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Effect of Various Microstructures Obtained from Heat Treatment on Machinability Behavior of Ti-6Al-4V Alloy

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ABSTRACT

Drilling test on cylindrical work-pieces was carried out to analysis the effect of various microstructures resulting from heat treatment on the machinability of the Ti-6Al-4V alloy. Chip morphology plays a predominant role in determining machinability and wearing of a tool during the drilling of titanium alloys. For this purpose, Ti-6Al-4V was heat treated in three variant cycles then drilled by 2mm diameter drill at 18.8 m/s speed and 0.1 mm/rev feed rate. Results show that heat treatment can affect on hardness. The SEM results showed that by changing their phase and morphology obtained from different heat treatment cycle, the machining conditions change. Increasing hardness led to increases length of spiral chips that indicate easy drilling. At a lower depth of cutting, ribbon chips are more compacted in comparison with samples which have a lower hardness. Drilling temperature was increased by increasing deep hole. Samples with lower hardness had a higher temperature in drilling.

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1. INTRODUCTION

Titanium alloys are excellent candidates for high performance applications owing to their high strength to weight ratio and excellent corrosion resistance, even at high temperature [1]. However, titanium alloys are regarded as extremely difficult to cut materials. Tool wear is intense because of the high cutting temperature due to low thermal conductivity [2]. In addition, the high chemical reactivity of titanium at high temperature with most of the tool materials produces a strong adhesion of the work-piece to the tool surface, thus leading to chipping and premature tool failure [3]. Thus, the high temperature generated close to the cutting edge of the tool when machining titanium is the principal reason for the rapid wear of the tools [4].

Microstructure plays a very important role in the mechanical properties of alloys, such as strength, ductility, creep resistance, fracture toughness and crack propagation resistance [5-7]. It depends primarily on the chemical composition, processing history and thermal treatment procedures [8-10]. The most widely used titanium alloy is Ti-6Al-4V. This alloy has an excellent combination of strength, toughness and good corrosion resistance and is useful in aerospace applications, pressure vessels, aircraft-turbine, compressor blades and discs, surgical implants and etc. [11].

Drilling is a widely used machining process and has considerable economic importance because it is usually among the final steps in the fabrication of mechanical components. The tool geometry and material deformation in drilling are complicated. In drilling, long drill life is essential to increase productivity and reduce cost [2, 3].

Titanium and titanium alloys are heat treated in order to increase strength, produce an optimum condition of ductility, machinability, and structural stability and reduce residual stresses developed during fabrication [12-14].

A large parts of Ti-6Al-4V alloy are used as machined structure and components. The machining cost of this alloy is high due to the wear of the machining tools, high

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strength and work-hardening. The mentioned problems can be reduced by controlling the microstructure of alloy by heat treatment. Studies have shown that the effect of different alloy microstructures on its machining behavior is not comprehensive. In this research, different cycles of heat treatment have been used to obtain different microstructures. Then, the morphology of the chips and the wear of the drill were investigated using the drilling method.

2. MATERIALS AND METHODS

The chemical composition (alloy is 6% Al, 4% V and the balance of Ti. The primary Ti-6Al-4V alloy rods with a diameter of 22mm and 45mm of height were prepared and heat treated in three temperatures (Table 1) to achieve various hardness. All heat treatments were performed in the electro-resistance furnace. Sample (1) was no heat treated, sample (2) was heat treated at 800°C for 1 hour and quenched in air, sample (3) was heat treated at 950°C for 1 hour and quenched in water, sample (4) was heat treated at 1050°C for 1 hour and quenched in water then aged at 550°C for 4 hours and quenched in air.

Macro hardness was measured according to the ASTM E92 standard with a force of 10 kg and a time of 15 seconds. Measurements were made from 5 points of each sample and their average hardness was reported. The micro hardness measurement was performed according to ASTM E384 standard with a force of 500 g and a time of 15 seconds. In each sample, 3 measurements were performed with a distance of 1 cm. Then their average was reported.

