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The effect of heat treatment on the tensile strength and ductility of pure titanium grade 2

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Abstract. The commercially pure titanium (CP) and titanium alloy are widely used in medical, aerospace and automotive industries due to their attractive mechanical properties especially because of its strength-to-weight ratio that is the highest among all known metal. A thorough understanding of the mechanical properties of titanium is very important so that an optimize machining parameters can be selected. Pure titanium has a higher level of corrosion resistance compared to titanium alloy due to the presence of an oxide layer on its surface. In this paper, heat treatment especially the annealing process was used prior to machining in order to study on the variation of its tensile strength and ductility at two different annealing conditions. The three conditions that were used in this experiment are untreated (T1), heat-treated at 700°C for 1 hour (T2) and 900°C for 1 hour (T3). In this work, a higher level of oxidation was observed for T3 compared to T2 due to the exposure to a temperature that is above the beta transus temperature that triggered the formation of acicular martensite. It was also observed that there was a decrease in the tensile strength when treated at T2 and a recovery of the strength was noticed at T3. The ductility properties were more significant at T2.

1. Introduction

The commercially pure (CP) titanium and its alloy are widely used for industrial applications due to its strength-to-weight ratio, high corrosion resistance and high temperature resistance [1]. Pure titanium differ itself from its alloy counterparts due to its high biocompatibility with human body environment and free from toxic elements such as vanadium and aluminum that are found in titanium grade 5. In the dental manufacturing industry, most of them make use of pure titanium and titanium alloys with a treated surface in order to optimize the contact between alveolar bone and the device surface that is also known as osseointegration [1]. According to ASTM F67, the CP titanium are classified into four distinct grades, G1-G4. On the other hand, CP Ti are seldom use in application that are subject to a high stress such as orthopaedic prostheses. In addition, some of the main disadvantage of CP Ti over the alloys are higher young modulus, low mechanical strength, poor wear resistance and a limitation to improve the mechanical properties. The mechanical properties of CP Ti are generally determine by the weight percentage of nitrogen, oxygen and carbon. These three key elements are kept at a lower percentage if a high toughness is required. Heat treating titanium are carried out for three main reasons, namely to reduce residual stress that are developed during fabrication, to customize the material to produce a better combination of ductility and machinability, to increase the strength and finally to optimize special properties such as fracture, toughness, fatigue strength and high temperature creep strength [2]. Titanium and its alloys exist in three structural forms: alpha (α), beta (β) and alpha-beta. In titanium alloy, aluminium is the alpha-phase stabilizer whereas vanadium is the beta-phase stabilizer. CP Ti undergoes an allotropic transformation at 882,5ºC and changes from its initial structure of alpha to beta phase that is from an hexagonal close pack (HCP) crystal structure to body centered cubic (BCC) [3]. In a study, the authors investigated the effect of heat treatment on three different metal namely mild steel, titanium grade 2 and stainless steel. The annealing temperature applied for mild steel and stainless steel were set at 200 ºC and hold for 120 mins, then furnace cool. In addition, Titanium grade 2 was annealed at 450ºC and also furnace cool. They concluded that the ductility decreases significantly for stainless steel but increases for titanium and mild steel [4, 5].

2. Materials and methods

The titanium grade 2 round bar which originate from Japan was manufactured according to ASTM F67 and was purchased from a local distributor that is E-Steel Sdn. Bhd. The length of the round bar was one meter and 15 mm in diameter. A total of nine tensile specimens were prepared according to ASTM E8M standard as shown in Figure 1 for small size specimens. The choice for selecting smaller size specimens in this study was mostly motivated base on the limited budget allocated for this research and also saving the amount of material. The chemical composition and mechanical properties of the titanium grade 2 provided by the manufacturer are listed in Table 1 and 2. The tensile test was perform on an Instron Universal Testing Machine that has a maximum load of 100 kN.

