MICROSTRUCTURE AND MECHANICAL PROPERTIES OF CP-TITANIUM (GRADE 4) IMPLANT MATERIALS

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ABSTRACT

Titanium is came out on top in many areas. A major advantage of titanium alloys from a medical point of view is avoiding chemophysical reactions, eliminates the danger of a metal allergy so that it is fully biocompatible. Especially, commercially pure titanium is used in medical applications due to its purity. From material scientist point of view, most significant properties of titanium is higher corrosion resistance and the highest strength-to-density ratio. In this manner, titanium alloys are proven themselves in medical applications and also, finding new titanium alloys are in the interest of many material scientist. This paper reports investigations of the microstructure and mechanical behaviors of commercially pure titanium (Grade 4) bars produced by cold drawing. Accordingly, microstructural analysis are performed by using Scanning Electron Microscopy (SEM) techniques. In order to examine the mechanical behaviors of CP-Titanium Grade 4, tensile test, hardness test and Charpy-impact test with a different temperatures are practiced. These results indicated that CP-Titanium has higher tensile strength but lower impact toughness.

Keywords: CP-Titanium, Metallography, SEM, Tensile Test, Charpy-Impact Test, Hardness

INTRODUCTION

In medical sector, commercially pure titanium and titanium alloys have been used for many years due to its biocompatibility. Biocompatibility implies that it is non-toxic and also, it is not rejected by the body.

Titanium has the natural ability to osseointegrate which gives us an opportunity to use in dental implant and orthopedic implants applications. This benefit comes from its lower modulus of elasticity which is more closely match with the bone. Thus, loads are shared between bone and implant, leading to a lower incidence of bone [1].

Some medical applications of titanium implants are the joint replacement parts for hip and knee, bone fixation materials such as nails and plates, dental implants and parts for orthodontic surgery, dental prosthetics, surgical instruments for heart and, heart pacemaker housings and artificial heart valves. In addition to medical applications, they are used in many other areas because of

- Its excellent corrosion resistance to seawater and acid rains which provides long service period.
- Easy formability and machinability as much as stainless steel.
- Other properties of titanium that can contribute to applications include its low coefficient of thermal expansion, absence of magnetism.

Grades from 1 to 4 are considered as commercially pure or "CP" titanium or α titanium alloys. α indicates the phases present in the material. α titanium alloys are based on low temperature and, consisted of hexagonal close packed structure. The difference between titanium grades is primarily due to the quantity of interstitial elements which is generally oxygen. Table 1 shows the chemical composition of the CP-Titanium grade 4.

Generally, tensile and yield strength of commercially pure titanium goes up with grade number. CP-Titanium Grade 4 displays the highest strength of all the unalloyed grades. It combines excellent corrosion resistance with good formability and weldability. It cannot be hardenable by heat treatment.

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Table 1. Chemical composition of CP-Titanium Grade 4 [2].

<table>
<thead>
<tr>
<th>Components</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Max 0.1</td>
</tr>
<tr>
<td>Fe</td>
<td>Max 0.5</td>
</tr>
<tr>
<td>N</td>
<td>Max 0.005</td>
</tr>
<tr>
<td>O</td>
<td>Max 0.4</td>
</tr>
<tr>
<td>H</td>
<td>Max 0.015</td>
</tr>
<tr>
<td>Ti</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of CP-Titanium Grade 4 in annealed condition [2].

Mechanical properties

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Rockwell C</td>
<td>23</td>
</tr>
<tr>
<td>Hardness, Vickers</td>
<td>280</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>105 GPa</td>
</tr>
<tr>
<td>Ultimate Tensile</td>
<td>660 MPa</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
</tr>
<tr>
<td>Yield Strength</td>
<td>480-590 MPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.37</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>99-140 MPa x m(^{1/2})</td>
</tr>
</tbody>
</table>

Table 2 shows the mechanical properties of CP-Ti grade 4. Mechanical properties of α-titanium alloys are dependent on phases present, composition, and crystallographic structure and also, strongly dependent on the processing history since history of material controls the grain size, preferred orientation and texture.

Strengthening options of α-titanium alloys are solid-solution strengthening which is both substitutionally and interstitially, grain size strengthening, texture strengthening and precipitation hardening by formation of α2 phase.

Titanium which used in this project is strengthening by using texture strengthening and by solid-solution in which there is 0.4wt % oxygen as an interstitially element. Texture strengthening mechanism is highly dependent on direction. During cold-drawing, material is deformed and, grains are elongated in preferential direction because slip occurs only in favored direction. Material is strengthen in the deformed direction. This phenomenon is known as mechanical anisotropy. There is a specific direction creating a deformation texture.

At low temperatures and in combination with high loading rates, α phase becomes very strong, especially in grades 3 and 4 that have high oxygen content. Under these conditions plastic flow is limited and, α phase can fracture by cleavage.

The impact resistance of CP titanium grades 1-3 is compared to two other titanium alloys can be seen in Figure 1. Because of the potential for brittle cleavage fracture of CP titanium, the use of grades 3 and 4 should be restricted at low service temperatures with high loading rates.