The samples for metallographic analysis were grounded, polished and then etched in kroll's reagent with below composition 2ml HF + 6ml $(HNO)_3$+92ml H_2O. Investigation of the microstructures and chips morphology were carried out by an optical microscope and a Mira3 FESEM scanning electron microscope. Vickers hardness test was performed in kappa 100 with 15s time and 10kg force.

For machining process cutting speed and feed rate were fixed in 18.8 m/s and 0.1 mm/rev, respectively. Drilling was done without lubricant and performed in Konig CNC machine. Two holes were drilled in each sample and the height of holes was 10mm.

TABLE 1. Heat treatment cycles applied to samples

	Annealing	Aging
Sample 1	No heat treatment	-
Sample 2	800°C/1h/air	-
Sample 3	950°C/1h/water	-
Sample 4	1050°C/1h/water	550°C/4h/air

3. RESULTS AND DISCUTION

3. 1. Heat Treatment

Heat treatment of the (α+β) titanium alloy above the β transus temperature leads to a 'lamellar' microstructural morphology, consisting of α platelets with an inter-platelet β phase. The 'lamellar' structure varies with cooling rate, ranging from colonized plate like α at a low cooling rate, a basket-weave morphology at an intermediate cooling rate and Widmanstatten at a high cooling rate, to martensite, when quenched in water [13, 14]. When processed below the β transus, Ti–6Al–4V showed an (α+β) structure with the prior α phase retained to room temperature and the β phase transformed partly [15-18]. The first sample with no heat¬ treatment, its microstructure is shown in Figure 1. Figure 1(a) shows the equiaxed microstructure consists of α and β phases, the α phase is light and β phase is dark. In SEM image (Figure 1(b)) very fine precipitated β particles in the alpha matrix is clear.

In sample (2), heat treatment at 800°C was performed stress relieving condition [19]. After heat treatment, obtained images by SEM, show β particle have further distribution in the matrix and precipitated particle is larger than sample (1) (Figures 2(a) and 2(b)). For study, drilling affects, images were taken of 10 mm depth of sample (Figures 2(c) and 2(d)). Because of the lower cooling rate in sample's core, the core had a higher

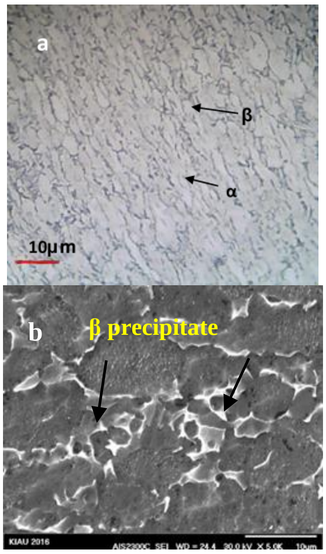

Figure 1. Received sample microstructure, a: optical microscope. and b: SEM images

temperature than the surface. More time for transformation was provided, thus, more beta phase transforms to alpha phase and lower beta phase was observed in the images.

In Ti-6Al-4V alloy, martensite starting temperature is 600°C (M_s=600°C) and β to α transformation temperature is 1000°C (M_s=1000°C). Sample 3 was annealed in 950°C and quenched in water, the expected martensitic transformation being occurred and because of the annealing temperature is below 1000°C, the primary α phase remains in the structure. In Figures 3(a) and 3(b) acicular martensite with spherical primary alpha can be seen. Move toward the depth, at distance 10 mm from the surface (Figures 3(c) and 3(d)), heat transfer is lower than the surface, additional, heat conductivity in Titanium is low also acicular structure was grown and coarsening and a widmanstatten structure was formed.

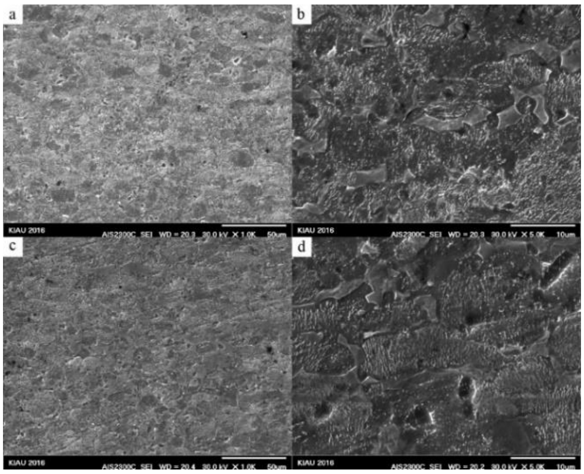

Figure 2. SEM image of the microstructure of sample 2, (a) and (b) microstructure of surface (c) and (d) microstructure of 10mm depth

