Titanium and titanium alloys

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Lecture 3: Technological aspects of Ti alloys

• Pure Ti – metallurgy, properties and applications
• α+β alloys
  • microstructures, metallurgy, heat treatment
  • Ti-6Al-4V alloy properties and applications
• High temperature alloys
• Metastable β-alloys
  • Metallurgy, heat treatment
• High strength alloys
Pure titanium and $\alpha$ - alloys

- After cooling $\rightarrow \alpha$ – phase only
- Alloys contain Al and Sn, interstitial O, C, N and only limited amount of $\beta$-stabilizers
- Comparatively low strength (pure Ti)
- Pure Ti – strengthened by interstitial O
- $\alpha$ – alloys strengthen also via substitutional strengthening and precipitates ($\text{Ti}_3\text{Al}$)

[Diagram showing temperature changes and phases I, II, III: Homogenization, Deformation, Recrystallization.]
Pure Ti – grade 1 - 4

- Commercial purity – CP Ti is manufactured with four different oxygen contents (grade 1- 4)
- Oxygen content is decisive for strength of the material
- CP Ti is cheaper than Ti alloys
- Corrosion resistance is the key advantage when compared other classes of materials
- Corrosion resistance can be further increased by small content of Pd or Ru (0.05 -0.2 %)

<table>
<thead>
<tr>
<th>Grade</th>
<th>O [wt.%]</th>
<th>Fe (max.) [wt.%]</th>
<th>$s_{02}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Ti Grade 1</td>
<td>0.18</td>
<td>0.2</td>
<td>170</td>
</tr>
<tr>
<td>CP Ti Grade 2</td>
<td>0.25</td>
<td>0.3</td>
<td>275</td>
</tr>
<tr>
<td>CP Ti Grade 3</td>
<td>0.35</td>
<td>0.3</td>
<td>380</td>
</tr>
<tr>
<td>CP Ti Grade 4</td>
<td>0.40</td>
<td>0.5</td>
<td>480</td>
</tr>
</tbody>
</table>
Pure Ti - applications

• Chemical and petrochemical industry, power plants
  – Resistant to aggressive chemicals
  – Heat exchangers, pipes,…

• Pressure vessels
  – Can be used over wide range of temperatures and pressures
  – Chemically resistant

• Cryogenic vessels
  – Storage of liquid oxygen and hydrogen
    • used in space-shuttles – lighter than steel
Pure Ti – biomedical use

• Non-toxic inert material
• Pure Ti can be used only for implants without extensive demands for strength, otherwise stronger alloys must be used
  – Some small orthopaedic fixation implants
  – Dental implants (stents)
    – current use of ultra-fine grained CP Ti
\(\alpha + \beta\) - alloys

- After cooling → mixture of \(\alpha\) and \(\beta\) phases
- The original and still the most common high-strength Ti alloys
- Three different types of microstructures can be achieved by thermal treatment
  - Fully lamellar
  - Bimodal (also called duplex)
  - Equiaxed (also called globular)
\( \alpha + \beta \) – alloys – lamellar microstructure

- Above beta-transus temperature, the material consist of beta grains only
- Upon cooling the structure transforms to lamellar structure. Alpha lamallae are created within the grains.
- Key parameter is cooling after recrystallization treatment
  - The higher speed the finer lamellae are created
  - Typical width is 0.5 – 5 µm
  - Typical length – hundreds of µm
- Lower strength and formability, good low-cycle fatigue performance (when compared to other microstructures)
**$\alpha + \beta$ – alloys – duplex microstructure**

- Duplex (bimodal) structure consists of lamellar structure ($\alpha + \beta$ area) and in the grain triple-points there are created equiaxed $\alpha$–particles – so-called primary alpha ($\alpha_p$)
- Duplex structure can be achieved by annealing in the $\alpha+\beta$ field (just below $\beta$-transus temperature)
- Key parameters are:
  1. Cooling rate after homogenization treatment in $\beta$–field
    - The rate is decisive for the $\alpha$ lamellae size
  2. Temperature of annealing in $\alpha + \beta$ field
    - Temperature is decisive for volume fraction of primary $\alpha$ phase ($\alpha_p$)
**α + β – alloys – globular microstructure**

- Globular (equiaxed) microstructure consists of equiaxed particles of primary α phase ($\alpha_p$), β–phase is along the grain boundaries

- Equiaxed structure can be achieved similarly to duplex structure
  - Lower cooling rate after recrystallization
  - Lower recrystallization annealing temperature

- Small grains might be achieved
\( \alpha + \beta \) – alloys – microstructure comparison

