Investigation of Ti-6Al-4V surface integrity from milling process

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Abstract. The applications of titanium alloys vary from aerospace industry, medical device and military, however having many challenges in the machining process due to difficult-to-machine characteristic of the material. This study focused on surface integrity of titanium alloy grade Ti-6Al-4V after milling process with different set of parameters. This research investigates the effect of surface integrity of titanium alloys (Ti-6Al-4V) after milling operation with difference cutting parameters such as feed rate, depth of cut and cutting speed. Characterization and measurements were taken on the surface morphology, residual stress, surface roughness and surface hardness. It was found out that from the experiment, the highest cutting speed at 8000 rpm produced lowest surface roughness value of 2.066 μm, while lowest cutting speed at 4500 rpm produced highest surface roughness of 2.55μm. The residual stress analysis shown that all the surfaces produced compressive stresses of more than 500 MPa. It is also found out no evidence of transformation at the morphology of the machined surface. Microhardness measurement at the depth 10 μm to 500 μm from the machined surface only shows slight increase of hardness, however, at the range from machined surface to 10 μm indicates low hardness due to softening effect from the machining process. This demonstrated that surface integrity of titanium alloys does effect by the machining parameters.

1. Introduction

Titanium alloy machining process is considered as a challenging process, with regards to its material property which is acknowledge as difficult-to-machine material. Besides, the machining process may also influence by huge chemical reactivity, causing the modification at its surface integrity and may cause the tool failure [1-2]. These challenges make the research focus on the machining of titanium alloys become limited for only specific application in aerospace, medical and military industry. Other influence that affect the machining process of titanium alloys are including residual stress, high heat stress and inconsistency of chip thickness. The impact of these factors contributes to overall production costs and final quality machined surface due to poor machinability of titanium alloys [3].

The machining performance of titanium alloys can be defined by the machining output of its surface integrity, for correlation with machining parameters used. Amongst the basic characteristics that can be evaluated for the surface integrity is such as morphology, residual stress, surface roughness and surface hardness. For topological parameters, the surface finish of the material is one of the examples of the surface integrity used. If essential objective of the product development is to reach...
extra reliability levels such as in aerospace industry, the most significant parameters used to determine the quality of the product is surface integrity [4].

The desired machining outputs from the machining of titanium alloys may be hindered by surface defects. Mostly, the defects happen due to the high heat generated during the machining process, thus defects such as plastic deformation and microcracking may occurred during the process [5].

In order to obtain some insight about the correlation, this study had focus on initial data for the investigation. The attention was to characterize and measure the morphology, residual stress, surface roughness and microhardness for depth profile. The machining parameters used were depth of cut, feed rate and cutting speed.

2. Research methodology
In this experiment, titanium alloy of grade Ti-6Al-4V was used with chemical elements properties as in Table 1. As the aim for this study is to obtain primary results, the titanium alloy block was machine with three different set of parameters as in Table 2, with identification name of Sample A, Sample B and Sample C as shown in Figure 1.

Table 1. Chemical composition of Ti-6Al-4V

| Element | Ti | Al | V | Fe | O | C | N | N |
|---------|----|----|---|----|---|---|---|---|
| Wt. %   | Base | 5.8 | 3.8 | 0.8 max. | <0.2 | <0.05 | <0.05 | <0.02 |

Table 2. Machining parameters

|         | Cutting Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) |
|---------|---------------------|---------------------|-------------------|
| Sample A | 4500                | 240                 | 0.1               |
| Sample B | 4500                | 320                 | 0.3               |
| Sample C | 8000                | 240                 | 0.1               |

Figure 1. Machined specimens with different machining parameters

Upon completion of the machining process, the machined areas were cut to various size with wire EDM in order to characterize the microstructure, residual stress and microhardness. For microstructure characterization, the samples were ground and polished until mirror finish, then etched with Nital solution for 30 second. The microstructure then observed with Hitachi SU3500 Scanning Electron Microscope (SEM) was used.

