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# STUDY ON EFFECT OF HEAT TREATMENT ON CHIPS FORMATION AND FORCES IN DRILLING TITANIUM ALLOY 6Al-2Sn-4Zr-6Mo

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***ABSTRACT***

***This paper focusses on effect of heat treatment on chips formation and forces resulted during drilling titanium 6246. Aim of the research is to improve drillability of this material. The heat treatment steps were heating at a certain temperature for three hours followed by different cooling methods. Three heat treatments were chosen out of several trials: (i) at 595°C, (ii) at 870°C and (iii) at 985°C. Optic microscope and scanning electron microscope (SEM) were employed for observing the microstructure of the chips before and after drilling. Quantitative analysis of chips is based on degree of serration measurement. The Kistler dynamometer was used for recording the forces during drilling. It was evident that heat treatment at 985°C followed by furnace cooling resulted in the highest degree of serration which indicate that chips are easier to brake. This heat treatment also resulted in the lowest thrust force and torque. It may be related to extremely bigger grain boundary compared to other heat treatments and the as-received one.***

***KEYWORDS: Ti-6246, Heat Treatment, Microstructure, Chips & Forces***

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**Original Article**

## 1. INTRODUCTION

The demand of new materials for a specific function has increased significantly for the recent years. In aerospace industry, for example, they are looking for material with high strength to weight ratio. Further, for such component that works at elevated temperature, they need a material that can retain its properties at high temperature. In addition, the material which has a corrosion resistance is an advantage. Titanium alloys have answered these three requirements. Titanium alloys have ratio of strength to weight three times than that of steel [1]. The most widely used titanium at the moment, Ti-6Al-4V, is able to withstand at 400°C for long time. Titanium alloys also have high corrosion resistance [2]. Furthermore, titanium alloys are biocompatible [3].

Apart from the advantages, titanium alloys are among the difficult-to-machine materials due to the fact that the tool would be quickly deteriorate. Some reasons have been explained by previous researchers on why it happened. Firstly, titanium alloys have low heat conductivity, by which the heat emerged from the machining process will be absorbed by the tool, work piece and chips at the comparison of 80, 10 and 10% respectively [4]. Therefore, the temperature of the tool that will be increased consequently will get weakened. This fact is in contrast to that of steel where the heat is absorbed 80% by the chips, 10% by the tool and the rest by the work piece. Secondly, titanium alloys have high affinity [5], that means these alloys have a tendency to easily react with other materials. Machining results in chips as a by-product. These chips tend to stick on the hot surface of the tool and create a built-up edge (BUE). Lastly, the titanium alloys tend to be a springy behavior, which mean during machining, the material tend to behave like a spring – extracted when tool is penetrating the material and back to its normal position after penetrating [6]. Therefore, the intended surface would not be easy achieved.

Attempts have been carried out to develop machinability of titanium alloys, whether they concerned on the tools such as using harder tool for machining [7] or varying the tool design [8]. Other researchers apply different types and methods of coolant to reduce the heat and protect the tool from premature failure [9], [10]. Some researchers are concerned with the changing microstructure and mechanical properties of the titanium alloys prior to machining [11], [12].

One of the newly introduced titanium alloys named titanium alloy 6Al-2Sn-4Zr-Mo or usually shorted as Ti-6246 has some advantages in compared to the most popular titanium alloys in the world, Ti-6Al-4V. Ti-6246 is more heat treatable [13], meaning, it potentially increases its machinability by changing the microstructure and the mechanical properties. It is also more corrosion resistant [14], that lead to potentially be used for sea water and corrosive environment.

This paper is concerned in heat treatment of Ti-6246, prior to drilling and it potentially increases the machinability from aspect of hardness alteration, chips formation and forces that work during drilling.

## 2. METHODOLOGY

**The Material:** A bar of 56 mm in diameter of titanium alloy 6246 is used for this experiment. Unfortunately, the processing method and the heat treatment of this bar were untraceable. This bar was noted as received (AR), which nominally comprises of 6% aluminum, 2% tin, 4% zirconium, 6% molybdenum and other impurities less than 0.5% and the composition is titanium [2]. The bar then machined to the dimension of 25 x 25 x 35 mm in order to fit the fixture. Heat treatments were carried out with different temperatures and cooling methods; however, the holding time were kept the same for 3 hours to ensure that the microstructure uniforms all sides of the block.