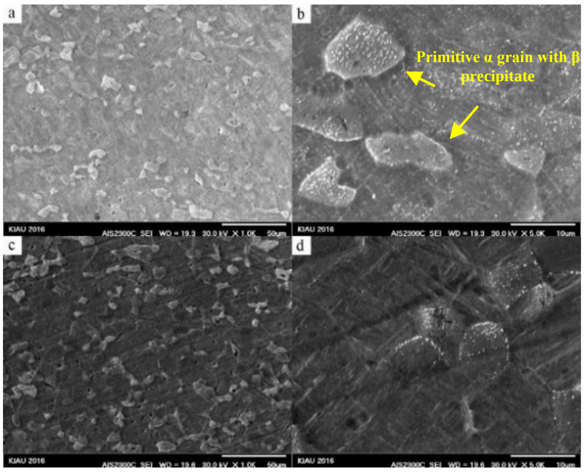

Figure 3. SEM image of the microstructure of sample 3, (a) and (b): microstructure of surface. (c) and (d): microstructure of 10mm depth

In sample 4, heat treatment at 1050°C leads to all α phase transforms to β phase and water quenching from 1050°C leads to formation ά martensite, subsequent aging in 550°C causes ά decomposition to α and β phases. In Figure 4, prior β grain is present and acicular martensite formed inside it. By aging martensite decomposes to α and β (Figures 4(b) and 4(c)), thus these precipitates particles prevent the movement of dislocations and result in hardness increasing. In the surface of the specimen due to fast cooling rate, precipitated particles are further distributed and their size are finer.

3. 2. Hardness

Average Vickers and micro Vickers hardness of samples were shown in Table 2. Sample 1 without any heat treatment with 339 Vickers hardness in the surface. Micro Vickers hardness test to compare 10 mm depth of hole and surface was done. Both surfaces had 340 micro Vickers hardness. Sample 2 was annealed at 800°C/1h and stress relieving was performed, so the hardness decreases, however, hardness is lower than sample 1. In sample 3, martensite formed and it has a high density of dislocation and twins so leads to obstacle the dislocation movement and increasing hardness. In 10mm depth, the widmansttaten structure was formed so ductility and hardness are lower than the surface that martensite observed. In sample 4, aging was led to martensite phase decomposition to alpha and beta precipitated also these precipitates phase was obstacle dislocation movement and increasing hardness.

Work material ductility is an important factor. Highly ductile materials not only permit extensive plastic deformation of the chip during cutting, which increases work, heat generation, and temperature, but also result in longer, continuous chips that remain in contact longer with the tool face, thus causing more frictional heat.

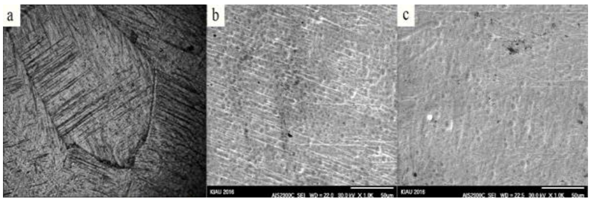

Figure 4. Microstructure of sample 4. (a): martensite structure, Optical Microscope (b): precipitated particles in surface, (c) precipitated particles in 10mm depth

TABLE 2. Hardness test results in samples 1, 2, 3 and 4

Sample No.	Surface (Vickers) (Hv)	Surface (micro Vickers) (Hv)	10mm depth (micro Vickers) (Hv)
1	339	340	340
2	320	332	301
3	393	340	328
4	500	362	336

Chips of this type are severely deformed and have a characteristic curl. On the other hand, some materials, such as gray cast iron, lack the ductility necessary for appreciable plastic chip formation. Consequently, the compressed material ahead of the tool can fail in a brittle manner anywhere ahead of the tool, producing small fragments. Such chips are termed discontinuous or segmented [20-22].

