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Micromechanical characterization of ultrasonic assisted plasma oxidized Ti-6Al-4V by means of nanoscratching test

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Abstract

Ti-6Al-4V is considered to be the most important and useful alloy in the aerospace industry and many other applications. It has good mechanical properties as well as lower machining properties, especially in traditional drilling processes. In the previous study, ultrasonic assisted plasma oxidation grinding (UPOG) had been reported. This technology showed better material removal ability for Ti-6Al-4V. In this study, in order to investigate the material removal process for ultrasonic assisted plasma oxidation grinding (UPOG), scratching test was carried out with plasma oxidized samples. For the purpose of comparison, Ti-6Al-4V sample was also probed under similar conditions. This study has clearly demonstrated that the nature of plasma electrolytic oxidation present in the mechanism of deformation or material removal during nanoscratching test. During the test the deformation was distinctly captured with a high speed camera.

Keywords: Ultrasonic vibration, Plasma electrolytic oxidation, Nanoscratching, Ti-6Al-4V,

1. Introduction

Ti-6Al-4V have many excellent properties (such as high specific strength, good heat and corrosion resistance and light weight) so that it is popular in the aerospace industry and many other applications. These above applications have now become energy conscious, and every industry is going to follow the health and safety requirements at all levels. The concept of sustainable manufacturing has now become the key focus, which deals with the economic, social, safety and environmental issues.

In most industrial applications, Ti-6Al-4V products are firstly manufactured by precision casting, followed by finishing machining processes to shape and remove excess materials[1]. Grinding is one of the common methods to improve form accuracy, dimensional accuracy and surface quality. In grinding processes, every abrasive grain removes a small amount material from the workpiece, benefit to improve the surface finish and structure accuracy. However, the grindability of titanium alloys are not so good, causing low efficiency and high tool wear, which means high cost[2]. Actually, Ti-6Al-4V are typically difficult to machining due to these factors: 1) high specific strength; and 2) low thermal conductivity[3]. Its physical and mechanical properties include high specific strength and hardness lead to higher machining force. The low conductivity result in heat accumulation at the tool-workpiece interface and lead to higher machining temperature. These problems become more critical when grinding the Ti-6Al-4V, the thermal-mechanical stress induced by high machining force and temperature result in tool wear, bad surface roughness and mechanical properties alterations. The grinding wheel wear rotates quickly due to high temperature in the grinding zone and heavy friction between the workpiece and the grinding wheel. [4]

In recent years, numerous research about the grinding process, grinding force and ground surface quality were reported. For example, Zhao et al.[5] carried out grinding experiments of Ti-6Al-4V at different parameters respectively, and studied the influence to the grinding force, material removal efficiency and grain wear characteristics. They found the wear dominantly consists of the grain and bond fracture; subsequently leading to a dramatic increase in grinding force. Therefore, it is vital to develop a better grinding process for Ti-6Al-4V.

As a promising grinding technique, UAG has attracted great attention for decades for the sake of its excellent features, such as smaller grinding force, higher material removal rate, better surface quality, longer grinding wheel working life, and lower grinding heat generation compared with those in conventional grinding (CG). Nik et al.[6] showed that compare with conventional grinding(CG), UAG of Ti-6Al-4V can get higher cutting depth and feed rate, as well as better surface roughness in the feed direction, even though ultrasonic vibration induced on the grinding wheel. Pujana et al.[7] found that lower feed force and higher processing accuracy was achieved when ultrasonic vibration was induced on the drilling of Ti-6Al-4V. Further, the materials removing mode in ultrasonic-assisted-grinding of brittle materials and titanium alloys was studied experimentally and theoretically by Qin et al.[8] On the other hand, UAG process of Ti-6Al-4V is not rapid and brilliant as its use in hard and brittle materials. In order to improve the grinding ability and ground surface quality of Ti-6Al-4V, Li et al.[9] proposed a kind of hybrid grinding technique, which calls ultrasonic-assisted plasma oxidation grinding (UPOG). His study showed the grinding ability and ground quality was obviously improved, however, the material removal mode of oxidized Ti-6Al-4V is still not very clear.