**Hardness Measurement:** Micro Vickers hardness machine was used to measure the hardness of the blocks before and after heat treatments and also the chips, with load of 100 g for 10 s.

**Tool used**: The TiAlN coated carbide of 10 mm was used for drilling. Other key specifications of the drill bit are point angle, helical flute angle and clearance angle of 140°, 30° and 7° respectively. The drill bit was inserted on the HSS tool shank with the same helical flute.

**Machine used**: A universal milling center was used for drilling the blocks.

**Forces Measurement**: The block was mounted on the fixture and then clamped on a Kistler dyanometer to measure the forces that work during drilling. This dynamometer was fixed on the machine bed and then connected to PC outside the machine to record and display the forces.

**Microstructure Observation**: Both optic microscopy and scanning electron microscopy were carried out to observe the microstructure of the before and after drilling and also the chips. Prior to observation, the blocks were ground, polished, mirror polished and then etched with HF solution. With regard to the chips, it was clamped on a brass ring, and then hot mounted in a thermosetting plastic. The next step before observations was the same as that was done to the blocks.

## 3. RESULTS AND DISCUSSIONS

Discussions following the results are presented in the following paragraphs:

### 3.1. Heat Treatment

Ti-6246 is among the α + β alloy, therefore, there are three possible microstructures according to the temperature, as presented in figure 1. At upper its beta transus temperature, this alloy in form of β phase, while it will be in α + β phase below this temperature. Within α + β phase, it possible to form a martensite (α") when the cooling stage passed the martensite start line (Ms). For this research, the beta transus temperature is determined as 940$^{\circ}$C [2] though another literature mentioned as 935$^{\circ}$C [15]. With regard to Ms temperature, it is related to molybdenum content, but not depend on the quenching rate as presented in figure 2 [17]. The Mo content of this alloy was calculated according to the following formula [18].

$$Mo(eq.) = 1.0\,[Mo] + 0.22[Ta] + 0.28[Nb] + 0.44[W] + 0.67[V] + 1.25[Cr] + 1.25[Ni] + 1.7[Mn] + 1.7[Co] + 2.5[Fe]$$

Mo (eq.) of Ti-6246 = 6%.

Interpolation of between Mo contents of 5.75 and 7.1% results in temperature of Ms alloy of this alloy to be 662$^{\circ}$C. The heat treatment temperatures, then determined at 595, 870 and 985$^{\circ}$C as the representative of temperature lower than Ms, between Ms and β transus and upper the β transus correspondingly. It is emphasised that the chosen temperatures were the temperatures in which the samples were heated at the holding time of three hours. Following the heating, the samples were cooled by three possible methods: (i) furnace cooling, (ii) air cooling or (iii) water quenching.

