Analysis on Turning Ti-6Al-4V with Different Cooling Methods

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The aim of this paper is to optimize the machining of Ti-6Al-4V alloy, by studying the chip formation, roughness and tool wear for different cooling conditions. The results were compared between cooling methods, minimal quantity of fluid (MQF) and flooding, and also without fluid for the tool H13A. The turning of Ti-6Al-4V has shown good results on roughness (0,8μm) and tool life, which was 11% lower with MQF than with the flooding method. The tool wear causes variation of the shear angle, which promotes strength hardening of the chip. As a result, the machined surface could be damaged. The use of the cutting fluid helps to save the cutting edge and could reduce the strength hardening. Nevertheless, it could also facilitate the formation of built-up edge. The nucleation of alpha lamellar colonies can occur due to a combination of deformation rates and temperature, mainly when the flooding is used, but it's not conclusive. The lamellar colonies were also found with the MQF in some regions, however, this structure did not show hardness variation compared to equiaxial. For all this reasons, the machining parameters might be carefully chosen.

Keywords: *Titanium (Ti), machining, roughness, wear*

1. Introduction

The titanium and its alloys are widely used in aerospace industry due to its excellent combination of tensile strength (strength-to-weight ratio) maintained even under high temperatures, resistance to fracture and exceptional resistance to corrosion. [1]. The titanium alloy is the most common Ti-6Al-4V, which belongs to the group $\alpha+\beta$, which is responsible for more than 50% of the production of titanium alloys. The Ti 6-4, as well as it is known, has about 80% of primary alpha in its structure[2]. They are used to up to 500℃, applied in pieces such as the compressor of aircraft engines, for example. Specifically, in Ti 6-4 identify two types of evolution: the first has improved resistance to creep and the second has improved the resistance of low cycle fatigue[3].

Titanium has relatively low modulus of elasticity, thin parts exhibit the tendency of deflection with the efforts of cutting[4]. The high temperatures reached during the cutting of the material they promote great fall of the hardness of the tool, which causes plastic deformation and thus great wear of cutting tool.

In addition, the low thermal conductivity of the material also has decisive influence, because 80% of the heat generated is concentrated in the material of the tool is only 20% in the chip. Thus, the thermal conductivity is characterized as another important factor in the life of the cutting tool[1].

As to the effect of the use of cutting-fluid, the lubricant acts by preventing or even limiting the micro-welding places that occur due to the high pressure and high temperatures in the interface chip-tool. The strength needed to break this micro-welding and friction force, an important source of heat in the process.

Its drastic reduction or even complete elimination, will certainly cause a temperature rise in cases falling income of the cutting tool, loss of dimensional accuracy and part geometry, enhanced content of particulates in the atmosphere, warm chips with higher difficulty of acquiring suitable format, increased risk of welding and thermal behavior in the machine[5].

The MQF consists of a small amount of water soluble oil and compressed air are applied directly on the cutting edge. Lubrication allows less pressure on the tool chip interface, and reduces abrasion and components of forces generated during machining. The decrease in temperature in the cutting area is derived mainly from the cooling effect of both the air and by partial evaporation of the lubricant[6].

Flank wear, crater wear, notch wear, chipping and catastrophic failure are the main failure modes of the tools in machining of titanium alloys. The first two are the result of dissolution and diffusion at the interface part-tool and chip-tool, attrition and plastic deformation depending on cutting conditions and tool material. Since the notch wear is primarily caused by a fracture process and/or chemical reactions[1].

There are two prevailing theories about the formation of chip: a thermoplastic instability and the onset of crack propagation within the primary shear zone of the workpiece material. The morphology of titanium chip is due to plastic instability during the cutting process, the result of competition between thermal softening and hardening in the primary shear zone[7]. Already, chips saw-tooth is the result of cracks that start at the chip free surface and propagate from the tip of the tool[8,9].

2. Materials and Methods

The tests were performed on a CNC lathe Romi Centur 30S, 10 kW power, the cutting parameters were: cutting speed of 110 m/min, feed rate 0.1 mm/rev and cutting depth of 0.5 mm. The tests were performed machining with three types of cutting tools supplied by SANDVIK Coromant both VBMT 110204-UF ISO geometry (Table 1). As an end tool life it used the maximum flank wear VB=0. 6 mm. The tool holder used for fix the insert was SVJBR-220K11.