Table 1. Chemical composition of pure titanium grade 2

Element	**Fe**	**O**	**C**	**N**	**H**	**Ti**
Content (Wt.%)	1.143	0.285	0.286	0.593	0.286	0.593

Table 2. Mechanical properties of pure titanium grade 2

Properties	**Values**
Tensile strength (Mpa)	344
Yield strength (Mpa)	375
Elongation (%)	20
Poisson ratio	0.37
Modulus of elasticity (Mpa)	105
Hardness (HRB)	80

2.1 Fabrication of tensile specimens

The nine tensile specimens were fabricated according to the ASTM E8M dimension shown in Figure 1. The CNC Mazak nexus 200 turning machine as shown in Figure 2 was used for the fabrication of the specimens. A preliminary turning was performed using mild steel as raw material to verify the uploaded machining program and few adjustment were done for the turning parameters. A few samples made of mild steel were damaged due a high cutting speed. Given that the gage diameter is 6 mm in diameter, a lower cutting speed was more suitable to achieve the required dimension for the tensile specimen. The final tensile specimen is as shown in Figure 3.

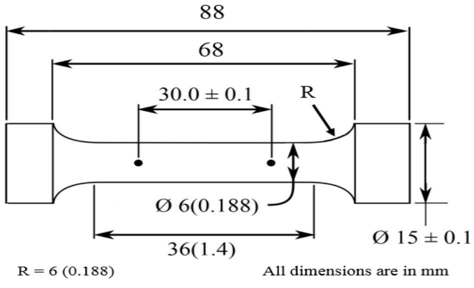

Figure 1. Tensile test specimen according to ASTM E8M

IOP Conf. Series: Materials Science and Engineering **429** (2018) 012014 doi:10.1088/1757-899X/429/1/012014

Figure 2 . CNC turning Mazak nexus 200

Figure 3. Machined specimen

2.2 Heat treatment of tensile specimens

The type of heat treatment that was used in this study was annealing. Three batches of tensile specimens namely T1 for untreated specimens, T2 for specimens annealed at 700°C for 1 hour and T3 for specimens that was annealed at 900°C for 1 hour. All the specimens were cool down in the furnace. The heating rate was set at 25°C/min until it reach the required annealed temperature and hold for one hour. In addition, the cooling rate was set at 12°C / min to allow a more suitable rearrangement of the grain. The annealing process was performed in a furnace as shown in Figure 4. The selection of the annealing temperature were done base on the literature reviews where it was stated that above the annealing temperature of 883°C, phase transformation start to occur. In the case of titanium grade 2, the phase transformation is from alpha to beta-phase. However, in a study it was stated that at 700°C it was observe that the Vickers hardness was among its lowest value [6]. In addition, the second annealing temperature of 900°C was selected among others because at this specific temperature the microstructure is fully transform into a beta-phase and the maximum hardness was reached [6]. Furthermore, mechanical properties such as yield stress, strength coefficient and strain demonstrated a significant variation [6].

Figure 4. Furnace

Figure 5. Nine tensile specimens

3. Results and discussion

The change in physical appearance of the specimens after the different heat treatment was related to the phenomenon of oxidation that occur to the tensile test specimens as shown in Figure 6. At T2, a dark scale was form on the sample suggesting an oxidation that occur due to the interaction with atmosphere in the furnace. In addition, T3 exhibit a higher level of oxidation and a light brownish colour scale was formed on the specimens. The oxidation product of titanium during exposure to air is known as TiO_2(titania) which is a tetragonal rutile crystal structure that allow titanium to be one of the most corrosion resistant material [7]. During this process, the high affinity of titanium to oxygen and the high solid solubility of oxygen in titanium that is around 14.5% results in the formation of scale that varies in colours according to the exposed high temperature [8]. Moreover, this oxygen rich layer that is

IOP Conf. Series: Materials Science and Engineering **429** (2018) 012014 doi:10.1088/1757-899X/429/1/012014

observe on the specimens are widely known as α-case. It adheres strongly to the titanium substrate surface and its strength is fully dependent on three components namely the oxidation temperature, thickness of oxide layer and the influence of nitrogen on the oxidation in air [8]. It was also reveal in a study that the strength of the oxide layers to the substrate decreases with the decrease in the layer thickness as well as the oxidation temperature increases [9, 10]. Figure 7 shows the specimen after that

