rake angles of 0° to 10° for high-speed steel and approximately 0° for carbide or Stellite.

> **Practical note:** Tool technology and coatings have advanced substantially since the source document was prepared. Current manufacturer data should take precedence when defining cutting parameters and tool geometry.

4. Drilling, Threading, Sawing and Grinding

Drilling

For drilling, the source documentation recommends a relatively high feed at low cutting speed, a rigid and vibration-resistant machine, and intensive cooling. Drill geometry should support reliable chip evacuation. In deep holes, regular chip breaking and removal are especially important.

High-speed steels and carbides are listed as drill materials. For through holes, the historical document describes a point angle of approximately 140° and clearance angles in the range of 10° to 15°.

Threading

A rigid machine setup and secure tool mounting are particularly important for threading. As historical guide values, the older documentation gives peripheral speeds of 5-15 m/min for unalloyed titanium, 3-10 m/min for annealed titanium alloys and 1-5 m/min for hardened titanium alloys.

External threads should preferably be produced mechanically. For internal threads, thread milling or circular milling can offer advantages because chips can be evacuated more effectively and process reliability can be improved, especially in blind holes.

Sawing

Titanium can be separated using reciprocating, circular or band saws. The source documentation recommends sufficiently high contact pressure, effective cooling and tooth pitch matched to wall thickness. As a historical orientation, it cites a cutting speed approximately 25% below that used for steel.

Grinding

Grinding can generate high local temperatures because of the high proportion of friction. This can lead to smearing, surface damage, residual stresses and, under unfavorable conditions, grinding cracks. The source documentation lists aluminium oxide, silicon carbide and resin-bonded diamond wheels among the possible abrasives.

Safety: Titanium dust and fine titanium chips can be readily ignitable or pyrophoric. Suitable operational fire-protection and occupational-safety measures are required for extraction, collection, storage and disposal.

5. Cooling, Tool Selection and Special Machining Notes

Cooling and lubrication

The previous documentation describes water-based solutions and emulsions as common coolants and lubricants for machining. Their purpose is to remove heat effectively and reduce friction, adhesion and galling.

Historically, the document also mentions sulfur- and chlorine-containing cutting oils and other chemically active lubricants. Such information should not be adopted without review today. Selection and use of metalworking fluids must comply with current manufacturer approvals, occupational-safety requirements, disposal rules and the intended downstream process.

Diamond-coated cutting materials

One section of the source documentation describes laboratory tests using PCD cutting materials for titanium machining. Under defined conditions, cutting speeds of up to 160 m/min and long tool lives were investigated. At the same time, the document points to the high thermal load on the diamond at the cutting edge.

These results relate to specific tool types and test conditions and should not be interpreted as generally applicable cutting values. They nevertheless illustrate the major influence of tool material, cutting-edge geometry and cooling strategy on productivity in titanium machining.

Planing

For planing, the older documentation describes a substantial reduction in cutting speed compared with austenitic chromium-nickel steel and the use of tungsten-carbide cutting tools. Depending on the component, the process is now supplemented or replaced by other machining strategies.

6. Cutting and Separation

Titanium and titanium alloys can be processed using thermal cutting methods as well as abrasive waterjet cutting. The source documentation covers oxy-fuel cutting, plasma cutting, laser cutting and waterjet cutting.

Thermal cutting methods

For oxy-fuel and plasma cutting, the older documentation reports qualitatively satisfactory cuts up to approximately 50 mm material thickness; for laser cutting of that period, a limit of approximately 10 mm is described. These historical performance limits do not necessarily reflect the capabilities of modern equipment.

Thermal methods create heat-affected zones. As historical test values, the documentation gives orders of magnitude of approximately 1 mm for plasma cutting, 0.5 mm for oxy-fuel cutting and 0.1-0.2 mm for laser cutting. Heat-affected regions should be professionally assessed before critical downstream processes - especially welding - and removed where necessary.

Abrasive waterjet cutting

The principal advantage of abrasive waterjet cutting is the absence of thermal heat input. As a result, no conventional heat-affected zone is created and there is no thermally induced edge hardening.

TiAl4Mo4Sn2Si, hardened	26 mm	50 mm/min, straight cut
TiAl6V4	110 mm	7 mm/min, straight cut
TiAl6V4	110 mm	1 mm/min, radii

The values above originate from individual tests in the source documentation and must not be generalized. Modern equipment may operate in substantially different performance ranges.

7. Welding and Joining

Fusion welding

Titanium is generally readily weldable provided that the high affinity of the heated material for gases is taken into account. Molten or strongly heated titanium must be reliably protected from air during welding and throughout the cooling phase.

The source documentation lists TIG, electron-beam and laser welding as suitable methods; MIG is also mentioned under particular conditions. High-purity argon is described for shielding. Current process specifications and the requirements of the selected welding method are decisive.

- **Protect the weld zone:** maintain shielding-gas coverage during cooling.
- **Protect the root side:** provide suitable backing or an additional shielding-gas flow.
- **Cleanliness:** clean joint surfaces thoroughly and keep them free of contamination.
- **Dissimilar materials:** direct welded joints with steel or aluminium are problematic because brittle intermetallic phases can form.