3. 3. Drilling Survey

3. 3. 1. Chips Morphology Chips were taken to determine chips morphology. The macroscopic and SEM images of chips obtained from all samples are shown in Figures 5 and 6, respectively. Based on the chip forming mechanisms, continuous chips can be categorized to spiral chips and string chips (ribbon chip). When chips are initially generated, because the inner cutting edge moves significantly slower than the outer cutting edge, the inner chip is inherently shorter than the outer chip, this difference in length within the chip forces it flows to the drill center instead of perpendicular to the cutting edge. Furthermore, the center part of the drill flute forces the chip to curl and form a spiral shape. However, when spiral chips move in the drill flute, in order to maintain its spiral shape, they have to rotate constantly on their own axis. This rotational motion causes the spiral chips to have difficulty maintaining their shape as the hole gets deeper. If chips cannot keep up with the rotational motion, they will either break or will be forced to move along the flute without spinning, and form string chips [20]. It has been reported that the spiral cone chip is easier to be ejected so the length of spiral cone chip can be considered as a scale to evaluate the difficulty for chip evacuation in drilling [21-24]. As shown in Figures 5 and 6, in all samples both spiral and ribbon chips produced but in samples 2, 3 and 4, short and irregular chips are visible due to large resistant force, long ribbon chips will be broken into irregular short shapes.

As the hardness of the samples increases (samples 3 and 4), smaller chips are formed. Figure 5 c and d shows a reduction in chip size and the formation of small chips. This phenomenon was observed with increasing drilling depth. As explained earlier, an increase in hardness is due to the change of phases in the heat treatment cycle. Creating hard phases such as martensite changes the deformation behavior during machining. In these phases, the formation and movement of dislocations during deformation is different from soft phases such as the α phase due to the change in the crystal lattice. They have a higher coefficient of hardness and are more agile. Therefore, the chips formed during machining are broken and formed with smaller sizes.These irregular chips can block the exit way and increase force and torque in machining [23]. In Figure 5, the length of spiral and ribbon chips observed. Samples 3 and 4, have longer spiral chips rather than samples 1 and 2. These samples have higher hardness, so can report an increase in hardness which leads easy drilling. Samples 3 and 4, have more irregular chips, these irregular chip represent friction in depth is high, high friction leads to difficulty exit and ribbon chips breaking to small and irregular chips so can report in surface heat treatment leads to ease of machining. Increasing depth and microstructure change in depth, causes machining becomes more

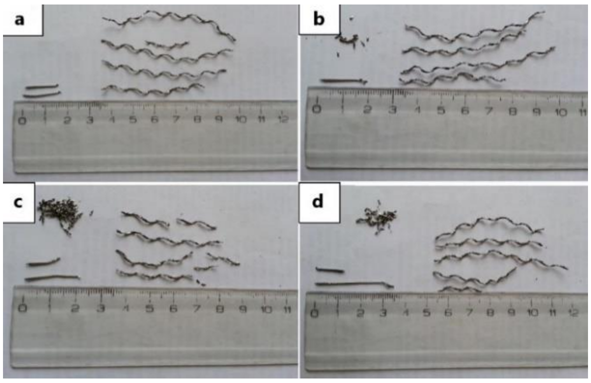

Figure 5. Macroscopic image of chip type and chip ejected from samples 1, 2, 3 and 4

