



Experimental Evaluation of Surface Alterations Induced in Machining of Ti-6Al-4V Alloy

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ABSTRACT

Surface integrity of workpieces after machining processes is one of the most essential requirements of engineers in advanced industries, since it has significant effect on performance and service life of the components. Based on this, thermal and mechanical loads generated by machining are responsible for change in mechanical properties of the machined workpiece and consequently, they should be controlled. Among them, Ti-6Al-4V is utilized extensively by engineers because of its excellent properties. Therefore, at the present study, extensive experiments were conducted to characterize the performance of machining operation regarding the surface integrity of Ti-6Al-4V super alloy. Hence, the effect of experimental conditions on microhardness profile, surface roughness, grain size, and maximum machining temperature was studied. The results indicated that, cutting speed is a predominant parameter for enhancement of surface microhardness and increase in feed rate has the striking influence on thermal loads enhancement. The results also demonstrated that, increasing depth of cut has the lower influence on grain size variation.

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1. INTRODUCTION

Exceptional features of Ti-6Al-4V alloy have led to its extensive use in military and automotive industries and the manufacture of sensitive parts of jet engines. Suitable toughness, maintaining its hardness at high thermal loads, and resistance to wear and corrosion are a number of the properties of this material [1]. Despite the mentioned properties, due to the existence of a hard phase in the Ti-6Al-4V alloy, there are numerous problems in the machining of this material. Owing to the sensitivity of machined workpieces and generation of severe thermal-mechanical loads during operation, machining in inappropriate conditions causes important damage, including microcracks in the material [2,3]. In recent years, hard machining has been employed in industry due to its countless benefits. Hence, experimental investigations have recently been conducted to enhance machining performance and increase workpiece quality [4]. Physical contact between tool and workpiece during

the process creates thermo-mechanical loads and consequently severe plastic deformation on subsurface layer of the machined samples. These changes cause preformation of work hardening and microstructural changes, and thereby, affect the efficiency and service quality of parts. Thus, controlling the quality of machined part of the final product is a key issue for proper operation [3,5].

Surface integrity in machined workpieces has various aspects including metallurgical alterations (phase transformation, microstructural changes, and recast layers), mechanical loads (plastic deformation and residual stresses) and surface texture (surface roughness and geometry accuracy) [6]. It should be noted that, different indications of surface integrity is an essential requirement of costumers especially in advanced industries. Surface roughness is a dominant indicator of surface texture and characterizes the quality of a machined workpiece. High surface roughness reduces service life of the workpiece and leads to the easier crack

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propagation and difficulty in assembling different components [7,8]. Due to the fact that during machining, the workpiece is subjected to severe plastic deformation, work hardening, strain hardening and dynamic recrystallization phenomena occur, and subsequently, microstructural changes are induced in the surface layers. These variations cause microstructural changes in the machined sample [9]. In addition, thermal loads produced in the cutting region are also one of the factors affecting microstructural changes and tensile residual stress, being able to reduce the performance of the workpieces [10]. Based on the above-mentioned issues, the indications of surface integrity are affected by cutting parameters. For improvement of each one, cutting parameters should be controlled. The following more investigations on surface integrity after machining operations of titanium alloys are presented.

An experimental study was conducted by Parviz et al. to evaluate the influence of the tool type on roughness of machined alloys [11]. According to their results, the use of coated tools increased the surface quality, and the uncoated tools created more thermal loads and improved the surface quality. Liang and Zhanqiang evaluated the effect of worn tool on microstructural changes during machining process of titanium alloys [12]. It was found that, tool wear increases the plastic deformation in the machined workpiece. In a similar study by Sun et al. [13], they reported that by increasing in tool wear, cutting forces and depth of the recrystallized layer also increased. Revankar et al. [14] performed experiments on surface quality of the Titanium alloy and it was concluded that higher cutting speed led to enhancement of surface roughness. According to Che-Haron's research [15], with increasing cutting speed, surface hardness values increased in machining of Ti-6Al-2Sn-4Zr-6Mo alloy. The results of experiments conducted by Hughes et al. [16] on the indicators of the surface integrity of Ti-6Al alloy showed that, the higher cutting speed resulted in the creation of compressive residual stress. Research carried out by Shokrani et al. [17] to study the effect of cryogenic machining on surface roughness of titanium alloy indicated that enhancement of cutting depth and feed rate causes an increase in the roughness. In similar study, the performance of cryogenic coolant on surface quality of the Ti-6Al-4V alloy was examined by Jun [18]. Ibrahim et al. [19] investigated the influence of machining time on surface roughness of titanium alloy. They concluded that, surface quality initially improved and increased as the machining time increased. Ginting and Nouari [20] evaluated surface integrity in turning process of Ti-6242S alloy. They concluded that, decreasing the cutting speed led to the reduction of hardness values in surface layers in such a way that at higher cutting speeds, the hardness of surface layers would be less than that of the bulk material. Patil et al. [21] studied the thermal loads generated in the machining region. During their studies,