In this study, in order to investigate the material removal mode for ultrasonic assisted plasma oxidation grinding (UPOG), nanoscratching test was carried out with ultrasonic-plasma oxidation samples to simulate the single-grain grinding processes. For the purpose of comparison, Ti-6Al-4V sample was also probed under similar conditions. Normal Forces and tangential force during the scratching test are collected, and the scratching result have been observed by laser microscope and scan electron microscope. This study can clearly demonstrate the influence of ultrasonic-plasma electrolytic oxidation in the mechanism of deformation or material removal during nanoscratching test.

2. Processing principle and experimental

2.1. Principle and experimental setup

In order to simulate the plasma electrolytic oxidation in UPOG, as shown in Fig.1, an ultrasonic plasma electrolytic oxidation (UPEO) device was set up. The adhesive of grinding wheel is Ni alloys. Therefore the cathode material was made by Inconel 718, which was most overuse Ni alloys. Before the UPEO process, the Ti-6Al-4V workpiece would be polished. In this work insulate holders were used to make sure the plasma discharge only occur between cathode and anode.

Z axis lift (by sh-lianyi Co.,Ltd.,China) was used to control the width of plasma discharge gap with an accuracy of 20 μm. The ultrasonic wave generator was amplified and transfer to PZT, which will generate ultrasonic vibration. The metal elastic body was stuck with PZT. DC pulse power can generate single square wave current, the voltage of plasma DC power is 0-10 V and pulse width of plasma DC power is 10 μs.

After the UPEO treatment, thickness of the oxide layer was measured by ellipsometer (Film Sense Co., Ltd., USA). The measured thickness of UPEO layer is shown in Fig.2, five points were measured on each sample then calculate the average and standard deviation. As the result, the thickness of oxidized layer increases with the voltage. Ultrasonic vibration on cathode can promote the oxidation occurs, especially when the voltage is higher, this effect can be more obvious. The thickness of the oxide layer can up to 35nm under 10V-10μs with UV assisting.