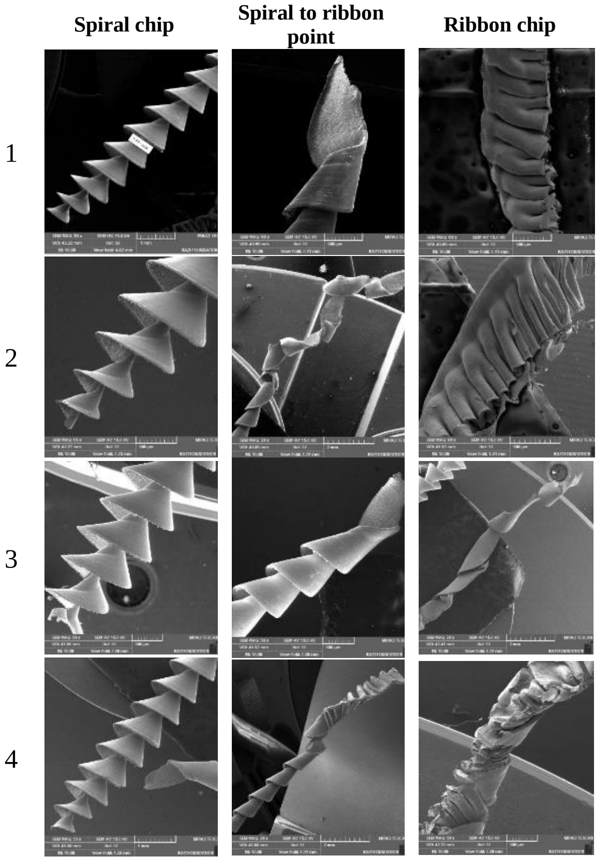

Figure 6. SEM image of chip type and chip ejected from sample 1, 2, 3 and 4

difficult. In Figures 5 and 6, spiral chips, spiral to ribbon chips point and ribbon chips observed. In all samples first spiral chips were created, then spiral chips are broken and ribbon chips produced. In sample 1, spiral chips were fractured and following ribbon chips produced. Whatever compacted ribbon chips indicated eject chips are difficult also wear in drilling hole increase and cause a decrease in tools life. In sample 2, after spiral chip, the fracture has not occurred and some spiral chips fractured after produced, this feature indicates friction is somewhat low then in the following compact ribbon chip produced. Ribbon chip in sample 2 is more compact than sample 1, can report sample 2 have difficult drilling rather than sample 1. In sample 3, after fracture, ribbon chips are not produced and morphology of chips is semi spiral and semi ribbon, because of low wear and low friction can report drilling is partly easy. Sample 4 is the only specimen which fracture has not occurred and ribbon chips following the spiral chips were formed, but as can be seen in Figure 5 the compression in ribbon chips is higher than all samples.

3. 3. 2. Drills Wear

In each work-piece 2 holes were drilled because a number of holes are limited, wear in drills is not high. Maximum wear occurred in three areas: drill point, side point and cutting edge. Figure 7 show SEM images of drills were used in drilling.

In sample 1 the morphology of drill has not been changed but abrasion wear in drill point was observed, as well as, the work-piece materials were adhered to point of drill and side edge and cutting edge nothing was observed.

In sample 2, adhered materials were more than sample 1, because, in depth of the hole, the hardness of sample 2 is lower than sample 1, so the materials adhered to the drill. At side edge and cutting edge, no wear occurred. EDS analyses of drill used in sample 2 as shown in Figure 8 (a and b) that work-piece materials were adhered to drill. In sample 3, adhered materials are low and cutting edge is very clear. In sample 4, like the previous sample adhered materials observed in EDS analyses (Figure 8 (c) and (d)), in point of a drill, the Ti, Al, and V can be observed.