thermal loads were measured for a variety of feed rates, and it was found that with increasing the feed rate, heat generated in the cutting region increased. Ramesh et al. [22] investigated the surface quality after turning process of titanium alloys. According to their findings, feed rate was significant item on surface quality and as the feed rate enhances, machined sample roughness is also increased. In addition, Hughes et al. [16] reported that surface roughness increased at low cutting speeds and reduced at high cutting speeds. Rotella et al. [23], in their research on orthogonal operation of Ti-6Al-4V alloy, found that with increasing cutting speed, the grain size decreased. Unfortunately, in spite of industrial application of surface integrity for titanium alloys, it has not been evaluated extensively for different machining conditions. In addition, it deserves to be extended and investigated on various indications of surface integrity.

Although studies have been conducted on surface integrity of other alloys, despite the importance and application of machining process in different areas, few studies have been carried out on surface integrity of machining processes of titanium alloys. It seems more studies are essential in this regard thanks to the unique properties and high utilization of this alloy in industry. Based on the above-mentioned issues, the novelty and innovative feature of this study is an extensive evaluation of different indications of surface integrity after turning operation of Ti-6Al-4V alloy for different process conditions. In this paper, influence of each experimental condition on surface quality, microhardness, grain size, and thermal loads was evaluated and results were discussed.

2. MATERIALS AND METHODS

To evaluate different aspects of surface integrity after turning of Ti-6Al-4V alloy, 10 experiments were conducted on samples prepared with diameter and length of 100 mm and 16 mm, respectively. The carbide cutting tool with specification of TCMW16T308-ARNO (without chip breaker) was used. It provided cutting edge and nose radius of 10 μm and 0.8 mm, respectively. The experiments were performed at various experimental conditions as reported in Table 1. Figure 1 shows the machine tool, workpieces, inserts, and tool holder used in this research. To investigate the microstructure changes induced due to turning operation, the workpieces were cut by Wire-EDM, then polished and finally etched.

After preparation of the samples, the microhardness changes of each workpiece were measured at a depth of 20-160 μm from top layer of samples using a microhardness measurement system of Koopa company. For measurement of microhardness, a load of 300 g was applied so that the device created a square pyramid at the desired location, then hardness value (in Vickers) was calculated automatically

TABLE 1. Experimental conditions for conducting machining experiments

Test No.	Cutting speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)
Test_1	460	0.24	0.065
Test_2	300	0.24	0.065
Test_3	765	0.24	0.065
Test_4	1255	0.24	0.065
Test_5	460	0.44	0.065
Test_6	460	0.64	0.065
Test_7	460	0.84	0.065
Test_8	460	0.24	0.104
Test_9	460	0.24	0.174
Test_10	460	0.24	0.261

**Figure 1.** Machine tool, inserts, tool holder and samples

by Haresh software. This system provides movement of samples in X and Y directions with precision of 10 μm that is used for extraction of microhardness variation from the machined surface.

The surface quality in each workpiece was measured three times by a roughness tester (PCE RT 2200 model) and the average of measurements was reported. The maximum machining temperature was also measured by the thermal camera in different conditions of machining parameters. Finally, the surface grain size was measured by a light optical microscope and its changes at the surface of the samples were reported. In the following of the present study, the obtained experimental results are reported and discussed.