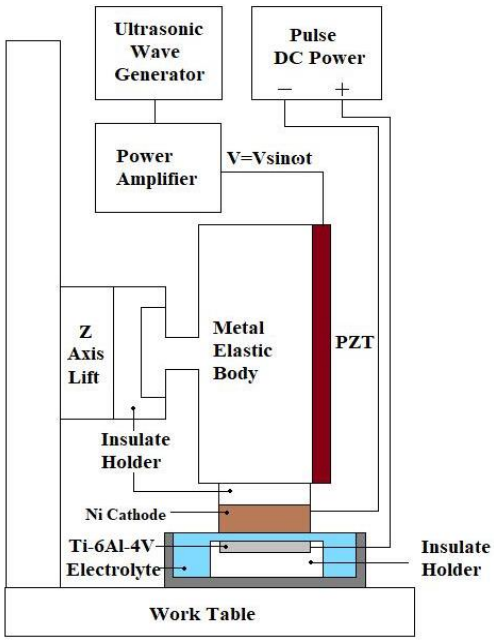

Figure 1. Schematic of setup for UPEO of Ti-6Al-4V

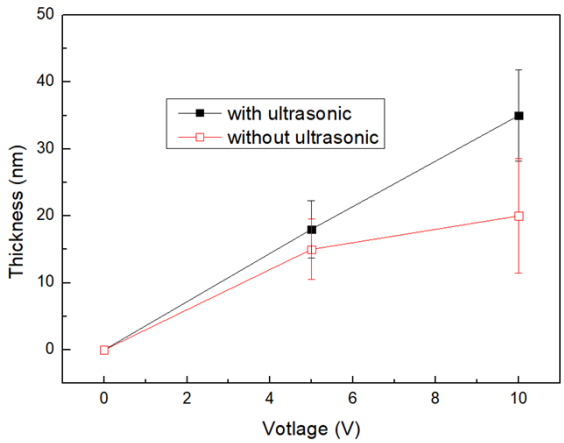

Figure 2. Thickness of oxide layers

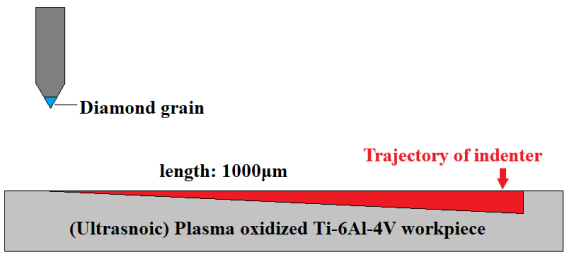

Figure 3. Schematic of nanoscratching test

In order to simulate the single-grain grinding processes, scratching test (by Anton-Paar Co., Ltd., Germany) was carried out with ultrasonic plasma oxidation samples. Non-treated workpiece was also tested for comparison. As shown in Fig.3, the load of indenter was gradually increased to the set value, as well as the depth in the scratching test, this mode is similar to the micro-cutting mode of grain on the grinding wheel.

Finally, chips formed in scratching test were collected and observed by SEM-EDX (Hitachi Co., Ltd.), morphology of scratching chips and groove were observed by SEM (Zesis Co., Ltd.). Meanwhile, confocal laser scanning microscope (CLSM) (by KEYENCE Co., Ltd.) was used to measure the depth of scratching grooves.

2.2. Experimental conditions

Table 1 Experimental conditions

Ultrasonic vibration	Frequency (*f*)	40 kHz
	Amplitude ($A_{p\text{-}p}$)	5.0 μm
Workpiece	Ti-6Al-4V (L10 X W10 X T4 mm)	
Ultrasonic plasma oxidation	Discharge gap	20 μm
	Pattern	Square
	Plasma voltage(*U*)	0,5,10 V
	Pulse width(*T*)	10 μs
Scratching test	Speed(*V*)	5000 μm/min
	Length(*L*)	1000 μm
	Load(*P*)	0-50 mN
	Indenter	B-T74 (Diamond)
Electrolyte	NaCl solution, 5% wt	

In grinding, the maximum undeformed thickness, t_m, of the chip formed by the cutting action of the cone-like abrasive grain can be expressed as [10]:

$$t_m \approx 2a\frac{V_w}{V_g}\sqrt{\frac{\Delta}{d_s}} \quad (1)$$

Where *a* is the successive cutting point spacing. In order to determine the processing parameters of Δ, Vg, and Vw. Typically,

cBN abrasives require a speed of over 50 m/min for grinding Ti-6V-4Al [11], which means the undeformed thickness will be less than 1 μm. Therefore, nanoscratching test was conducted under the conditions listed in Table 1. Especially the scratching speed, which is the largest value allowed by device.

3. Results and discussion

Firstly, as shown in Fig. 4, the depth of scratching grooves was measured by CLSM. Obviously, the depth of oxidized workpieces were larger than TC4 comparison at most of the normal force point. Further, the UPEO samples shown larger depth than the general plasma oxidized samples. It means oxidation increased material remove ability, and ultrasonic vibration on cathode could promote this effect. It is noteworthy that the increasing depth of general plasma oxidized samples tend to stable after 20mN, which means the chip forming processes would be affected by oxide layer and this effect would be weakened with the deeper depth of cutting. This subsequently results in the minimization of chips and makes it easier to remove the chips from the grinding zone.