Table 1. Material, characteristics and code of cutting tools

Material Class	Characteristics	Code
SANDVIK H13A ISO S15	Uncoated cemented carbide	H13A
SANVIK GC 4225 ISO M25	Coated cemented carbide (CVD)	4225
SANDVIK GC1025 ISO S25	Coated cemented carbide (PVD)	1025

At the end of each test were measured in surface roughness of machined parts using a roughness tester Mitutoyo SJ301 Surftest with mechanical type probe and stylus tip radius of 5 μm.

The obtained chips were prepared for metallography, this preparation being done in stages: sanding with sandpaper water 400 μm, 600 μm, 1200 μm and 1500 μm, immediately after sanding, polishing was done on samples of alumina solution (1. 0 μm), and etching with an aqueous 10% HF and 5% HNO_3.

The analysis of the tools was performed in a Zeiss stereomicroscope Stemi 2000 with SPOT Insight QE camera attached to 32x, 40x and 50x, were shot out of the rake and flank face of each cutting tool. The microscopic structure of the chips was performed in an optical microscope NIKON NEOPHOT 21, equipped with Carl Zeiss camera with 250x magnification for chips machined with abundant fluid and 200x for chips MQF. It was also used for some chips MQF EPIPHOT 200 NIKON Microscope with 200x magnification, and camera AxioCam ICc3 of Carl Zeiss.

3. Results and Discussion

Figure 1 shows the values of the roughness as a function of tool life in 1025, it is possible to observe the condition of MQF machining results in lower roughness (about 1. 0 μm) with the life time of 1. 44 min. When the 1025 tool is used in the machining fluid in abundance, on his first pass already shows roughness higher, with end of life of 2. 20 min. at a level of roughness of 3. 3 μm. In the Figure 1 is shown the comparison between life in 4225 with abundant fluid and MQF. In the first case, the tool has reached end of life in the first pass (1. 15 min.), reaching the surface roughness of about 1. 6 μm, more than double the theoretical roughness. In this light, the feed length has been reduced from 115 mm to 70 mm, again, that was held with the machining MQF. Here, the roughness remained in the range between 0. 8 μm and 1. 0 μm and tool life was slightly higher (1. 26 min.). Figure 1 depicts the relationship between roughness and tool life for H13A. This tool achieved a longer life for the two methods, in MQF machining, the roughness levels remained in the range between 0. 6 μm and 0. 8 μm always below the theoretical roughness and tool life was 5. 78 min. . For the machining fluid in abundance, the roughness was maintained between 0. 8 μm and 0. 9 μm up to 6. 44 min. , when there was a large increase in roughness, depending on the deterioration of the cutting edge. At 7. 23 min. reached end of life with high roughness (1. 6 μm).

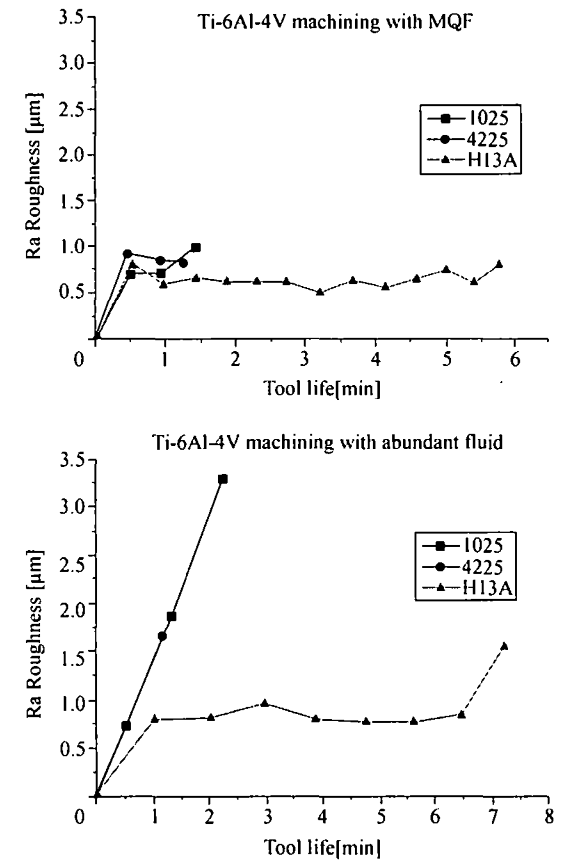

Figure 1. Graphics of Ra roughness in function of tool life for MQF and abundant fluid conditions

Figure 2 shows photographs of cutting tools at the end of the test situation. In both types of cooling are noticeable wear in a large emitting surface, probably due to the affinity of coverage (TiN) with titanium at high temperatures. Also there was a large surface wear off and it is interesting to note that there is formation of built-up edge cutting tool in both 1025 MQF (Figure 2(a)) and with abundant fluid (Figure 2(c)). This can speed cutting and chemical reactivity with the material of the tool that promote the adhesion of material, as indicated by the arrows in Figure 2(b).