Electron-beam and pulse welding

Electron-beam welding is described in the source documentation as particularly suitable for titanium. Pulse-welding processes are also mentioned.

Brazing and soldering

Joining titanium by brazing or soldering is possible in principle, but can be complicated by the formation of brittle intermetallic phases. The source documentation therefore emphasizes thorough cleaning and descaling of the joining surfaces and reports positive experience with certain silver-based filler metals.

8. Heat Treatment

Annealing and stress relieving

Annealing is used to reduce strengthening caused by forming or hardening, or to establish a stable material condition. Stress-relief annealing is intended to reduce residual stresses without substantially changing the microstructure.

For all heat treatments, the high reactivity of titanium toward hydrogen, oxygen and nitrogen must be considered. The source documentation notes that hydrogen absorption can become relevant from approximately 500 °C, while above approximately 700 °C oxygen and nitrogen increasingly contribute to scale formation and an oxygen-enriched diffusion zone.

Annealing CP titanium 3.7025 / 3.7035 / 3.7055 / 3.7065	600-800 °C	700 °C	2 min/mm; min. 10, max. 20 min	Air
Annealing TiAl6V4 (3.7165)	700-840 °C	730 °C	2 min/mm; min. 30, max. 300 min	Air or furnace to 500 °C, then air
Annealing TiAl6V6Sn2 (3.7175)	700-840 °C	730 °C	2 min/mm; min. 30, max. 480 min	Air or furnace to 500 °C, then air
Stress relieving CP titanium	500-600 °C	550 °C	30-60 min	Air
Stress relieving TiAl6V4	550-700 °C	675 °C	60 min*	Air or furnace to 500 °C, then air
Stress relieving TiAl6V6Sn2	550-650 °C	600 °C	60-120 min	Air or furnace to 500 °C, then air

* At this point the source table contains a typographically ambiguous entry ('60 - 60 min.'). It has not been independently corrected in this new edition; the original value should be technically verified before release.

Furnaces and charging

Protective-atmosphere and vacuum furnaces, as well as electrically or gas-heated air furnaces, are listed as heat-treatment equipment. For gas-heated furnaces, the source documentation describes an air excess of approximately 10-15% and requires direct flame contact with the workpiece to be avoided.

Workpieces in a batch should have broadly comparable thicknesses. Parts must be clean and dry. Contact with materials that can cause undesirable reactions or low-melting phases at high temperatures should be avoided.

9. Surface Treatment and Pickling

Descaling and pickling

Scale and oxide layers formed during heat treatment can be removed mechanically, for example by blasting, grinding or brushing, followed by chemical treatment where appropriate. Light heat tint can be removed by suitable pickling processes depending on its condition.

The older documentation contains specific formulations involving nitric and hydrofluoric acid. Because of the severe hazards associated with such chemicals, these mixing ratios are deliberately not reproduced in this new edition as work instructions. Current approved process instructions, safety data sheets and operational protective measures are authoritative for pickling operations.

Anodic oxidation

Anodic oxidation strengthens or modifies the natural oxide layer on titanium. Depending on process control and applied voltage, different interference colors can be produced. The source documentation describes color ranges from silver and gold through blue and purple to lighter blue shades.

Layer formation depends significantly on surface condition, pretreatment, electrolyte and voltage. A clean, contamination-free starting surface is required for uniform and reproducible finishes.

Occupational safety: Hydrofluoric acid and other highly corrosive process chemicals can cause extremely serious injury. Chemical surface treatments must only be performed in suitable facilities by trained personnel and under a current risk assessment.

10. Practical Notes on Component Design and Bending

Bending titanium bars and tubes

The final practical note in the previous documentation warns against simply bending titanium bars or tubes by hand or in a vice without suitable guidance. Uneven loading, local surface damage and excessively small bend radii can lead to irregular deformation or cracking.

For reproducible results, a suitable bending machine or at least a forming fixture is advisable. The bending zone should be treated uniformly and - where appropriate for the material and process - heated in a controlled manner. The older documentation gives a temperature range for this purpose, but the exact figure is not clearly legible in the surviving scan. It has therefore not been reconstructed in this new edition.

Manufacturing-oriented alternative

For larger quantities of identical geometries, it may be economically advantageous to consider a near-net-shape casting or another manufacturing process instead of a complex bending operation. The original documentation specifically mentions investment casting as a possible alternative.

The decisive factor is an overall assessment of material, geometry, quantity, scrap risk, finishing effort and required component quality.

Summary

Titanium is not inherently a difficult material to process, but it requires process conditions appropriate to the material. Controlled heat generation, sharp and suitable tools, stable machining conditions, effective shielding during thermal processes, and consideration of the relevant titanium grade and microstructural condition are particularly important.

The historical reference values reproduced in this document are intended for technical orientation. For actual production, current material specifications, tooling and equipment manufacturer data, and the applicable quality and safety requirements must be used.

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