3. RESULTS and DISCUSSION

In this part, the result of tests on microhardness, surface roughness, thermal loads and grain size are discussed. After machining the samples for various experimental conditions, samples were prepared to evaluate the changes made. Then, using a microhardness tester, the microhardness of each

sample was measured and its curve was extracted. In the next step, by means of a roughness tester, the surface roughness was obtained at three points and the average was taken into account. The maximum machining temperature was also measured by the thermal camera and the temperature changes in the experiments were studied. Finally, the size of the grain was measured at the surface of each sample by a light optical microscope.

3. 1. Microhardness Evaluation

The microstructure change is a significant indication of surface integrity and some of the mechanical properties of workpiece including wear resistance are dependent on it [24]. During the process, due to the cutting forces and high friction between tool and material, mechanical plastic deformation occurs on the surface, which increases the hardness and tensile strength and consequently reduces the material ductility [25]. As a result, by studying this indication, useful information about properties of workpiece under static and dynamic loads is obtained. For this purpose, after machining of the samples, the microhardness curves were extracted at various distances from the surface (20-160 μm). In the following, the effect of machining parameters is investigated on microhardness variations at superficial layers influenced by machining process.

In Figure 2 (a), the microhardness changes from machined surface are given at various feed rates. As shown, by enhancement of feed rate (from 0.065 to 0.174 mm/rev), amount of hardness at the surface layers increased. In contrast, at maximum feed rate (0.26 mm/rev), hardness decreases. More in detail, at 0.065 mm/rev feed rate, microhardness at top layer of sample was 341.7 HV and at 0.261 mm/rev feed rate, hardness was 322 HV. It seems that at higher feed rates, the temperature in machining region becomes higher and the thermal softening effect prevails and, subsequently, hardness decreases [3].

Figure 2 (b) represents the microhardness variations for different depths of cut. Generally, increment of depth of cuts causes enhancement of microhardness of surface layers of the machined workpiece. At 0.24 mm cutting depth, microhardness at surface layer was 334.8 HV and increased to 354.4 HV in 0.84 mm depth of cut. The microhardness variations in the subsurface layers also had a similar trend to the surface layers. In fact, with increase of depth of cut, the machining forces increase and the mechanical strain hardening occurs at the surface, resulting in the enhancement of hardness of surface layers [3].

Figure 2 (c) demonstrates the microhardness changes by variation of cutting speed. It indicates that enhancing the cutting speed results in higher hardness in the surface layers. More in detail, with increasing cutting speed from 460 to 1255 rpm, the microhardness of the surface layers rose from 338.8 to 370.6 HV. The results of the study

conducted by Haron et al showed similar trend [15]. In addition, the microhardness of the subsurface layers was not changed significantly by increment of cutting speed. It can be said that at maximum cutting speed, owing to the existence of Built-Up Edge (BUE), more mechanical contacts and consequently higher plastic deformations are induced in surface layers [26].

The comparison between the findings indicates that increment of the cutting speed is a more effective factor than other investigated parameters on increasing the microhardness. On the one hand, hardness increment on the surface, enhances wear resistance of surface, and on

the other hand, makes the material more brittle and reduces its toughness. Therefore, determination of critical level for microhardness variations in superficial layers is an essential task and depends on workpiece application in industry.

3. 2. Surface Roughness Evaluation Surface roughness in the machining process is considered as the most important aspect of surface texture and depends on the machining parameters. Furthermore, this parameter is an extremely effective factor in the fatigue life of the material [25]. In addition, high roughness values cause crack formation, premature failure of the material, and a reduction in the performance. Experimental conditions affect the surface quality, and each change in the cutting process leads to a remarkable effect on surface quality. In this respect, after machining, the average of surface roughness (three times) was measured. Finally, surface quality values at different cutting conditions were investigated as illustrated in Figure 3.

In Figure 3 (a) the effect of depth of cut on surface quality is demonstrated. In general, surface roughness is enhanced at higher depth of cut. First, increment of depth from 0.24 to 0.44 mm resulted in an enhancement of roughness from 0.82 to 0.924 μm , and a further increment of cutting depth from 0.44 to 0.64 mm decreased the surface roughness (0.924 to 0.75 μm). With increasing the cutting depth, tool penetration in material is expected to increase, causing vibration and chatter to occur, and subsequently, surface roughness becomes more.