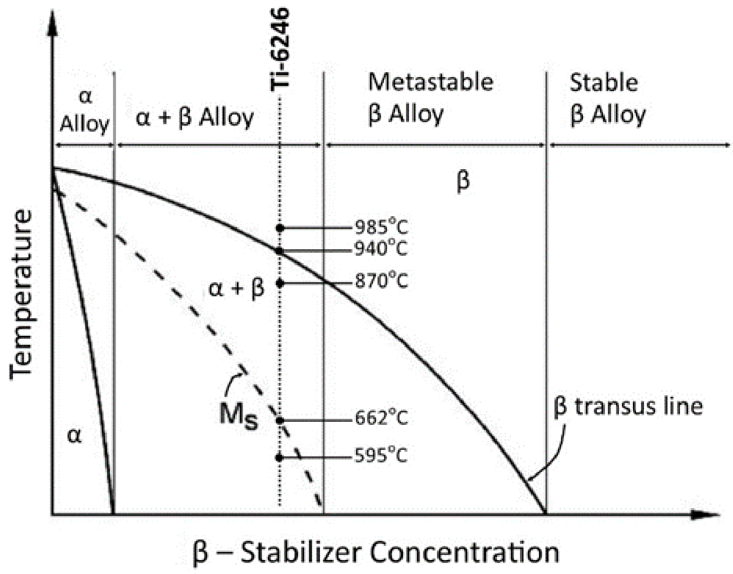


**Figure 1: Plotting of Potential Temperatures of Heat Treatments for Ti-6246.**

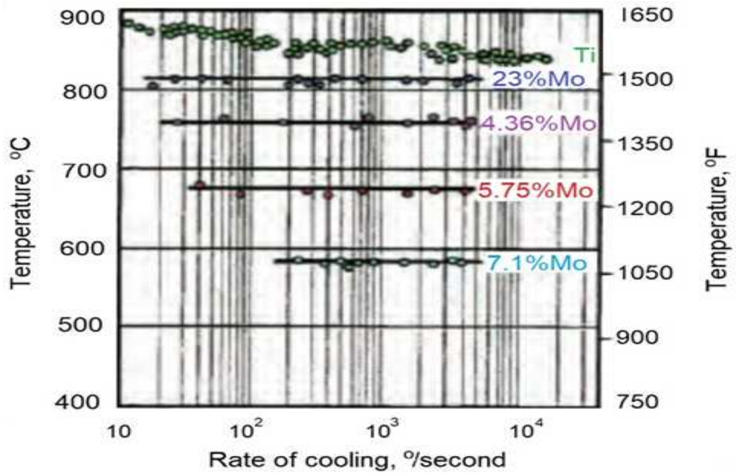


**Figure 2: Effect of Molybdenum Content to Temperature of Martensite Start (Froes).**

### 3.2. The Microstructures

Microstructure of each sample after heat treatments is presented in figure 3. It is apparent that heat treatment at 595°C (below the Ms temperature) did not change the microstructure in comparison to the as-received condition regardless of the cooling methods applied. Heating at this temperature did not change the alloy phase. Therefore, the microstructures remained the same to the as-received. At heating between Ms and β transus temperature, a significant difference in microstructures can be seen as effect of different applied cooling methods. The furnace cooling resulted in the microstructure similar to that of as-received one. A finer microstructure was achieved by applying air cooling and so did the as water cooled sample. Completely different microstructures were resulted from heating at 985°C followed by different cooling method. In case of furnace cooling, it performed a Widmanstatten α structure with α phase present on prior β grain boundaries. The second case (air cooling) resulted in the equiaxed α and transformed β microstructure. The last case (water quenching) generated martensitic structure with prior β boundaries. Result of the third case is comparable to that of Ti-6Al-4V which were heated at 960°C for 1 hour, then followed by the same cooling method [19].