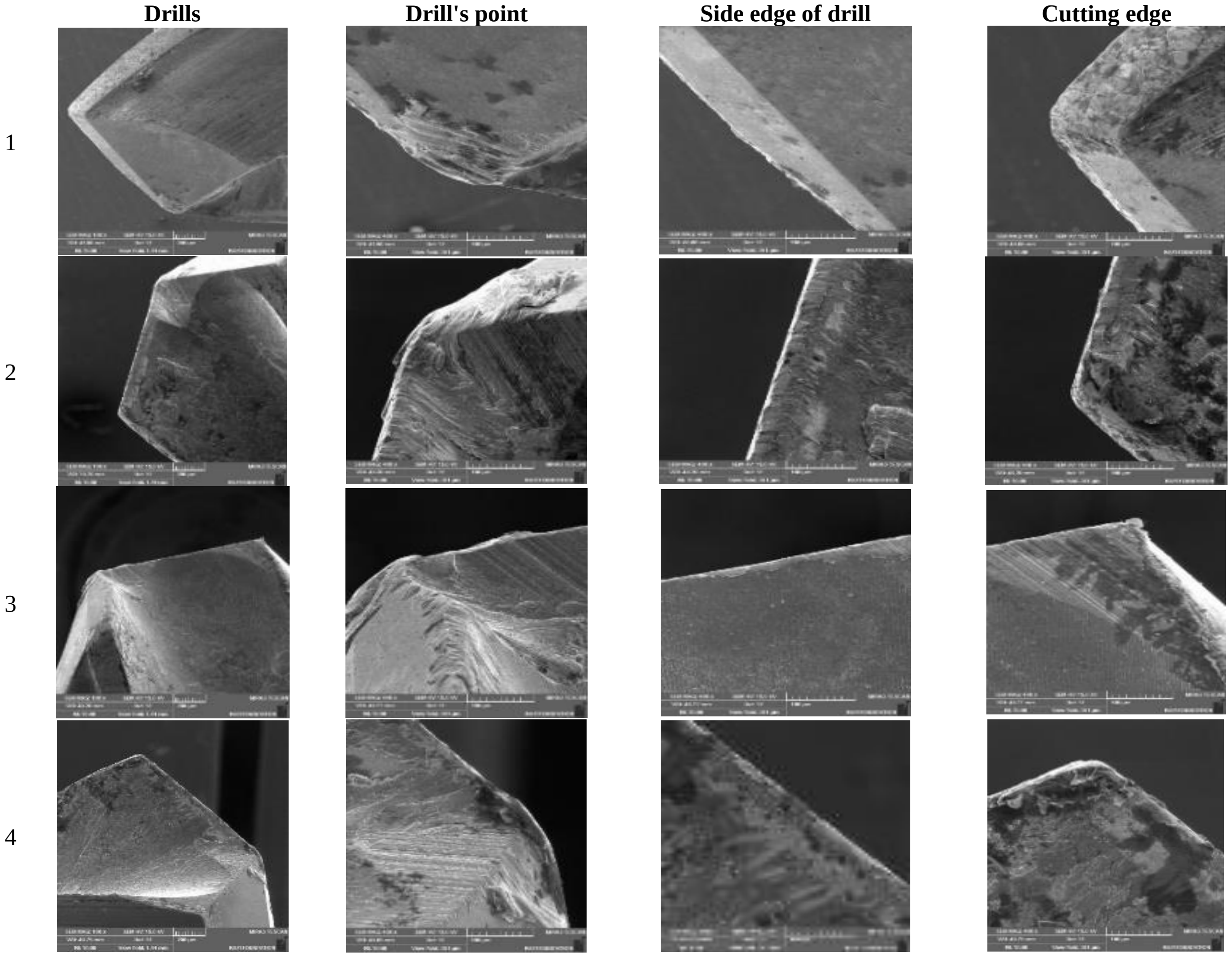

Figure 7. SEM image of different part of drills on the sample 1, 2, 3 and 4

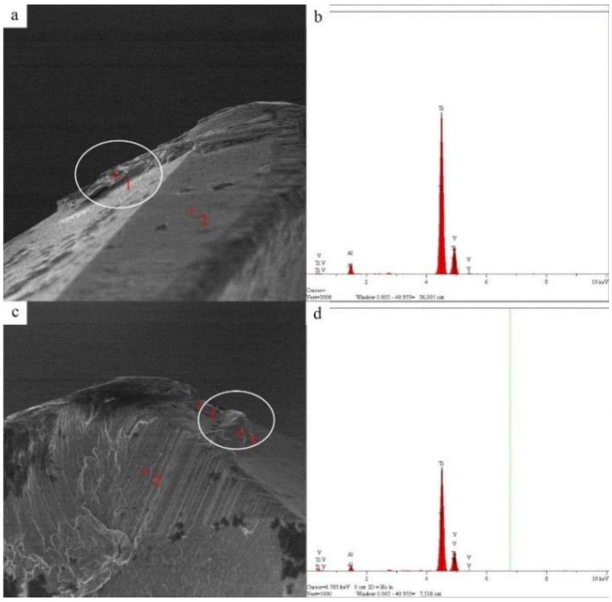

Figure 8. EDS analyses of drills point, (a) and (b): EDS analyses of sample 2 drills, adhered material are Ti, V and Al. (c) and (d): EDS analyses of sample 4: adhered material are work-piece material include Ti, V and Al..