Figure 3 (b) shows surface roughness values by variation of cutting speed. According to the results, with increasing cutting speed, the surface quality is firstly impaired and then is improved. When cutting speed was changed from 300 to 1255 rpm, the surface quality became better and changed from 0.861 to 0.733 μm . Figure 3 (c) shows roughness variations at different feed rates. It is demonstrated that with increasing feed rate, the machined surface quality significantly impaired. Ramesh et al. [22] also observed similar results in their research. With changing feed rate from 0.055 to 0.261 mm/rev, the surface quality changed from 0.872 to 5.387 μm .

3. 3. Temperature Measurement The maximum temperature generated in the machining is one of the significant parameters that influence the tool life, making the microstructural changes and residual stress. The mechanical contact between tool and sample and intense plastic deformation at cutting region are major factors of heat generation during the machining process [23]. With increase in the temperature of the cutting region, tensile residual stress was generated at top layers that impairs fatigue life of the workpiece [27]. In order to measure the thermal loads generated in this study, a thermal camera was used. In Figure 4, the captured temperature using the thermal camera in machining region can be observed for

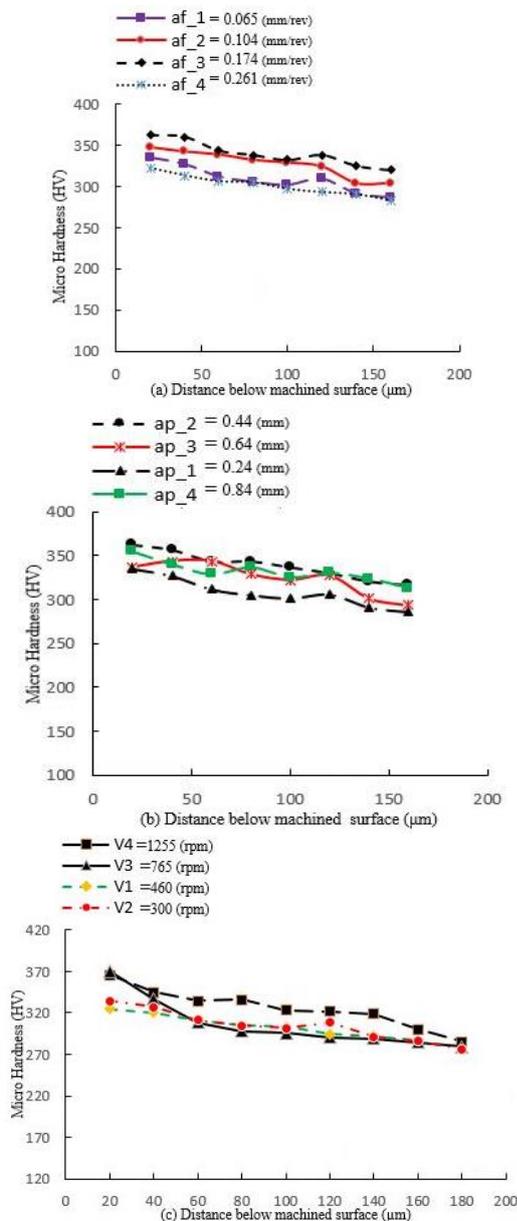


Figure 2. Microhardness variations at different (a) feed rates (b), depths of cut, and (c) cutting speeds