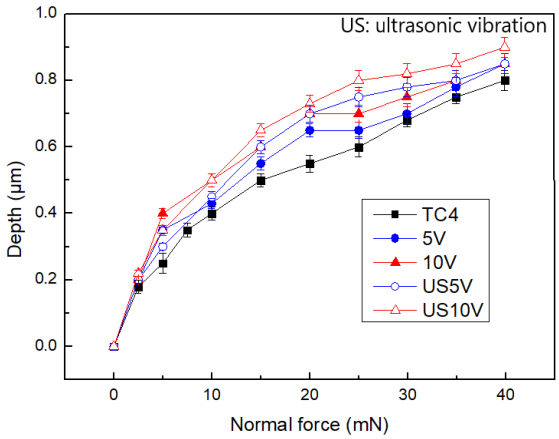

Figure 4. Depth of scratching grooves at different normal force

Fig.5 showed the relation between the tangential force and the normal force, as mentioned earlier, the weakening effect may be invalid when the normal force is larger than 20mN, therefore the analysis of the curve in 0-20mN is highly specialized. Oxidized sample shown lower scratching force, especially the 10V UPEO sample. At 5V condition, there was little difference between UPEO and PEO samples, result from the smaller thickness of the oxide layer. The decrease in the tangential force was probably achieved for the sake of friction. As the TiO_2 layer formed on the work-surface is a well-known lubricating material, implying that the resultant TiO_2 leads to a significant decrease in the tangential force.

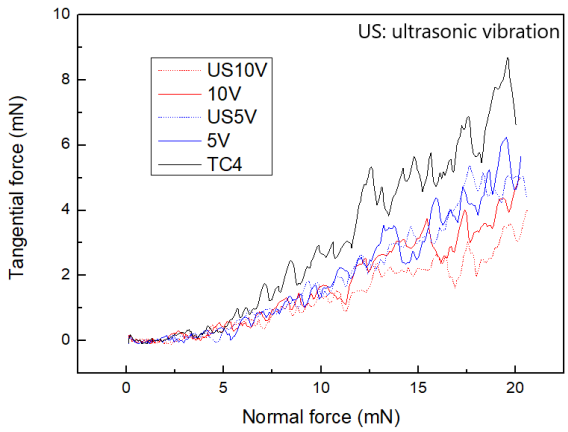

Figure 5. Scratching force to normal force diagram

Scratching grooves were observed by SEM, the result is shown in figure.6. There is obviously material piling up on the both side of the groove in UPEO sample (b, c). While in the TC4 comparation, there is none or little materials piling up. Further, the striping (c) or tending to strip (b) oxide layer was observed in UPEO samples. What is more, in Figure.6c showed the region where all the oxide layer has been scratched away. In Figure.6c, the groove at right side of arrowhead tag is totally different to the left side, which has piling chips and oxide layer at the bottom of the groove. This appearance can be the evidence of the previous guess.

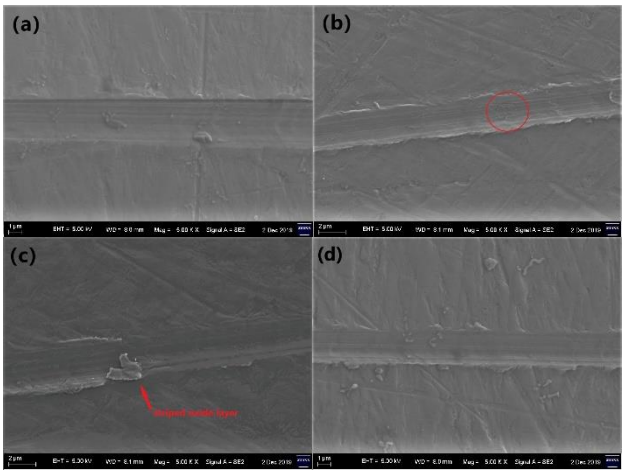

Figure 6. Scratching grooves of TC4 (a,d) and 10V UPEO sample (b,c)

Besides, SEM observation of forming chips in scratching test was carried out. As shown in Fig.7, the chips from 10V oxidized sample are more fragile, means the oxidized sample has a brittler and weaker surface. SEM-EDX analysis was carried out to 10V UPEO chips, the result (Fig.8) shows that the main element of chips is titanium, proving the collected chips are from workpieces. In addition, there are also some particles with sodium element in the EDX result, it may be from NaCl electrolyte. The difference of chips from TC4 and oxidized sample. It is supposed that the displacement mode influences the equivalent internal friction angle of interlayer. Armarego and Brown [12] concluded that the shear angle φ is independent of both the indenter width of cut and the chip thickness and can be determined by Eq. (2).

$$\tan(\varphi + \beta) = \cot\alpha \qquad (2)$$

Where β is the friction angle and determined by the friction coefficient μ (ratio of tangential force to normal force in Figure.5) between the rake face of cutting edge and the chip through the relationship of $\tan\beta=\mu$ and α is the rake angle of cutting edge. In CG, the angle α is usually the same with the half vertical angle θ of the grain; hence, it can be figured out from Eq.(2) that as long as the indenter is performed with a given size at a given depth of cut, the α will be a given constant, consequently the φ would increases as the β decrease.