Cleavage fracture generally occurs when the local normal stress across the cleavage plane exceeds a critical value. Cleavage fracture occurs along a crystallographic plane, which is the basal plane in α titanium. Thus, in the hexagonal α phase, the role of texture directly affects the tendency for cleavage fracture since the relative orientations of the basal plane and the loading axis affect the normal stress component across the cleavage plane. The tendency for cleavage fracture is also decreased with decreasing grain size. This shows that difficulty of nucleation of cleavage cracks is higher in small grains. Thus, components at low temperatures are more suitably made from fine grained, lower oxygen grades of CP titanium. In these cases, the strengthening due the fine grain size partially offsets the strength reduction of the low oxygen material.

![Figure 1. Impact Energy vs. yield stress of several titanium alloys (Figure adapted from [3]).](image-url)
EXPERIMENTAL PROCEDURE

Metallographic Studies

Microstructure should be revealed by metallographic specimen preparation in order to predict the material properties and also, processing conditions. There are mainly five steps for metallographic sample preparation.

1. Sampling and Sectioning: The radial section and the longitudinal section were taken as representative sample by using abrasive mechanical cutter.
2. Mounting: Specimens were mounted into bakelite to easily handling.
3. Grinding: The emery papers were used from 80 grit to 2000 grit in order to obtain flat surface.
4. Polishing: Solutions with 3, 1 and 0.1 micron diamond particles were used in mechanical polishing.
5. Etching: The objective of the etching is simply creating an image by creating level difference on specimen surface. Kroll’s reagent was used for etching and, the specimen was hold 20 seconds in the etchant.

After metallographic preparation specimen was observed under optical microscope and SEM and average grain size was determined.

Mechanical Studies

Mechanical properties of Grade 4 Titanium were observed by using hardness test, tensile test and Charpy impact test. EMCO universal hardness tester was used to measure hardness of both longitudinal and radial sections of specimen. One of the specimen was used in tensile test by using INSTRON 5582 Universal Testing Machine. In addition, three of the Charpy V-notch specimen were tested with a different temperature in TINIUS-OLSEN pendulum type Charpy impact tester. Charpy impact test temperatures were 21, 0 and -20°C.

RESULTS AND DISCUSSION

After revealing the microstructure by etching, micrographs were taken by using optical microscope and scanning electron microscope. By using optical micrographs, average grain size was determined as 7 microns.

Figure 2. Radial section of specimen under Optical Microscope 800x, 2400x respectively.

Figure 3. Longitudinal section of specimen under Optical Microscope, 3800x.
Figure 4. Radial section of specimen under Scanning Electron Microscope (SEM).

Figure 5. Longitudinal section of specimen under Scanning Electron Microscope (SEM).

Figure 6 shows the results of chemical compositions of CP-Titanium Grade 4 as expected from Table 2. Titanium is a much harder metal compared to the aluminum and approaches the high hardness possessed by some alloy steels. Commercially pure titanium has a hardness of about 160 VHN and, when titanium is alloyed and heat-treated, titanium can reach hardness values in the range of 250 to 500 VHN. According to hardness test shown in Table 3, results of specimen were a little bit higher than specimen in annealed condition due to mechanical anisotropy behavior of cold drawing. But these difference can be acceptable.
Unalloyed titanium may have tensile strengths ranging from 250 MPa to 690 MPa depending on the processed history and composition. As in the case of material used in this project, tensile strength is 828 MPa. It shows the effect of interstitial solid solution strengthening and also, texture strengthening effect along direction of deformation. Solid solution strengthening is increased the strength however, it is decreased the ductility. Figure 7 shows the tensile test results and, Figure 8 shows the fracture surface after tensile test.
Titanium falls among the few metals capable of possessing good toughness along with high strength and ductility. Charpy impact energy for the commercial unalloyed product to 5 or 10 Joule for some of the high strength grades but brittle alloys [4]. As the test was operated at low service temperatures in combination with high loads, highly low impact energy was obtained which can be seen in Figure 9. Figure 10 shows the brittle, cleavage fracture after impact test.
CONCLUSION

The aim of this project basically examination of the microstructure and mechanical behaviors of commercially pure titanium Grade 4 produced cold drawing. In this context, microstructural analysis were performed by using Scanning Electron Microscopy (SEM) techniques. In addition, the mechanical behaviors of CP-Titanium Grade 4 were determined by using tensile test, hardness test and, Charpy-impact test with a different temperatures. These results indicated that the CP-Titanium has higher strength but lower impact toughness due to oxygen present as interstitial element in it. These results is proven that CP-Titanium is suitable to be implant material from mechanical point of view.

REFERENCES


AUTHOR INFORMATION

Gözden TORUN is a junior student of METU majoring in Metallurgical and Materials Engineering. Her advisor for this project is Prof. Rıza GÜRBÜZ from Metallurgical and Materials Engineering Department of METU. Her academic interests include mechanical behaviors of metals, failure analysis, heat treatment and computational analysis.