

Effects of Cooling Conditions on Surface Integrity in Turning of TC4 Alloy

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Abstract. Machined induced surface integrity of titanium alloy is of great importance due to its strong correlation with the functional performance and service life. In this paper, the effects of different cooling conditions on the surface integrity of TC4 alloy were studied experimentally. The results showed that the values of surface roughness and surface residual stress under cryogenic condition were lower than those under dry condition and emulsion cooling condition with the same cutting parameters, while the influence of cooling condition on the microhardness of the machined surface is not obvious. Cryogenic cutting is an effective way to machine titanium alloy.

1. Introduction

TC4 is widely used in aerospace industry, chemical industry and health care industry due to its excellent inoxidability, thermal stability and specific strength[1]. To satisfy the instant requirements of good surface integrity for engineering practice, high efficiency and clean machining of TC4 is an inevitable trend.

However, due to its excellent mechanical and physical properties, TC4 is a typical difficult-to-machine material. During the machining process, TC4 is often accompanied by high cutting temperatures, severe tool wear[2]. These adverse processing characteristics inevitably have certain impacts on the surface integrity of TC4 component, thereby affecting its performance[3].

In recent years, with the development of cryogenic machining technology, it offers a potential processing technology to machine TC4 and other difficult-to-machine materials[4]. Cryogenic cooling can effectively reduce the cutting temperature during the machining process, change the thermal deformation form of the machining area, and effectively improve the machining quality[5]. In addition, cryogenic machining is a clean and sustainable processing technology. This paper carried out the single-factor comparison test of machining TC4 to explore the influence of cooling conditions on surface integrity.

2. Experimental Procedure

2.1. Experimental Material

The material used in the test was TC4 bar material, whose chemical composition is shown in Table 1. The material was machined into a dish workpiece of $\phi 110\text{mm} \times 4\text{mm}$ by WEDM. After being fixed with a fixture, the material was subjected to conduct a radial turning test.



Table 1. The chemical composition of TC4 (The mass fraction, %)

Al	V	Fe	Si	C	N	H	O	Ti
5.6	3.86	0.18	0.01	0.02	0.023	0.01	0.17	allowance

2.2. Experimental Method

The turning test was carried out on CAK3665 CNC lathe, uncoated carbide tool (Kennametal grade: K313, inserts TPGN220408 geometry) was selected in this experiment, the rake angle of the tool after installation was 3° and the back angle was 8° . In the turning test, the TC4 was machined using radial turning, and the test parameters were shown in Table 2. Liquid nitrogen has good cooling effect and no pollution, so liquid nitrogen was used as coolant in the process of cryogenic cutting. In the turning test, a circular liquid nitrogen nozzle was adopted, and the injection area was the workpiece in front of the cutting area. During the cutting process, the pressure in the nitrogen canister was always kept at 1.5 MPa. Figure 1 shows the operating conditions of cryogenic cutting.

Table 2. Cutting test parameters

cooling condition	v_c (m/min)	f_z (mm/r)	a_p (mm)
dry cutting			
emulsion cutting	80	0.1	0.8
cryogenic cutting			

**Figure 1.** Testing apparatus of cryogenic cutting

After the cutting test, the surface roughness, surface residual stress and microhardness of the machined workpiece were measured. The surface roughness was tested by Mitutoyo Sj-410 profilometer. The surface roughness was measured along the cutting feed rate direction at the middle position of the machined surface. Each parameter was measured for 5 times and the average value was calculated as the final measurement result. In order to further study the variation of machined surface, Usp-sigma white light interferometer was used to take photos of the 3D morphology of the machined surface. The surface residual stress was measured using PROTO iXRD-Combo residual stress instrument, and the residual stress of the workpiece along the cutting feed rate direction was measured. The target material selected for residual stress test was Cu-K α , the diffraction crystal plane was {213}, and the Bragg Angle was 140° . The microhardness was tested by 402MVD microhardness tester. The loading force was 0.5N and the dwelling time was 10s. Each workpiece was measured 5 times and its average value was taken as the measurement result.

3. Results and Discussion

3.1. Surface Roughness

Surface roughness refers to the roughness of the machined surface with small spacing and small peaks and valleys[6]. And it is an important index to measure the quality of workpiece after cutting process. Figure 2 shows the test results of the effects of cooling conditions on surface roughness.