3. 3. 3. Drilling Temperature

One of the important factor of drilling which can effect on tools wear, hole quality and chip easily exit is drilling temperature [25,26]. In Figure 9 the average temperature of 2 holes drilling was reported. In all samples with an increase in time of drilling and depth of the hole, temperature increases. These temperatures are in the range of the surface of drilling and inside the hole, where chip, drill and work material are in contact, so friction and abrasion are high. Chip exit rate was lower than produce chip so it produces more heat. Samples (3) and (4) have higher hardness and recorded the lowest temperature, in contrast, sample (2) that has the lower hardness which recorded the highest temperature.

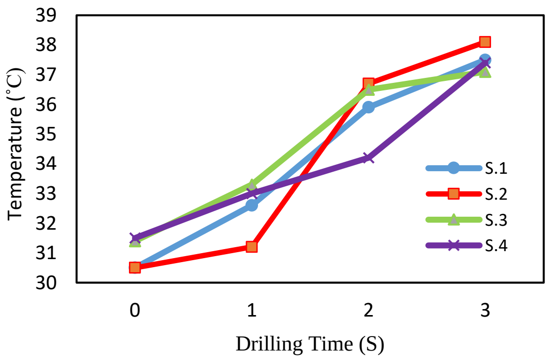

Figure 9. Drilling temperature of samples 1, 2, 3 and 4

4. CONCLUSION

Titanium has a low heat conductivity and this character affect to microstructure from surface to depth of samples in heat treatment. Hardness and microstructure of the received specimen remain with increasing depth. In other samples with an increase in depth, hardness decrease even in 10 mm far from the surface. In specimen 3, martensite was formed on the surface and moving to the depth, martensite lath was grown and widmanstatten was formed also aging lead to martensite decomposes to alpha and beta. Moving to the depth precipitated particle grew and a distance between them increased. Samples 3 and 4 had higher hardness and also had longer spiral chips, and a longer spiral chip is an evidence of easy drilling of samples. In all samples spiral chip was broken and ribbon chip produced but in sample 4 because of low wear, spiral chips were not broken and semi spiral semi ribbon chips were ejected. Also, samples 3 and 4 had a lower temperature of drilling. With an increase in hardness, temperature and drilling wear are low and by heat treatment can be provided lower-cost machining conditions.

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Persian Abstract

چکیده

به منظور بررسی تاثیرریزساختارهای مختلف بر خواص ماشین¬کاری آلیاژ Ti-6Al-4V، آزمایش دریل¬کاری بر روی نمونه¬های استوانه¬ای شکل از این آلیاژ انجام شد. مورفولوژی براده نقشی اساسی بر قابلیت ماشین¬کاری و سایش ابزار را در آلیاژهای تیتانیم دارد. بدین منظور نمونه¬هایی از آلیاژ Ti-6Al-4Vبا سیکل¬های مخلف، عملیات حرارتی شده و سپس توسط مته به قطر ۲ میلیمتر و با سرعت ۱۸/۸ متر بر ثانیه و نرخ تغذیه¬ی ۰/۱ میلیمتر در هر دور، سوراخ¬کاری شدند. نتایج بررسی¬های میکروسکوپ الکترونی نشان داد که با تغییر فازها و مورفولوژی به دست آمده از عملیات حرارتی، شرایط ماشین¬کاری نیز تغییر می-کند. با افزایش سختی آلیاژ، طول براده¬های مارپیچی نیز افزایش می¬یابد که بیانگر مته¬کاری آسان آن است. در این نمونه¬ها در عمق کم از ماشین¬کاری براده های روبانی شکل فشرده¬تری نیز ایجاد شد. با افزایش عمق سوراخ¬کاری، دما نیز افزایش یافت. از طرفی نمونه¬هایی که سختی پایین¬تری داشتند، دمای سوراخ-کاری پایین¬تری را ایجاد کردند.