Study on the Cutting Surface Formation Mechanism of TA2 and TC4

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Abstract: High speed machining of titanium and titanium alloy is an important and fundamental research topic in the field of machining. In this paper, the cutting experiments of commercial pure titanium TA2 and titanium alloy TC4 were carried out at different speeds. We used roughness measuring instrument and scanning electron microscope (SEM) to observe and analyze the cutting surface and particularly analyzed its roughness and microstructure characteristics under different cutting speeds. The experimental results show that in the cutting process, when the cutting speed of TA2 is higher than 79.13m/min, the surface roughness is reduced, the influence depth of extrusion and dislocation becomes shallow, and good surface quality is obtained; when the cutting speed of TC4 is close to 79.13m/min, the surface roughness is reduced, the influence depth of extrusion and dislocation becomes shallow, and good surface quality is obtained. At the same cutting speed, the surface roughness of TC4 is less than TA2, and the influence depth is also less than TA2, so Titanium alloy TC4 is easier to get good surface quality.

1. Introduction
Titanium is an important structural metal developed in the 1950s. Titanium alloy is widely used in various fields because of its high intensity, good corrosion resistance and high heat resistance. However, due to the small thermal conductivity of titanium alloy and its easy chemical reaction with tool material, mostly the cutting speed of titanium alloy in actual production is below 50m/min[1]. For titanium and titanium alloy, when the cutting speed is higher than 50m/min, it is considered to be high-speed cutting. Therefore, the research on high-speed cutting of titanium alloy is a hot topic today. At the same time, when aluminum (AL) and TC11 are used, the cutting speed increases from 60m/min to 100m/min, the surface roughness of workpiece decreases, and the surface morphology of 100m/min is better than that of 60m/min. Vanadium (V) is a key element in titanium alloy, especially in aviation titanium alloy. V element in titanium alloy can be used as strengthening agent and stabilizing agent when the content is 1%, and the alloy has good ductility and formability when the content is 4%[2,3].

In this paper, the surface of TA2 and TC4 under the condition of different cutting speeds is detected and analyzed by means of roughness measuring instrument and scanning electron microscope, and the surface formation mechanism under the condition of different cutting speeds and alloy elements such as Al and V is studied.
2. Experiment

2.1. Cutting Experiment
In order to obtain the surface structure of TA2 and TC4 at different cutting speeds, TA2 bar and TC4 bar were selected as the processing materials, with the diameter φ of 90mm and the length of 300mm. See Table 1 for chemical composition of commercial pure titanium TA2 and titanium alloy TC4. The heat treatment process is annealing at 620 °C, and the holding time is 120min. In the experiment, dry orthogonal turning is carried out on CA6140A general machine tool, and coated carbide tools produced by KENNAMETAL company are selected to turn titanium alloy bar. The insert brand is DNMG150608MP-KCM15. In order to avoid the influence of tool wear on the test, every time the cutting speed is changed, the insert is replaced [4]. TA2 and TC4 were tested in single factor respectively, and the experimental parameters are shown in Table 2.

Table 1 chemical components of TA2 and TC4

|        | Element | C   | O   | Fe  | N   | Si  | Ti  |
|--------|---------|-----|-----|-----|-----|-----|-----|
| (a) TA2| Quality%| 0.08| 0.25| 0.30| 0.03| 0.15| Margin|
| (b) TC4| Element | C   | O   | Al  | Fe  | V   | Ti  |
|        | Quality%| 0.08| 0.20| 0.30| 0.05| 5.50-6.75| 3.50-4.50| Margin|

Table 2 cutting parameters

| Test No. | Spindle Speed (n/min) | Cutting Speed (Vc(m/min)) | Feed Rate (f(mm/x)) | Back Cutting Depth (ap(mm)) |
|----------|-----------------------|---------------------------|----------------------|-----------------------------|
| 1        | 110                   | 31.09                     | 0.2                  | 0.2                         |
| 2        | 280                   | 79.13                     | 0.2                  | 0.2                         |
| 3        | 450                   | 127.17                    | 0.2                  | 0.2                         |

2.2. Roughness Inspection
In order to obtain the surface roughness of TA2 and TC4 under different cutting speeds, the CV-3200S4 surface roughness measuring instrument of Mitutoyo was selected in the experiment. 3 positions corresponding to each measuring speed were randomly selected for measurement and recording, and the average value of the results was taken for analysis.

2.3. SEM Test
In order to directly observe the influence of TA2 and TC4 on the microstructure under different cutting speeds, the experimental samples were processed by inlaying, polishing and corrosion, and then observed by SEM. The model of SEM is Hitachi high tech S-4800 cold field emission SEM.

3. Results and Discussion

3.1. Roughness of Machined Surface
It can be seen from Figure 1 that when other processing parameters are unchanged, the cutting speed of commercial pure titanium TA2 changes from 31.09m/min to 79.13m/min, and the average surface roughness value does not change significantly, but after accelerating from 79.13m/min to 127.17m/min, the average surface roughness value decreases significantly, which decreases from 1.6030 μm to 1.5236 μm. This means that when the cutting speed of commercial pure titanium TA2
reaches 127.17m/min, the surface fluctuation is weakened. The cutting speed of titanium TC4 changed from 31.09m/min to 79.13m/min, and the average surface roughness decreased significantly, which decreases from 1.5595 μm to 1.4389 μm; then the cutting speed is increased to 127.17m/min, the average surface roughness increased slightly, and the average roughness changed to 1.4548 μm. This means that when the cutting speed is 79.13m/min, the surface fluctuation is weak. Compared commercial pure titanium TA2 with titanium alloy TC4, the average surface roughness of titanium alloy TC4 is lower than that of commercial pure titanium TA2 at the same cutting speed from 31.09m/min to 127.17m/min.