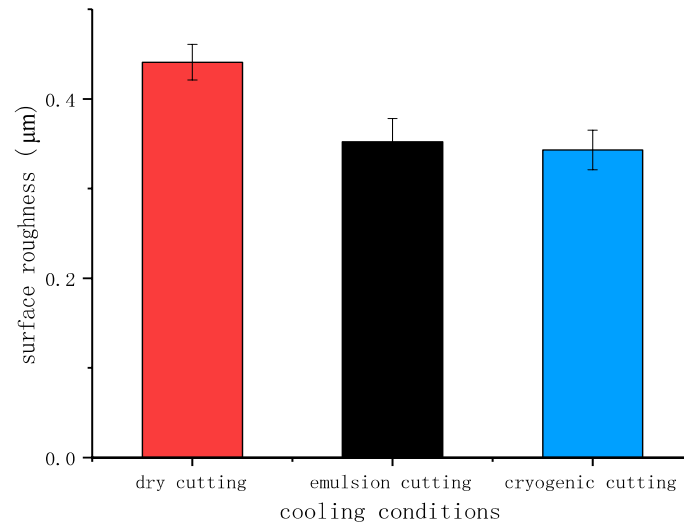


Figure 2. Surface roughness under different cooling conditions

By comparing the influence of different cooling conditions on the surface roughness in Figure 2, it was observed that at same cutting parameters, both the cryogenic cutting and emulsion cutting showed comparable results. Compared with dry cutting, both of them reduce the surface roughness of the machined surface, and the effect of cryogenic cutting is much better.

In dry cutting conditions, there are problems such as high cutting temperature, large cutting force and serious tool wear. In addition, the chip is not easy to discharge, and these will affect the quality of the machined surface, resulting in rise of surface roughness[7]. It is well known that both emulsion and liquid nitrogen have good cooling performance, which can reduce the temperature of the cutting area and to obtain low tool wear. Therefore, both methods are beneficial to improve the surface roughness. But, compared with emulsion, liquid nitrogen has a stronger cooling effect, so cryogenic cutting can obtain better surface roughness[8]. Besides, both the emulsion and liquid nitrogen can lubricate well, thus reducing the friction coefficient between the tool and the workpiece, which will greatly improve the surface quality of the workpiece. In addition, surface plastic side flow is an important factors which influence the machining induced surface roughness. The metal of workpiece in front of tool nose occur plastic deformation because of the tool extrusion and the coupling of cutting heat[9]. With the decrease of cutting temperature, the plasticity of material decreases and the trend of surface plastic side flow decreases, thereby reducing the surface roughness of the workpiece.

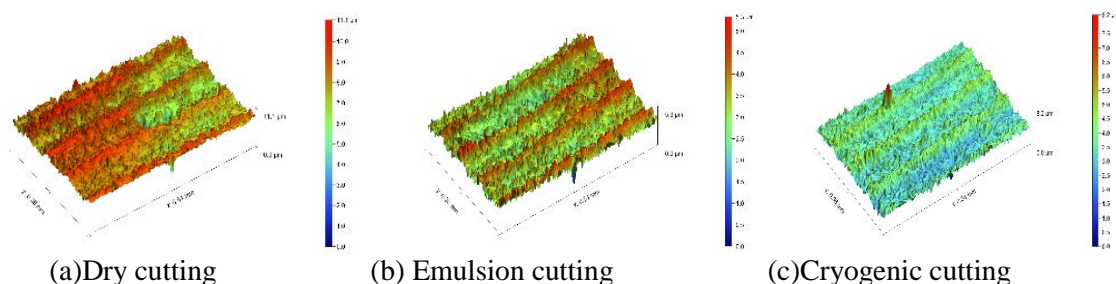


Figure 3. 3D topography of the machined surface under different cooling conditions

Figure 3 shows the 3D topography of the machined surface under different cooling conditions. In the meantime, by observing the three-dimensional topography of the surface under three cooling methods, it can be found that a lot of flash and burrs are generated in the dry cutting conditions, the surface is rough, and the surface quality is poor. In cryogenic cutting and emulsion cutting conditions, the surface quality is very good, and cryogenic cutting produces a highly polished surface.

3.2. Surface Residual Stress

Surface residual stress affects machining accuracy, dimensional stability, static strength, fatigue strength and corrosion cracking of components. During the machining, the combination of mechanical plastic deformation, thermal plastic deformation and phase transition produces the residual stress on the machined surface[10]. Figure 4 shows the influence of different cooling conditions on surface residual stress.