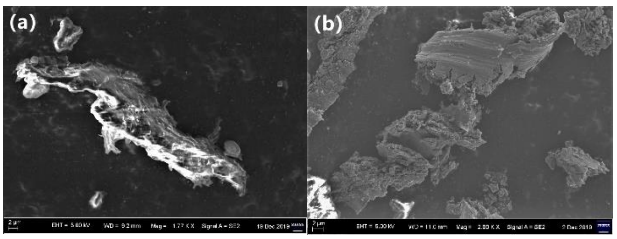

Figure 7. SEM image of chips from TC4 (a) and 10V oxidized sample (b)

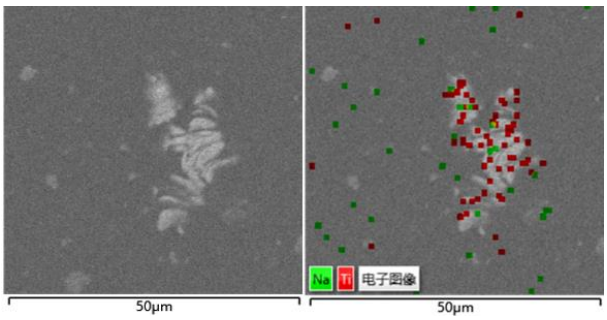

Figure 8. SEM-EDX analysis of chips from 10V UPEO sample

Finally, a high speed camera with 12X micro focus lens was used to the deformation of Ti-6Al-4V sample and UPEO sample in nanoscratching test. The chip deformation was difficult to be observed in Ti-6Al-4V sample nanoscratching process. In combination with the small groove area, the material was chipped out in UPEO sample nanoscratching process. It is obvious that the thin oxidation layer was enough to be affected the chip deformation process by the change of stress propagation. The extrusion of nanoscratching process lead to faulted of oxidation, which would release the stress and made more material removal rather than compressed under the surface.

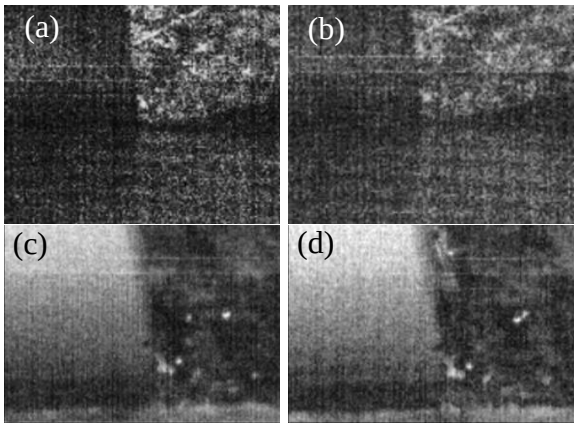

Figure 9. Chip deformation process of TC4 (a,b) and 10V UPEO sample (c,d)

4. Conclusions

Ti-6Al-4V samples were processed by UPEO with different parameters and then tested in nanoscratching. The results obtained in this work are summarized as following:

(1) Ultrasonic vibration on cathode can promote the plasma electrolytic oxidation, when the voltage is larger, this effect can be more obvious.
(2) The UPEO processes can form an oxide layer on the surface of Ti-6Al-4V, result in lower surface hardness and decreased cutting force in the scratching test.
(3) Chips from UPEO samples are brittler and more fragile.
(4) The scratching test of UPEO sample showed higher scratching depth which means a good material removal.

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