- **Lamellar**
  - Size of the \( \alpha \)-lamellae is decisive for strength (smaller is better)
  - Bigger lamellae cause slower propagation of fatigue crack (increased fatigue toughness)

- **Duplex**
  - Size of lamellae and volume fraction of primary \( \alpha \)-phase affect strength of the material
  - Higher strength when compared to lamellar structure
  - Optimal volume fraction of primary \( \alpha \)-phase is 15-20%

- **Equiaxed**
  - Grain size affects the strength of the material
  - Small grain size is achievable (even below < 2 \( \mu \)m)
  - Highest attainable strength
Ti-6Al-4V alloy

• $\alpha + \beta$ alloy

• The oldest and the most used titanium alloy (denoted Grade 5, just after 4 Grades of Pure Ti)
  - High strength (1000 MPa), excellent formability
    • Formability in $\alpha + \beta$ alloys is improved thanks to high content of beta phase (that is easier to form) at forming temperatures

• 50% of whole titanium and titanium alloys production (but $\beta$ alloys are being increasingly produced)

• $\beta$-stabilizing vanadium causes the presence of $\beta$-phase at room temperature
  - increased strength at room temperature
  - improved formability at elevated temperatures

• During recrystallization, both phases are chemically stabilized

• Aluminium causes solid solution strengthening, but more importantly precipitation strengthening due to precipitation of Ti$_3$Al particles during ageing
  - Solvus temperature of these particles is around 550°C
  - Typical final ageing treatment is 500°C/ 2-24 hod
Ti-6Al-4V alloy - properties

- Typical impurities content: O: 0.2; N: 0.04; H: 0.015; Cu: 0.35-1; Fe: 0.35-1 wt.%
- Density: 4.54 g/cm³
- Yield stress: 830 – 1100 MPa
- Ultimate tensile strength: 895 – 1250 MPa
  - Higher content of O, N a C increases strength but decreases formability
  - High cycle fatigue limit: 550 – 700 MPa
    - Approximately 0.6 x yield stress
    - Extreme notch sensitivity
      - Surface quality is the key factor of high-cycle fatigue
- Elastic modulus – 120 GPa
- Creep resistance up to 400°C
Ti-6Al-4V - applications

• Structural parts of airplanes
  – Higher specific strength and fatigue performance than aluminium and steels, moreover higher corrosion resistance
  – Structure and landing-gear of Boeing 747 (Jumbo Jet)
    • 20-30 tonnes of titanium (out of 180 tonnes)
  – Construction of wings and body of military aircrafts
    • fighter F-22
Ti-6Al-4V - applications

• Airplanes engines
  – Ti-6Al-4V alloy usable only up to 300 – 400°C
  – Rotating parts
    • Low specific density is even more important
    • Fatigue endurance
      – High-cycle fatigue – rotation of the engine parts
      – Low-cycle fatigue – each start of the motor (including „temperature fatigue“)
  – Non-rotating parts
    • Shafts and connections of engines to the wings and the body
    • Fatigue performance is still important due to vibrations
Ti-6Al-4V alloy – other applications

• Power plants – steam turbines
• Oil and gas mining
  – Deep-sea oil platforms
• Armor
  – Much lighter than steel, but expensive
• Sporting goods
• Medicine
  – Vanadium is believed to be toxic
  – Anyway still the most used alloy
  – Total endoprostheses of big joints
High-temperature alloys

• The aim is to suppress creep – decrease diffusivity
  → Smaller ratio of β–phase (5 – 10% vs. 15% in Ti6Al4V)
  → Diffusivity in Molybdenum is lower than in Vanadium
  → Increased temperature lead to dissolution of Ti₃Al particles (decreased strength)
    → IMI 384 – intermetallic particles (Ti₅Zr)₅Si₃ (solvus is above 1000°C)
    → Maximum working temperature Ti-6242 – 500°C; IMI 834 – 550°C
• Ti – 6242 (Ti-6Al-2Sn-4Zr-6Mo)
• IMI 834 (Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si)
• Applications
  – Airplanes engines
  – APU (auxiliary power unit)
Metastable $\beta$ – alloys

- Metastable b-alloys do not undergo martensitic phase transformation $\beta \rightarrow \alpha$ after quenching from $\beta$-region
- Solution treated material consist of pure $\beta$-phase, but equilibrium composition is $\alpha + \beta$
- **Precipitation hardenable by (precise) thermal treatment**
- Modern, fast developing field of research and application of Ti alloys
- Working can be done after homogenization treatment in $\beta$-region (more common) or in $\alpha + \beta$ field (material is hardened during working, but grain refinement can be achieved)
- Alloys can be divided according to processing to beta-annealed and beta-worked
- Beta-annealed alloys are recrystallized slightly above $\beta$-transus temperature after deformation
- Beta-worked alloys are not recrystallized in $\beta$-region
- Both types can be annealed/aged in $\alpha+\beta$ region.
Metastable $\beta$ – alloys – strengthening