The chips generated by the 1025 tool (Figure 3) show some significant differences. Taking into account the type of refrigeration for the initial condition (Figure 3(a) and 3(c)), note that in the chip where it was applied fluid in abundance, the shape of the grains are more elongated, with variations in its direction of training, while the format the grain of chips obtained with minimum amount of fluid present predominantly equiaxial grain.

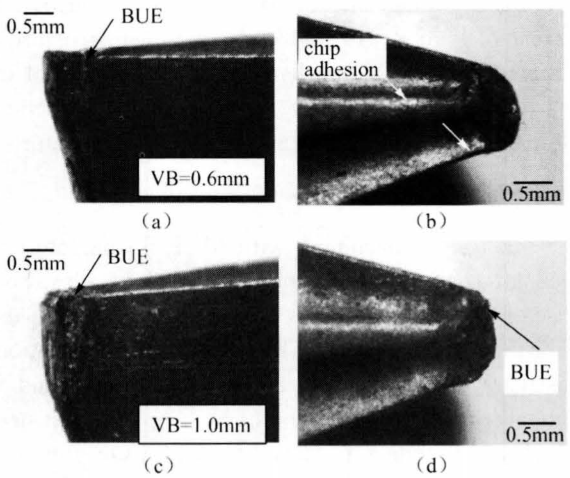

Figure 2. Aspects of tool wear for 1025 tool: (a) and (b) under MQF condition (c) and (d) under abundant fluid condition

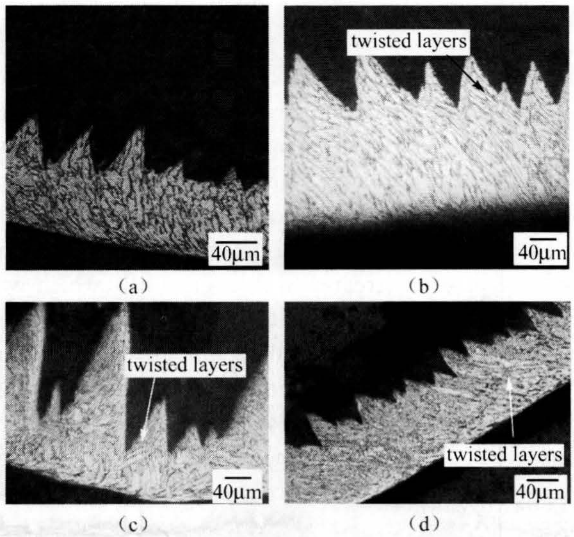

Figure 3. Aspects of chips by 1025 tool: MQF (a) initial cutting and (b) final cutting; abundant fluid (c) initial cutting and (d) final cutting

In the chip of Figure 3(a) and 3(b), a decrease of the angle of shear during the process, probably due to the formation of built-up edge cutting. For Figure 3 (c), the colonies were formed near the shear bands with primary and secondary shear bands, where the temperature and deformation are higher.

It is observed in Figure 4(a) and 4(c) that for the 4225 tool, flank wear was more regular with MQF, compared to the flank wear on the tool with fluid in abundance. This can be attributed to the shorter feed length used, the difference in friction coefficients of each situation and also the hardening of the machined surface. For l 4225 too (Figure 4(b) and 4(d)), both in machining and MQF fluid in abundance is observed in the cratering cutting tool. The formation of craters occurs by atomic diffusion that occurs at high temperatures, when there are materials with high chemical affinity.