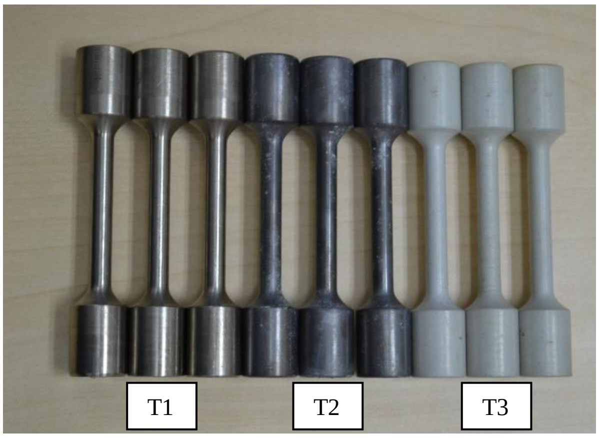

Figure 6. Titanium grade 2 specimen after heat treatment.

Figure 7. tensile specimen

the tensile test was conducted. Although that the different heat treatment specimens exhibit percentage of elongation, the location and trend of the necking behaviour is same for all of them. The generated results from the tensile test shown in Figure 8 and summarize in table 3 indicate that there is a decrease in the ultimate tensile strength at T2 compare to the other conditions. On the other hand, T2 has the highest ductility with a strain of 50 %. The high ductile behaviour of T2 and T3 can be attributed to the ease of plastic deformation when subject to an annealing condition. In the first case, T2 when heated at 700ºC that is a temperature below the transformation to beta-phase, is slightly more ductile than T3 with less tensile strength. Moreover, at T3 that is above the transformation temperature of 883ºC to beta phase for Ti grade 2, the ductility increases and the tensile strength bounce back to the original value of 376 Mpa.

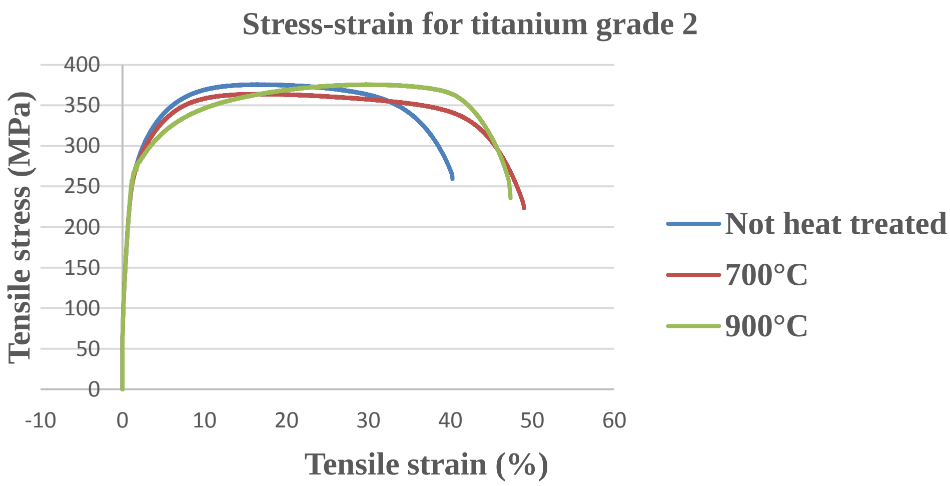

Figure 8. Engineering stress-strain curves of specimens

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Table 3. Tensile data of Ti grade 2 for three different conditions.

Sample	UTS (Mpa)	Elongation (%)	Area reduction (%)
T1	375	41	75
T2	360	50	82
T3	376	47	65

4. Conclusion

Heat treatment has been used mainly to harden and also to increase the strength of material. In this study, it was applied to observe the behaviour of the mechanical properties on CP Ti grade 2. It was found that oxidation layer on the specimens occur at different rate when subject to higher temperature. The two different heat treatment on CP Ti grade 2 had demonstrated that there is a possibility of softening the material at 700°C that is below the transformation temperature. In addition, the values of the elongation and the percentage in reduction of the area have also confirmed that the ductility for T2 as well as for T3 have increased. It was also revealed that the tensile strength decreases at T2 but recover to its initial strength at T3.

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