- After annealing in b-region material consists of pure $\beta$-phase
  - Comparatively low strength, given by chemical composition (solid solution strengthening and eventual precipitation hardening) and grain size
  - Strength can be increased from 450 MPa to 1200 Mpa (Ti-Nb-Zr-Ta-Fe-Si-O alloy)

- Low-stabilized alloys
  - Lamellae of $\alpha$-phase are created during annealing at high temperatures in $\alpha + \beta$ region
  - Ageing – small $\alpha$-plates can be created

- High-stabilized alloys
  - $\alpha$ precipitates can be formed after formation of precursors $\omega$ or $\beta'$
  - Strength can be increased from 600 MPa to 1400 MPa (Ti LCB)
Metastable $\beta$-alloys - examples

- Usually used as high-strength alloys in aerospace industry
- Often combines strengthening effects of $\beta$-stabilizing and $\alpha$-stabilizing elements
- **Ti-13-11-3** (Ti-13V-11Cr-3Al) – the first $\beta$-alloy (1955)
- **Beta III** (Ti-11.5Mo-6Zr-4.5Sn)
- **Beta C** (Ti-3Al-8V-6Cr-4Mo-4Zr)
- **Ti-10-2-3** (Ti-10V-2Fe-3Al)
- **Ti-15-3-3-3** (Ti-15V-3Cr-3Al-3Sn)
- **Timetal-LCB (low cost beta)** (Ti-4.5Fe-6.8Mo-1.5Al)
- **Timetal 21 S, Beta CEZ, Ti-8823, ...**
High-strength metastable $\beta$-alloys

- **Beta III** (Ti-11.5Mo-6Zr-4.5Sn)
  - Strength: 690 – 1240 MPa
  - Excellent cold-workability
    - After high deformation and thermal treatment $\rightarrow$ strength > 1400 MPa
  - Connecting parts in airplanes

- **Beta C** (Ti-3Al-8V-6Cr-4Mo-4Zr)
  - Strength up to 1400 MPa
  - Airplane components and deep-sea oil-wells

- **Ti-10-2-3** (Ti-10V-2Fe-3Al)
  - Excellent hot-formability (near net shape processing)
  - Boeing 777 – landing gear
    - (the first aircraft containing higher amount of $\beta$-alloys than Ti-6Al-4V)
  - At 315°C still more than > 80% of room temperature strength (750 - 1250 MPa)
  - Main rotor of helicopters

- **Ti-15-3-3-3** (Ti-15V-3Cr-3Al-3Sn)
  - Excellent cold formability – lower manufacturing costs than Ti6Al4V
  - Boeing 777 – tiny connecting parts (but more than 30 000pcs)
Timetal LCB

- **TIMETAL-LCB** (Ti-4.5Fe-6.8Mo-1.5Al)
  - „low cost beta“
  - Employs cheap iron content instead of vanadium and instead of extensive amount molybdenum
  - Ti-Mo „master alloy“ is used for casting
  - Strength 900 – 1400 MPa
  - Elastic modulus – 110 – 120 GPa (steels = 200 GPa)

- **Application** – **springs** (airplanes, cars)
  - Low-elastic modulus combined with high specific strength
  - Lowest elastic modulus – β-solution treated condition (but: lowest strength)
  - Strength can be increased by precipitation of α-phase (but: higher elastic modulus)
  - Trade-off between elastic modulus and strength can be „tuned“ by heat treatment
  - Saves up to 70% of weight (compared to steels)
Lecture 3: Summary

• Pure Ti (grade 1 – 4)
  – Oxygen content determines the strength of material
  – Generally lower strength than alloys (up to 500 MPa)
  – Application: pipes in chemical industry

• α+β alloys
  – Different microstructures (lamellar, duplex, globular)
    depending on thermo-mechanical treatment
  – Ti-6Al-4V alloy - the most used alloy – aerospace industry, orthopaedics...

• High-temperature alloys
  – Increased creep resistance (up to 550°C)
  – Airplane engines

• Metastable β-alloys
  – High-strength alloys (up to 1400 MPa)
    • Structural parts of airplanes
    • Developing field, expanding applicability
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Thank you!

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