The reasons for this phenomenon are as follows: (1) in the process of turning, under the action of the cutting force, the machined surface produces a kind of "tearing" effect, which makes the cutting surface uneven and the roughness is high. When a certain speed is reached, the time from tearing to fracture will be shortened, and the depth affected by the cutting force will be shallower for the parts below the machined surface. Before it reaches the deep layer of the processed material, the whole cutting process has been completed, the incision is relatively flat, and the roughness is low. [5,6] (2) During turning, titanium alloy TC4 reaches the critical cutting speed which makes the surface relatively flat earlier than commercial pure titanium TA2 [7]. This is because the addition of alloy element V makes the titanium base alloy have higher ductility and formability, and the alloy element Al can make it have better plasticity. It can be seen that under the joint action of alloy element V and alloy element Al [8,9], the surface roughness of the material becomes lower in the plastic processing, and the surface quality of titanium alloy TC4 is better than that of commercial pure titanium TA2.

The results show that in the turning process, when the cutting speed of commercial pure titanium TA2 is higher than 79.13m/min, the surface roughness can be reduced and good surface quality can be obtained; when the cutting speed of titanium alloy TC4 is close to 79.13m/min, the surface roughness can be reduced; at the same cutting speed, the surface roughness of titanium alloy TC4 is lower than that of commercial pure titanium TA2, and titanium alloy TC4 is easier to get good surface quality.

Table 3 surface roughness Ra results of TA2 and TC4 (unit: μm)

| Sample No. | First   | Second  | Third   | Average |
|------------|---------|---------|---------|---------|
| TA2-1      | 1.6205  | 1.6201  | 1.5686  | 1.6030  |
| TA2-2      | 1.5903  | 1.6186  | 1.6101  | 1.6063  |
| TA2-3      | 1.5528  | 1.5123  | 1.5056  | 1.5236  |
| TC4-1      | 1.5692  | 1.5596  | 1.5498  | 1.5595  |
| TC4-2      | 1.4304  | 1.4648  | 1.4216  | 1.4389  |
| TC4-3      | 1.4523  | 1.4723  | 1.4398  | 1.4548  |

Fig. 1 average roughness Ra of TA2 and TC4 at different cutting speeds
3.2. Organization Structure Analysis

Figures 2-4 show the SEM results of TA2 samples at different cutting speeds. From Fig. 2-4, it can be seen that TA2 is composed of a phase (α phase). Under the effect of different cutting speeds, TA2 has white stripes on the surface of turning downward, and the inclined direction is close to the cutting speed direction. This is because in the process of turning, under the combined force of the cutting force component generated along the machining surface and the reaction force generated inside and outside the material, the material surface and sub-surface are squeezed and dislocated. When the cutting speed increases, the extrusion effect becomes smaller and the influence depth becomes shallower, and the depth of white stripe becomes shallower[10].

Fig. 5-7 are SEM results of TC4 samples at different cutting speeds. TC4 is composed of α phase (dark area) and β phase (light or bright area). It can be seen from Fig. 5-7 that under the action of different cutting speeds, the change of α phase is not obvious, the β phase below the turning surface inclines and the inclining direction is close to the cutting speed direction. In the same way, this is due to the action of cutting force, which causes extrusion and dislocation. When the turning speed increases, the influence depth becomes shallow, and the depth of β phase migration becomes shallow[11].

The results show that in the process of cutting, when the cutting speed of TA2 is higher than 79.13m/min, the impact depth of extrusion and dislocation becomes shallow; when the cutting speed of TC4 is close to 79.13m/min, the impact depth of extrusion and dislocation is shallow.

Fig. 2 SEM results of TA2 at 31.09m/min

Fig. 3 SEM results of TA2 at 79.13m/min

Fig. 4 SEM results of TA2 at 127.17m/min
Fig. 5 SEM results of TC4 at 31.09m/min

Fig. 6 SEM results of TC4 at 79.13m/min

Fig. 7 SEM results of TC4 at 127.17m/min

4. Conclusion
The samples of TA2 and TC4 processed at different cutting speeds were tested and observed by using roughness measuring instrument and scanning electron microscope. The results show that in the process of cutting, when the cutting speed of TA2 is greater than 79.13m/min, the surface roughness is reduced, the impact depth of extrusion and dislocation becomes shallow, and good surface quality can be obtained; When the cutting speed of TC4 is close to 79.13m/min, the surface roughness of TC4 can be reduced, the impact depth of extrusion and dislocation is shallow, and good surface quality can be obtained. At the same cutting speed, the surface roughness of TC4 is less than TA2, and the surface influence depth of TC4 is also less than TA2, and titanium alloy TC4 is easier to get good surface quality.

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