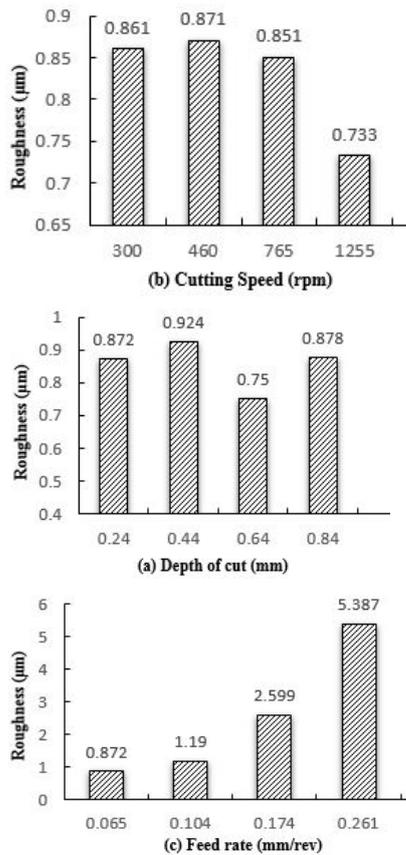


Figure 3. Surface roughness variations at different (a) depths of cut (b), cutting speeds, and (c) feed rates

feed rates from 0.065 to 0.261 mm/rev. In the following, the influence of each experimental condition on the maximum temperature was studied.

The results of maximum machining temperature at various cutting conditions were reported in Figure 5. As shown in Figure 5 (a), it is shown that the temperature significantly increases at higher feed rates. With increasing feed rate from 0.065 to 0.261 mm/rev, the temperature increased from 232.3 to 424.8 °C. It seems that with enhancement of chip formation rate and increase of work hardening, the temperature in the cutting region elevates. Temperature variation at different depths of cut was reported in Figure 5 (b). In general, increasing cutting depth increases the maximum machining temperature. Change in cutting depth from 0.24 to 0.84 mm, changed the temperature from 232.3 to 420.8 °C. In fact, by enhancement of cutting depth, tool penetration into the workpiece and consequently mechanical contact between tool and workpiece and cutting forces increased, and thus the temperature in the cutting region was elevated [28]. Figure 5 (c) demonstrates the impact of cutting speed on temperature changes. Based on this, change in cutting speed from 300 to 765 rpm caused temperature enhance from 275.6 to

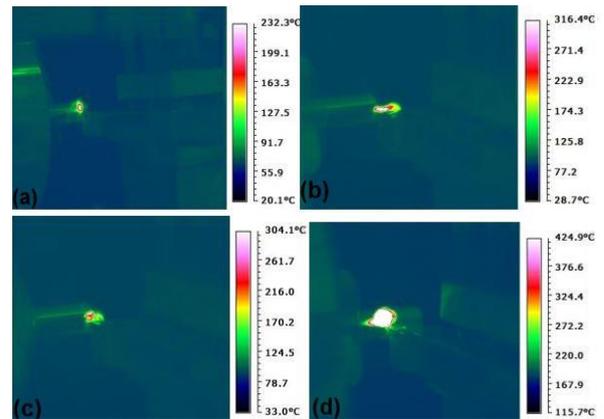


Figure 4. Example of temperature distribution at different feed rates of (a) 0.065 (b) 0.104, (c) 0.174, and (d) 0.261 (mm/rev)

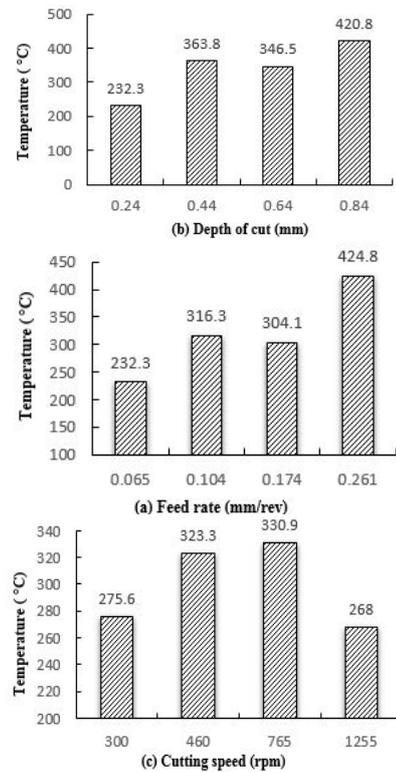


Figure 5. Maximum machining temperature at different (a) feed rates, (b) depths of cut, and (c) cutting speeds

330.9 °C, respectively, while increase in speed from 765 to 1255 rpm caused a decrease in temperature from 330.9 to 268 °C. It seems that with increasing cutting speed, shorter time will be available for heat exchange between the cutting zone and environment, and also friction is increased. As a result of these events, the maximum machining temperature is increased [3]. In contrast, the increment of cutting speed from a specific range does not

affect the temperature of the cutting region and the temperature decreases. It is probably because of the domination of thermal softening event that leads to the reduction of material strength and easier chip formation. Eventually, a comparison was made between the obtained results and it was shown that feed rate was the more influential factor compared to other parameters on generation of temperature.

