Titanium alloys are extensively used in a variety of applications because their biological, mechanical and physical properties play significant roles in the longevity of the prostheses and implants. Recently, β-type Ti alloys composed of non-toxic elements have received much attention, because they feature not only high specific strength, bio-corrosion resistance, no allergic problems and biocompatibility. Low elastic modulus is required to be close to that of a human bone, in order to transfer the adequate mechanical stress to the surrounding bone. Understanding the mechanical properties of materials can help predict the quality of a final product. Two β-type titanium biocompatible alloys Ti-25Ta-25Nb and Ti-25Ta-5Zr were subjected to thermo-mechanical processing and testing. Data concerning ultimate tensile strength ($\sigma_{UTS}$), yield strength ($\sigma_{YS}$), elongation to fracture ($\varepsilon_f$) and elastic modulus (E) were analysed. The fracture surfaces of the investigated samples were also analysed.

Keywords: β-type titanium biocompatible alloy, mechanical tests, comparative analyse

INTRODUCTION

Titanium alloys are extensively used in a variety of applications due to their good mechanical properties and corrosion resistance [1].

Recently, β-type Ti alloys composed of non-toxic elements have received much attention, because they feature not only high specific strength, bio-corrosion resistance, no allergic problems and biocompatibility. Recent studies revealed that a compromise along the biomedical constrains mentioned above can be obtained by designing Ti alloys which use the most biocompatible elements, i.e. Ta, Mo, Mb and Zr, as alloy ingredients for stabilizing the bcc β-phase.

In recent years there has been a significant development of novel implant alloys based on Ti such as Ti–Nb–Zr and Ti–Ta–Zr alloys systems. These alloys are produced from commercially pure materials (Ti, Nb, Zr and Ta) by a cold roll-milling method.

This section presents a comparison of the mechanical behaviour of two β-type titanium alloys subjected to various treatments. The section, also describes microstructure characterisation of reference alloys prior and post cold roll-milling and the mechanical properties analysis, including also the deformation mechanism of the alloys.

EXPERIMENTAL PROCEDURE

Cold-rolling

The investigated alloys, Ti-25Ta-25Nb and Ti-25Ta-5Zr has been produced using a vacuum induction melting in levitation furnace FIVES CELES with nominal power 25 kW and melting capacity 30 cm$^3$, starting from elemental components. All samples were cold-rolled using a laboratory roll-milling machine Mario di Maio LQR120AS.

From the as-cast materials, were obtained appropriate samples of Ti-25Ta-5Zr and Ti-25Ta-25Nb alloys, which were subjected to cold-rolling procedures.
Mechanical testing

Mechanical tests were performed on samples for each type of alloy, which were found in two states: as-cast samples, respectively cold-rolled samples.

The investigations were made using a micromechanical testing module GATAN MicroTest 2000N. All investigated samples, having 0.35x1.65x40 mm As-cast and cold rolled alloy samples with dimensions 0.35x1.65x40 mm for Ti-25Ta-5Zr alloy and 0.36x1.67x40 mm were subject to mechanical investigations in tensile tests. Therefore were obtained values for ultimate tensile strength (σ_{UTS}), yield strength (σ_{YS}), elongation to fracture (ε_f) and elastic modulus (E) were obtained. The main testing parameters were the following: testing speed 0.4 mm/min; testing temperature 20°C.

Fracture surface investigations

All samples were subjected to fracture surfaces investigations, using a TESCAN VEGA II – XMU SEM microscope. The investigations were performed in order to analyse the mechanisms of fracture in the case of as-cast and cold-rolled Ti-25Ta-5Zr and Ti-25Ta-25Nb alloys.

RESULTS AND DISCUSSION

Cold-rolling

The strain obtained after a rolling pass can be calculated using following formula:

\[ \varepsilon_{pass} = \frac{h_{i-1} - h_i}{h_{i-1}} \times 100[\%] \]  

(1)

where: \( \varepsilon_{pass} \) – represent the strain for rolling pass \( i \);
\( h_{i-1} \) – represent the height before rolling pass \( i \);
\( h_i \) – represent the height after rolling pass \( i \);

Total accumulated strain after the rolling process can be calculated using following formula:

\[ \varepsilon_f = \frac{h_i - h_f}{h_f} \times 100[\%] \]  

(2)

where: \( \varepsilon_f \) – represent the total accumulated strain during rolling; \( h_i \) – represent the initial sample height before rolling process; \( h_f \) – represent the final sample height after rolling process;

Figure 1. Total accumulated strain and number of passes during cold roll-milling.
The equation (2) can be rewritten as:

\[
\frac{1}{\varepsilon_i} = \varepsilon_{\text{pass}1} \cdot h_1 + \varepsilon_{\text{pass}2} \cdot h_2 + \varepsilon_{\text{pass}3} \cdot h_3 + \ldots + \varepsilon_{\text{pass}n} \cdot h_n
\]  

(3)

The roll-milling process was conducted in order to obtain an increase in total accumulated strain of about 6.6% between each rolling pass in the case of both investigated alloys (Figure 1).