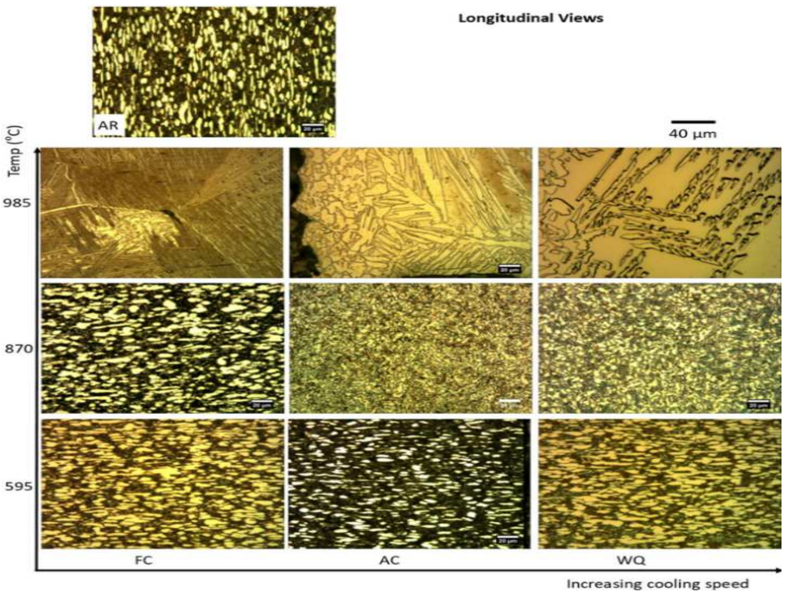


**Figure 3: Microstructure of the Specimens after Different Heat Treatment.**

### 3.3. The Hardness

Figure 4 presented the hardness of the specimens after having different heat treatments. Most of the heat treatment contributed in increasing the hardness. A significant increase in hardness was resulted from heat treatment at $985^{\circ}$C regardless of the cooling method applied. Only heat treatment at $970^{\circ}$C either followed by furnace cooling or water quenching resulted in decreasing of the hardness. Not a significant decrease in hardness also produced by heating at $595^{\circ}$C followed by air cooling. However, as previously discussed at microstructure section that the microstructure is relatively same with as-received, this temperature would not be used for further analysis. The drillability of a material is affected by microstructure as well as the mechanical properties, therefore, in the rest of the paper, discussion would be comparing four conditions: (i) as-received, (ii) HT1: heating at $870^{\circ}$C followed by air cooling, (iii) HT2: heating at $870^{\circ}$C followed by water quenching and (iv) HT3: heating at $985^{\circ}$C followed by furnace cooling.

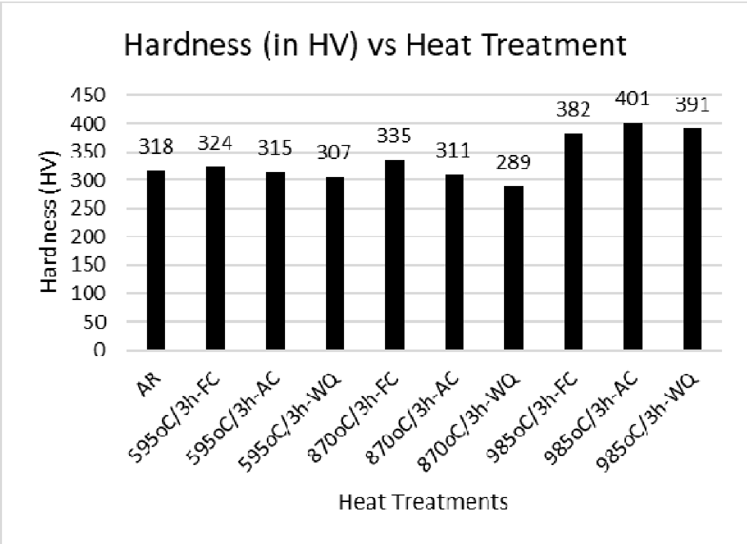


**Figure 4: Hardness of the Specimens after Different Heat Treatments Compared to as Received (AR).**

### 3.4. The Chips

Some different forms of chips were recognized as evident from figure 5. However, as a general pattern, the chips are in serrated form. It compounds of segments, saw teeth-like, with peaks and cliffs with a clear partition between each segment. It is obvious from figure 5 that heat treatment affects the chips form. Microstructure observation proved that all chips experienced grain elongation compared to as block before drilling. This grain elongation happened not only at the primary shear band but also at the secondary shear band. The hardness of the chips also decreased except for the as-received condition (figure 5a). The chips of as HT3 encountered the most severed reducing of the hardness (from 382 to 291 HV), while the chips of as HT1 and HT2 faced a moderation decrease of hardness. The decrease of the chips hardness may be related to the strain softening, a behavior in which the shear stress reduced during continuous plastic deformation [20].

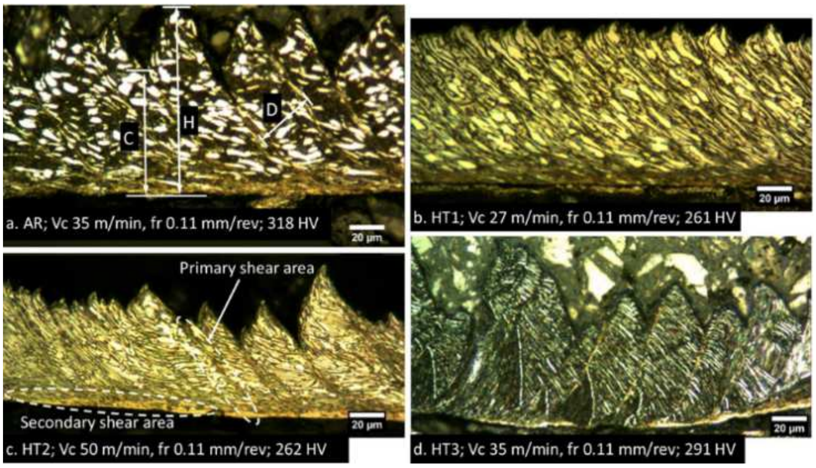


**Figure 5: Chips Variation Following Heat Treatment Prior to Drilling.**

The degree of serration was introduced by some researchers [20], [21] & [22] as a value to measure how easy a chip will be broken. The higher the degree of serration, the easier the chips to brake. Mathematically, the degree of serration was calculated using the following formula:

$$Gs = \frac{H-C}{H} \times 100\% \quad (1)$$

Where, Gs represents the degree of serration, H is the distance of the top of the hill to the base of the chip and C denotes the distance between the bottom cliff and the chip base as presented in the figure 5-a. The calculation was carried out on about twenty chips segments, and then taken the average. The result is shown in the figure 6. From the serration degree (Gs) perspective, the higher is preferable. In drilling, a long and unbreakable chip is avoided because it will twist on the drill body. On its way out from the hole, a long chip may scratch the drilled surface and left undesired mark on it. Therefore, it would result in a rougher surface. It is obvious that from the degree of serration, the HT3 material is promising as the highest drillability.

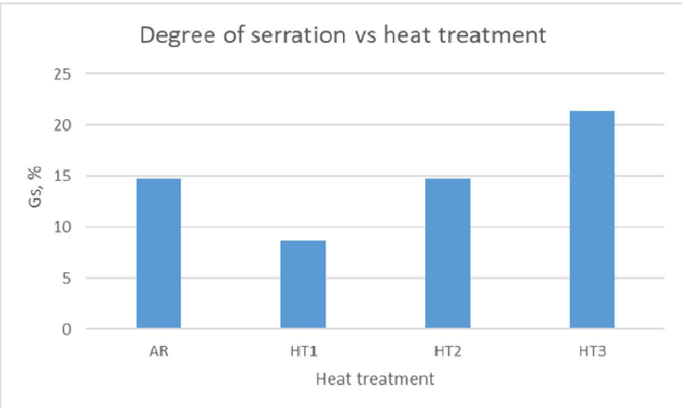


**Figure 6: Degree of Serration of Different Heat Treatments.**

### 3.5. The Forces

Two main forces that work during drilling, the thrust force (Fz) and torque (Mz). Both are presented in the figure 7. Thrust force is the force that works in line with the Z direction, while torque works in accordance with the rotation of the tool. Chip is formed by the shear force ($\tau_{cutting}$) which ploughs the material and separates the chip from the main material (figure 7a). The serrated form of the chips was due to periodic thermoplastic shear fluctuation which happens in the primary shear zone. A SEM observation result on the chip is presented in the figure 7-b. It is apparent that the chips experienced grain elongation at not only at the primary and secondary shear band but also at the middle of a segment.

Figure 8 shows the recorded thrust force and torque during full drilling cycle. With regard to thrust force, HT3 results in the lowest among other treatments. Furthermore, it also created a steady and the least fluctuated one. Moreover, the torque of drilling of HT3 is comparable to that of the AR and still the lowest in compare to the rest of other treatment. Therefore, from the force perspective, the HT3 material is also promising as the highest drillibility.