3. 4. Grain Size Variation In the machining process, the simultaneous presence of thermal and mechanical loads results in microstructural changes and eventually variation of material properties [29]. At the present study, after preparation of the samples, superficial layer of the machined workpieces were photographed using a light optical microscope $\times 800$ (Figure 6.). Finally, the grain size was measured at the surface of the samples. In the following, the influence of experimental conditions on grain size was investigated and reported in Figure 7.

The reason of the microstructure changes and grain refinement in Ti-6Al-4V alloy is Dynamic Recrystallization (DRX) described by Zener-hollomen parameter. According to this, the DRX is accelerated at high temperatures and severe plastic deformations [23]. As shown in Figure 7 (a), it can be observed that the grain size is mostly reduced by increasing the cutting speed.

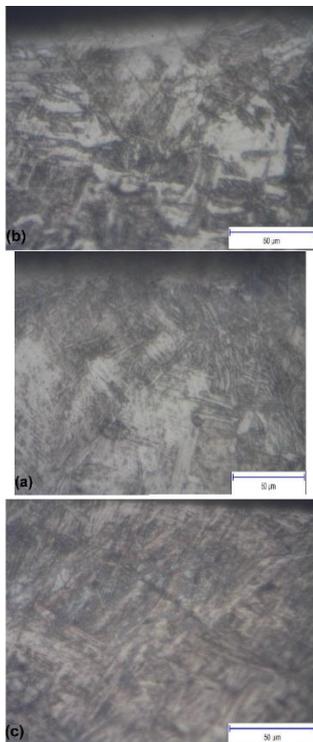


Figure 6. Samples of grain size pictures for increase of: (a) cutting speed (765 rpm), (b) depth of cut (0.84 mm) and (c) feed rate (0.174 mm/rev)

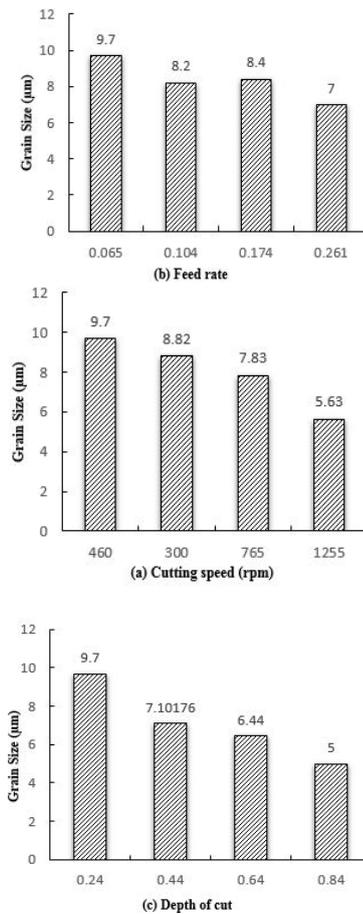


Figure 7. Surface grain size at various (a) cutting speeds, (b) feed rates, and (c) depths of cut

More in detail, with changing the cutting speed from 460 to 1255 rpm, the grain size decreased from 9.7 to 5.63 μm . In fact, with increasing the cutting speed, the workpiece does not find the possibility of exchanging heat with the environment. As a result, the temperature in the cutting region is increased and consequently, the grain size is decreased. Rotella et al. [23] also obtained similar results in their research. In Figure 7 (b), grain size variations are shown at various feed rates. In general, increasing the feed rate leads to the reduction of grain size at surface of the samples. As can be seen, with variation of feed rate from 0.065 to 0.261 mm/rev, the grain size decreased from 9.7 to 5 μm . It seems that by increasing the feed rate, chip formation rate and work hardening increase and consequently more plastic deformation is induced into the workpiece. As a result of this event, intensive recrystallization occurs in superficial layers and more grain refinement takes place. Figure 7 (c) demonstrates the grain size variation for enhancement of cutting depth. By variation of this parameter, grain size at the surface decreased, in a way that variation of depth of cut from 0.24 to 0.84 mm reduced the grain size from 9.7 to 7 μm . This can be attributed to higher machining

forces resulting from increasing depth of cut and consequently the increase in the work hardening and temperature in the workpiece.