**Mechanical testing**

**Ti-25Ta-25Nb alloy**

Two b-type titanium biocompatible alloys Ti-25Ta-25Nb and Ti-25Ta-5Zr were subjected to mechanical testing.

![Figure 2. Stress–strain curve of as-cast Ti-25Ta-25Nb alloy.](image)

![Figure 3. Stress-strain curve of cold rolled Ti-25Ta-25Nb alloy.](image)

As resulted from the analysis diagram presented in figure 2 and figure 3 were observed the following mechanical properties values, presented in table 1.

<table>
<thead>
<tr>
<th></th>
<th>as-cast Ti-25Ta-25Nb alloy</th>
<th>cold-rolled Ti-25Ta-25Nb alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength $\sigma_{YS}$ [MPa]</td>
<td>428.44</td>
<td>883.34</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>682.69</td>
<td>1028.22</td>
</tr>
<tr>
<td>$\sigma_{UTS}$ [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongation to fracture $\varepsilon_f$ [%]</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Elastic modulus E [GPa]</td>
<td>40.11</td>
<td>54.1</td>
</tr>
</tbody>
</table>

After the cold-rolling of Ti-25Ta-25Nb alloy, was observed a reduction in thickness of 87-90%.

Therefore in the case of Ti-25Ta-25Nb alloy a comparative stress-strain diagram analyse, figure 2.2.1 and 2.2.2 was made, and lead to the fact that for the as-cast material, the most preponderant mechanism was plastic flow.
**Ti-25Ta-5Zr alloy**

Figure 4. Stress–strain curve of as-cast Ti-25Ta-5Zr alloy.  
Figure 5. Stress-strain curve of cold rolled Ti-25Ta-5Zr alloy.

As resulted from the analysis diagram presented in fig. 4 and fig. 5 were observed the following mechanical properties values, presented in table 2.

<table>
<thead>
<tr>
<th></th>
<th>as-cast Ti-25Ta-5Zr alloy</th>
<th>cold-rolled Ti-25Ta-5Zr alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength ( \sigma_{YS} ) [MPa]</td>
<td>512.37</td>
<td>448.12</td>
</tr>
<tr>
<td>Ultimate tensile strength ( \sigma_{UTS} ) [MPa]</td>
<td>853.22</td>
<td>1303.84</td>
</tr>
<tr>
<td>Elongation to fracture ( \varepsilon_f ) [%]</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Elastic modulus E [GPa]</td>
<td>53.8</td>
<td>45.7</td>
</tr>
</tbody>
</table>

Complex analysis of tensile-strain diagram for as-cast material indicates that the material exhibits a ductile character.

**Fracture surface investigations**

**Ti-25Ta-25Nb alloy**

Ductility, as opposed to brittleness, is the ability of materials to undergo plastic deformations before it breaks. A measure for the ductility is the strain to fracture, \( \varepsilon_f \).

Due to the high plastic deformation Ti-25Ta-25Nb alloy exhibits a ductile fracture mechanism, which leads to void growth and fibrous surface due to the plastic flow, figure 6.

As for the case of cold-rolled Ti-25Ta-5Zr alloy, fractography (figure 7) of the test specimen revealed evidence of rupturing of atomic bonds by tensile stresses (cleavage fracture) and fracture by plastic void growth [2].

Cleavage fracture, as well as brittle intergranular fracture, leads to fracture surfaces that are macroscopically oriented normal to the applied tensile stress. On the microscopic scale the fracture path follows the possible cleavage planes of the grains or the grain boundaries. Cleavage is the predominant fracture mode in covalently and ionically bonded materials [3].
As for the as-cast Ti-25Ta-25Nb samples fractography (figure 6) of the test specimen revealed evidence of a mixture of plastic flow fracture by ductile void growth, which was also observed in the case of fracture surfaces analysis of as-cast Ti-25Ta-5Zr alloy (figure 8).

The fracture surfaces indicate a ductile behaviour for the as-cast material, due to the high plastic deformation to fracture.

In figure 9 it can be observed that the initial sample exhibited a typical brittle-ductile fracture due to the cleavage fracture mechanism and due to the presence of void nucleation.
CONCLUSIONS

From all performed experiments data concerning changes in mechanical properties for both as-cast and cold-rolled states were obtained. The cold-rolled alloy exhibits an increase in mechanical properties due to strain-hardening. Different fracture mechanisms were observed in all cases [4].

The ultimate tensile strength and yield strength of cold-rolled state have higher values than in the case of as-cast state. The cold-rolled alloy exhibits an increase in mechanical properties due to strain-hardening.

Therefore it was showed that from another point of view – low elastic modulus, the cold-rolled samples exhibit the most suitable mechanical properties (high mechanical characteristics and low modulus).

Solid material can fracture under constant or increasing load by one of several fundamental mechanisms, where some materials strongly prefer one of the fundamental mechanisms over the others. The predominant mechanisms of fracture for as-cast samples consist in a mixing of plastic flow and fracture by ductile void growth. In the case of cold-rolled materials the fracture mechanisms consist in a mixing of ductile void growth and cleavage fracture.

In the case of the ductile fracture the energy consumed is converted into plastic deformation while in the case of brittle fracture it leads to the formation of new surfaces.

Acknowledgements

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