For surface roughness measurement, the samples were measured by using Alicona Infinite Focus not contact measurement, several data such as smoothening depth (Rp), roughness (Ra), maximum peak of the profile (Rt) and root mean square (Rq) were obtained, however on Ra value was considered in this study. roughness value [16]. The process then repeated with sample A, B and C.
The residual stress measurement was taken by using Rigaku Ultima IV, X-Ray Diffractometer (XRD) with inclination scan range between 112° - 116° and step width of 0.02°. Other setting for the XRD machine was 1 second for the fixed time, and of 10 diverse tilt angles (ψ) at the range of -5° to 45° at each measurement point.

Microhardness measurement was taken by using Mitutoyo MVK-HI Hardness Testing Machine. Measurement was taken at the cross section of samples taken in order to obtain the microhardness depth profile, from the machined surface towards downward to the base of titanium alloy. The setting applied was 200 g load with indentation dwell time of 20 s.

3. Results and discussion

Morphological characterization was observed at the machined area towards downward area. It can be clearly seen that no white layer formation and phase transformation happen as shown in Figure 2. It also shown that sample B and C did not show changes at the microstructure and grain size as compared to Sample A. This happen due to relatively low cutting force applied and the behaviour of titanium alloy material itself.

For the surface roughness, it can be seen in Table 3 that there is improvement of surface roughness for the three samples after machining process. For Sample A was found to obtain highest average roughness value with 2.507 µm, while Sample C exhibited the lowest Ra value with 2.066 µm. Despite utilising highest feed rate and depth of cut on Sample B, the surface roughness value obtained 2.144 µm, slightly above Sample C. Therefore, it can be shown that both feed rate and depth of cut is not a determining factor for surface roughness on machined titanium alloys. It can be observed that among three different milling parameters, Sample C produced the most excellent surface roughness value.

| Sample   | Average Roughness, Ra (µm) |
|----------|----------------------------|
| Sample A | 2.507                      |
| Sample B | 2.144                      |
| Sample C | 2.066                      |

Table 4 shows the residual stress result for Sample A, B and C. Highest recorded compressive state happens to be at Sample C with magnitude of 970.90 MPa, followed by Sample A with 878.18 MPa and Sample B recorded the lowest reading with 579.00 MPa.

| Sample   | Residual stress, (Mpa) |
|----------|------------------------|
| Sample A | 878.18                 |
Sample B 579.99  
Sample C 970.90

Microhardness value across machine depth was shown in Figure 3. At the position of 10 µm below the machined surface, it indicates the microhardness value for all samples is below initial hardness value Ti-6Al-4V specimen. This is due to the softening effect after the machining process take place. Then, hardness values were increase at 100 µm, the trend shows increase of hardness and slightly increase accordingly. The significant increase happens due to work hardening effect.

Figure 3. Microhardness measurement along the direction of milling process

The reason on the correlation between parameters of cutting speed, the surface hardness value may be related to the excessive temperature generate at the titanium alloys surface during machining process which will induce the thermal softening of the surface. Similar behaviour also occurred at 100 µm - 500 µm depth machined surface that shows Sample C recorded lower hardness value compare to Sample A and Sample B, mostly due to higher value of cutting speed.

4. Conclusions
From this study, it can be concluded that, the machined area does not show any occurrence of phase transformation, microcracks and white layer formation on the titanium alloys. No changes also found not happen at the microstructure and grain. This is due to the cutting parameters used in this study which did not generate enough cutting force that will affect the microstructure and phase transformation on the surface and subsurface of the titanium alloys.

Residual stress shows that all the surfaces contained compressive stresses > 500 MPa. It was found out that with the increase of cutting speed, the residual stress value will decrease. Moreover, the residual stress generated becomes less compressive when the feed increases. Surface roughness was found to be very influenced by cutting speed during the machining process. Sample C with highest cutting speed of 8000 rpm produced the lowest surface roughness value of 2.066µm, while Sample A with lowest cutting speed 4500 rpm produced highest surface roughness 2.507µm. Hardness value at the cross section was influenced by softening effect, occurred until the depth around 100 µm. Overall conclusion from this initial study shows that cutting speed is the most influential parameter in the machining process of Ti-6Al-4V.
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