4. CONCLUSION

Enhancing demand for using titanium alloys in different industries, encourages researchers to understand and evaluate quality and mechanical properties of these alloys produced after manufacturing processes. Surface integrity has a variety of aspects, including metallurgical and mechanical properties, and surface texture that are the most effective parameters on service life of the final products. In this study, an experimental investigation was carried out for evaluation of surface integrity at turning operation of Ti-6Al-4V alloy. In this regard, at first, 10 experiments were carried out under various feed rates, depths of cuts, and cutting speeds. After that, the most striking indications of surface integrity including the microhardness changes, grain size, roughness and thermal loads were evaluated at different experimental conditions. It was shown that:

- Microhardness change at machined subsurface layers was evaluated at different experimental conditions. Among these cutting parameters, cutting speed was found the most effective factor in increasing surface microhardness. By enhancement of cutting speed from 460 to 1255 rpm, the hardness in the surface layers increased from 334.8 to 370.6 HV. It was demonstrated that, with enhancement of feed rate, surface layer hardness initially increased, but at higher feed rates, surface hardness slightly decreased.

- Increasing the cutting depth and cutting speed resulted in improvement of roughness while higher feed rate led to a significant deterioration of surface quality. When it changed from 0.065 to 0.261 mm/rev, the roughness increased from 0.82 to 5.387 μm .

- The thermal loads generated by machining are one of the most important issues that can cause microstructural changes and tensile residual stress at the machined workpiece. A comparison between the results indicated that, among cutting parameters, increment of feed rate had the greatest influence on temperature increase in a way that the maximum temperature (424.8 °C) was reported at $a_f = 0.261$ (mm/rev). It was reported that by enhancement of cutting speed, the machining thermal load firstly increased and then reduced. Since thermal loads lead to dynamic recrystallization, evaluation of thermal loads provides information for reasons of grain refinement at different cutting conditions.

- Grain size variations at machined surface for various machining parameters were investigated. The findings indicated that feed rate is the most effective parameter in grain size reduction at the surface. In fact, changes in feed

rate from 0.065 to 0.261 mm/rev led to the reduction of grain size from 9.7 to 5 μm . However, cutting depth increment had the lower effect on grain size variation compared to other parameters.

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Roughness

سلامت سطح در فرآیند ماشینکاری یکی از موارد بسیار مهم در ساخت قطعات در صنایع پیشرفته می باشد و تاثیر قابل توجهی روی عملکرد و عمر کاری قطعات دارد. از آنجایی که حین انجام فرآیند بارهای مکانیکی-حرارتی بر ماده اعمال می شود، برخی خواص مکانیکی ماده دستخوش تغییراتی می گردد. از همین رو نیاز است تا این خواص پس از ماشینکاری کنترل شوند. یکی از موادی که در صنایع مهندسی بسیار کاربرد دارد آلیاژ Ti-6Al-4V است که دارای خواص مناسبی می باشد. در تحقیق پیش رو آزمایش های تجربی به منظور بررسی شاخص های سلامت سطح پس از ماشینکاری انجام شد. سپس اثر هر یک از پارامترهای ماشینکاری بر تغییرات منحنی میکروسختی، زبری سطح، مقدار بیشینه بارهای حرارتی و اندازه دانه بررسی شدند. نتایج حاکی از آن است که افزایش سرعت برشی تاثیر گذارترین پارامتر بر مقدار میکروسختی در سطح را دارد. به علاوه افزایش نرخ پیشروی موجب افزایش قابل توجه بارهای حرارتی در فرآیند می شود. بر اساس نتایج افزایش عمق برشی بیشترین تاثیر را روی کاهش اندازه دانه دارد.

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