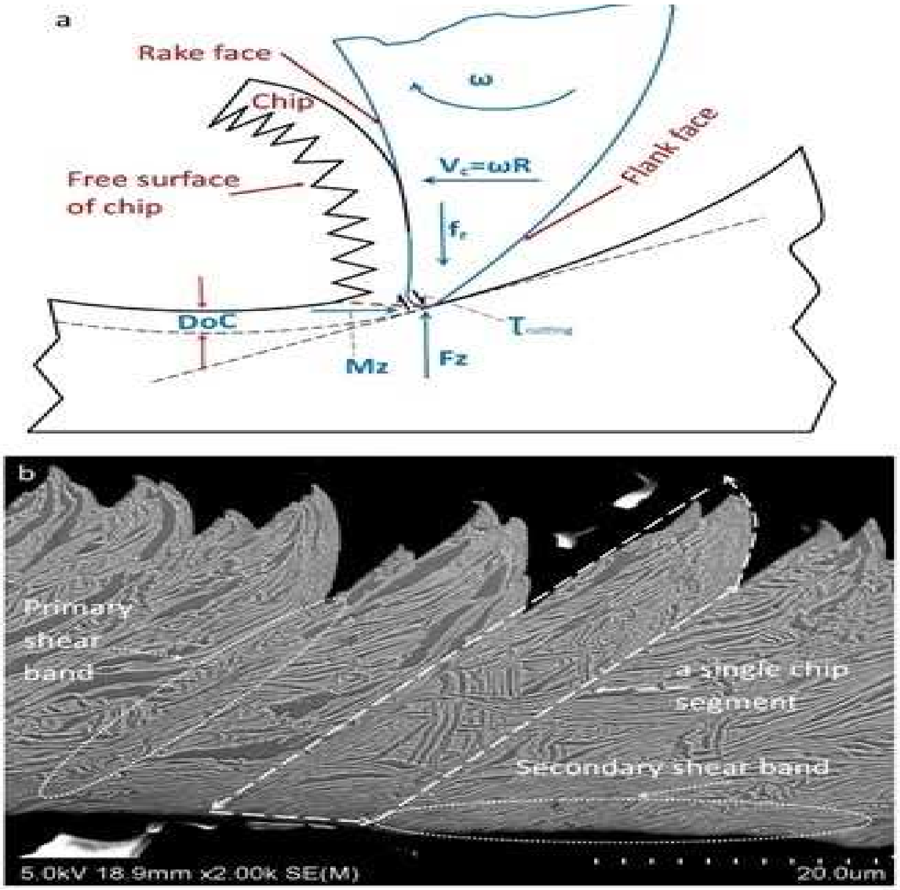


**Figure 7: Mechanics of Chips Formation in Drilling (a) and Typical Chips form with Shear Bands.**

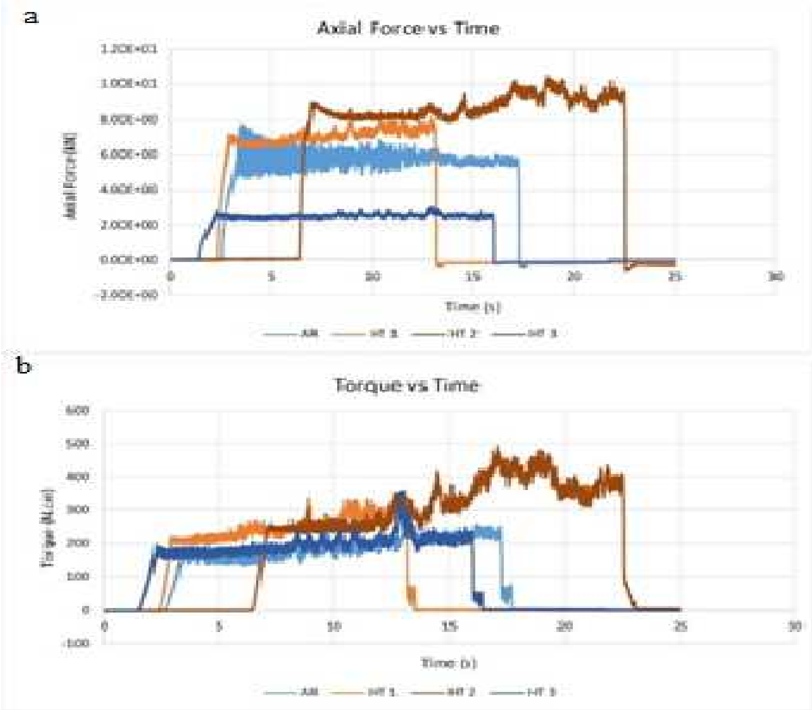


**Figure 8: Plotted of Axial Force (a) and Torque (b) of Drilling with Different Heat Treatments.**

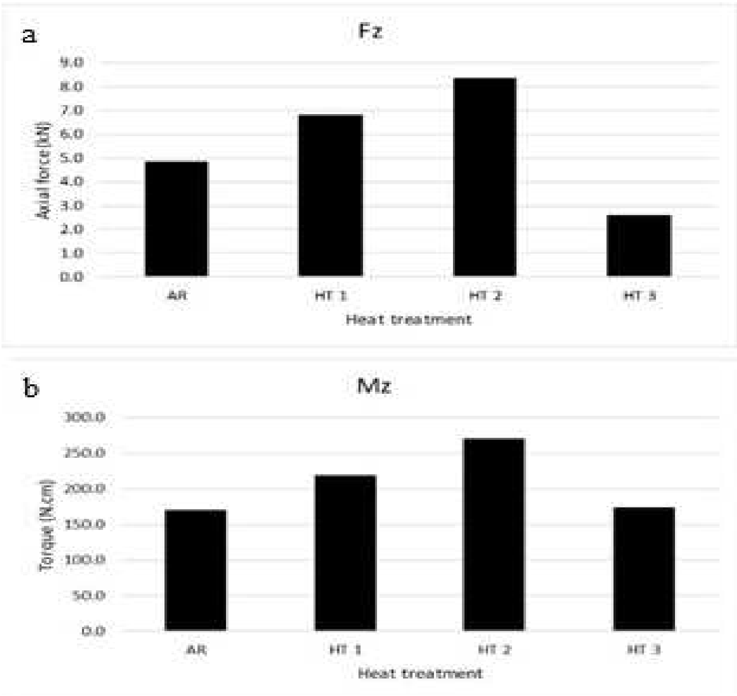


**Figure 9: Average of Axial Forces (a) and Torques (b) with the Blocks being Heat Treated Prior to Drilling.**

### 3.6. Further Discussion on the Chips of HT3 Material

The HT3 resulted in a microstructure that was completely different from other heat treatments and the as-received. The microstructure is a transformed beta with prior beta boundaries (figure 10-a). A tiny continuous alpha film is exist at the grain boundaries [19]. When it is compared to other titanium α + β alloys, this current microstructure is similar to Ti-6Al-4V or Ti-5Al-4V when they were beta annealed [12].

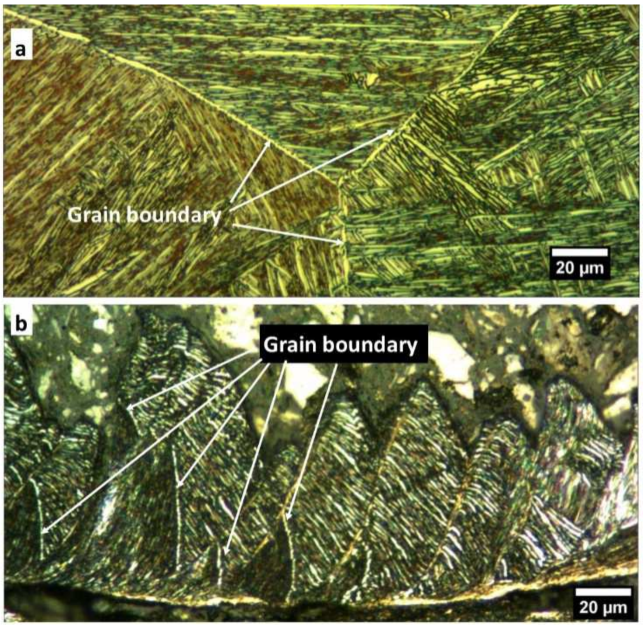


**Figure 10: Microstructure of Ti-6246 after Heat Treatment of 985°C for Three Hours then Furnace Cooled (a). The Chips and a clear Grain Boundary that were Cut along with Chips Formation (b).**

The most significant different of its microstructure is the giant size of the grain boundary, which reached about 500 microns. Change of grain size may affect the yield strength because the movement of dislocation interacts with the grain boundary. The grain boundaries hinder the sliding of dislocation along the slip planes. The succeeding dislocations that slide along the same slip plane will be accumulated at the grain boundary. When the grain boundaries are extremely big, then the number of boundaries will be reduced. Consequently, the cutting force would also be reduced. Machinability is also affected by grain size (and grain boundary). In the case of steel, the coarse grain size preferable for rough machining is favored while fine grain size is a better machining finish [26]. This is the most likely the explanation why the HT3 material needs the lowest forces for drilling in compared to other heat-treated materials.

The cutting of grain boundary was revealed in some chips as shown in figure 10-b.

## CONCLUSIONS

From this study, some conclusion may be withdrawn:

- Heat treatment gave effect significantly to the mechanical properties and microstructure of Ti-6246. The heat treatment below temperature of 662°C would not change the microstructure regardless the cooling method. The heat treatment above 940°C would change the microstructure to the basket wave form.
- Among the variety heat treatment methods, heat treatments at 985°C for three hours followed by furnace cooling resulted in the best drillability of titanium 6246 from chips formation and forces point of views by the reason that the degree of segmentation of the chips is the highest and the forces needed is the lowest.

## ACKNOWLEDGMENT

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