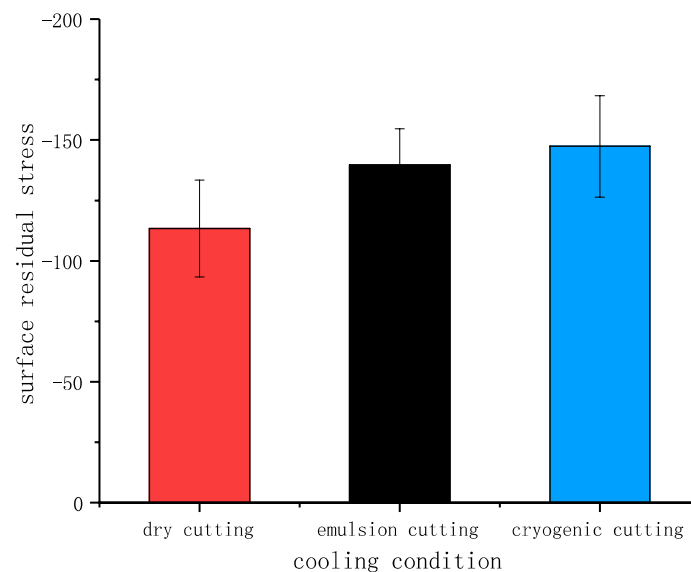


Figure 4. Surface residual stress under different cooling conditions

It can be seen from Figure 4 that all the residual stress generated by three cooling conditions is residual compressive stress, and the absolute value of residual stress generated by emulsion cutting and cryogenic cutting is greater than the absolute value of residual stress generated by dry cutting. The reason is that the cooling effect of emulsion and liquid nitrogen greatly reduces the cutting temperature, that is, reduces the tendency of thermal effect to produce residual tensile stress, so as to obtain better residual compressive stress. The cooling effect of liquid nitrogen is greater than that of emulsion, so in most cases, the inhibition effect of liquid nitrogen on residual tensile stress is greater than that of emulsion.

3.3. Microhardness

In the cutting process, because the cutting edge is not absolutely sharp, the surface material of the workpiece is plastically deformed by the effect of extrusion and friction, which results in a phenomenon that the surface layer hardness of the workpiece is strikingly improved, which is called work hardening[11]. At the same time, a certain extent of thermal softening is caused by the influence of cutting heat. Therefore, the microhardness of the surface is the result of the coupling of mechanical loads and thermal loads. Figure 5 shows the influence of different cooling conditions on microhardness[12].

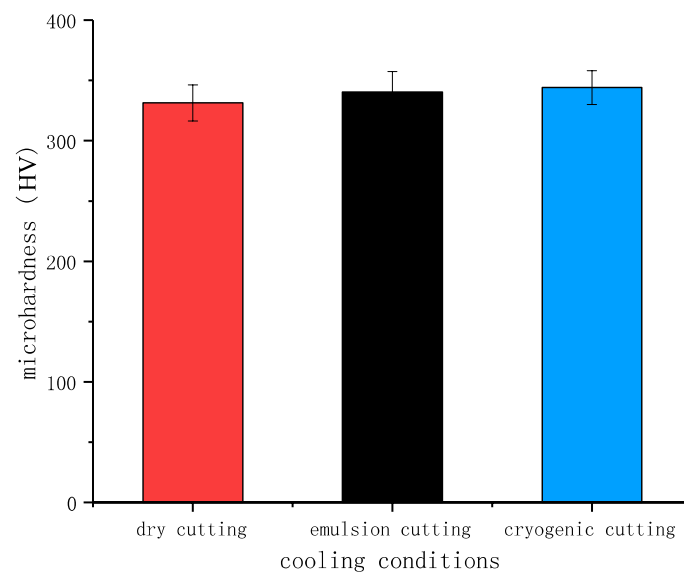


Figure 5. Microhardness under different cooling conditions

It can be found from Figure 5 that: the difference of micro-hardness of machined surface is not so big under the three cooling methods. Micro hardness produced by cryogenic cutting and emulsion cutting is slightly bigger than that produced by dry cutting, with a difference of about 10HV. The main reason is that a large amount of cutting heat is generated during dry cutting, resulting in the high cutting temperature, and the heat generated accumulates near the cutting edge, enhancing the phenomenon of machining heat softening, leading to the decrease of hardness. The cutting temperature can be reduced under the cryogenic cutting and emulsion cutting, which will inhibit the adverse influence of machining heat softening effect, and increase the micro hardness. At the same time, the literature of some scholars shows that low temperature cutting can help to keep the smaller grain size after dynamic recrystallization of materials, refine the grains on the machined surface, and improve the hardness.

4. Conclusions

According to the cutting test of TC4, the effects of cooling conditions on surface integrity under the same cutting parameters were discussed, and the following conclusions can be drawn:

- 1) Both cryogenic cutting and emulsion cutting reduce surface roughness, but cryogenic cutting has better surface roughness as its better cooling effect.
- 2) Cryogenic cutting can achieve better residual stress with its excellent cooling effect.
- 3) Cryogenic cutting and emulsion cutting effectively suppress the thermal softening effect of temperature and obtain higher microhardness.

In summary, cryogenic cutting can achieve a better machining induced surface integrity of TC4, which certainly could enhance its functional performance. Furthermore, cryogenic machining is more cleaner and sustainable, so it offers an excellent alternative processing technology for TC4 alloy.

5. Acknowledgments

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6. References

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