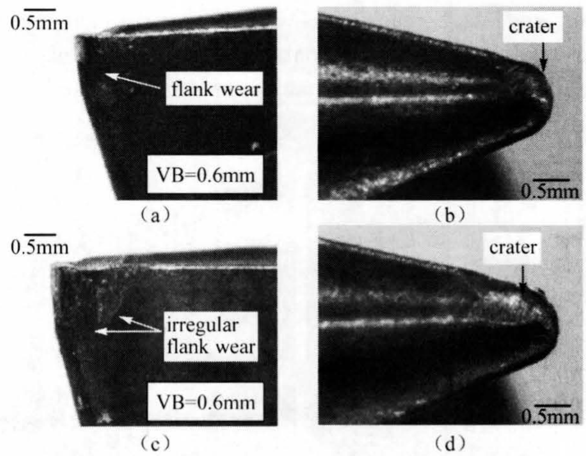

Figure 4. Aspects of tool wear for 4225 tool: (a) and (b) under MQF condition (c) and (d) under abundant fluid condition

For chips from 4225 tool (Figure 5), when comparing the two methods of cooling can be observed in Figure 5d elongated grains, whose chip with abundant fluid obtained with twisted lamellae microstructure and equiaxal grains (Figure 5(a), 5(b) and 5(c)) under MQF, where is possible to make a comparison between the tests and the different deformation levels.

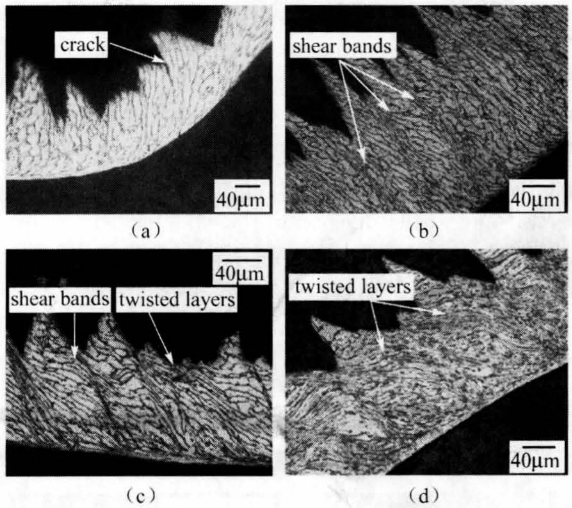

Figure 5. Aspects of obtained chips by 4225 tool: (a) under MQF and initial cutting situation; (b) and (c) both under MQF final cutting situation; (d) under abundant fluid and final cutting situation

In the Figure 5(a) it may notice a few shear bands and observe the formation of irregular chips. There is also a spread of microcracks in the shear bands of a segment, as indicated by white arrow. The presence of cracks propagating in the phase boundary between phases α and β suggests that there is a tendency to intergranular fracture in this case. In Figure 5(c) has a chip with very intense shear bands, and even an area with twisted lamellae. Such areas may have been obtained by recrystallization in colonies, as occurred in the chip generated in abundant fluid in the 1025 tools. Possibly due to tool wear, temperature and strain rate caused some regions also present this pattern in chips obtained by MQF.

Figure 6 presents the H13A tools for fluid abundant and MQF machining, which showed much lower levels of stress when compared to the others. This can be attributed to its great abrasion resistance and less chemical reactivity.

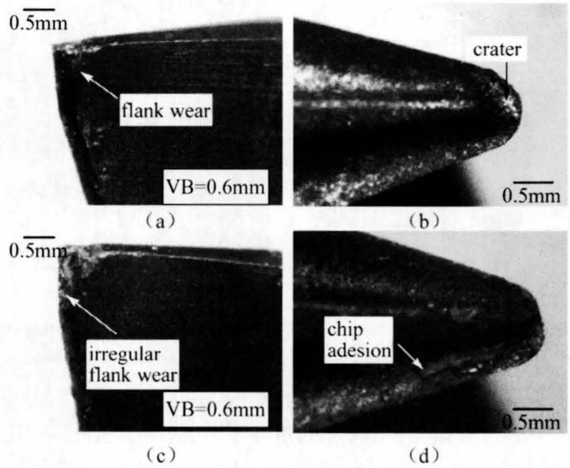

Figure 6. Aspects of tool wear for H13A tool: (a) and (b) under MQF condition (c) and (d) under abundant fluid condition

In Figure 6(b), which was used tool in the MQF, there was a significant crater wear, and may also be seen in Figure 6(a). In Figure 6(d) for the tool in which fluid was used in abundance there was no significant deterioration in the rake face. However, there are chips adhered to the rake face, one possible explanation for this is that the existence of fluid in abundance may have reduced the friction at chip-tool interface, so there was no significant adhesion to the rake face. Therefore, the MQF extended tool life in terms of flank wear, but did not prevent the wear crater evolve.

Figure 7 shows the images of the chips obtained for the two conditions in the early and later tests stage. In MQF with initial condition, shown in Figure 7 (a) show the grains strongly elongated, so the angle of shear in this case was minor

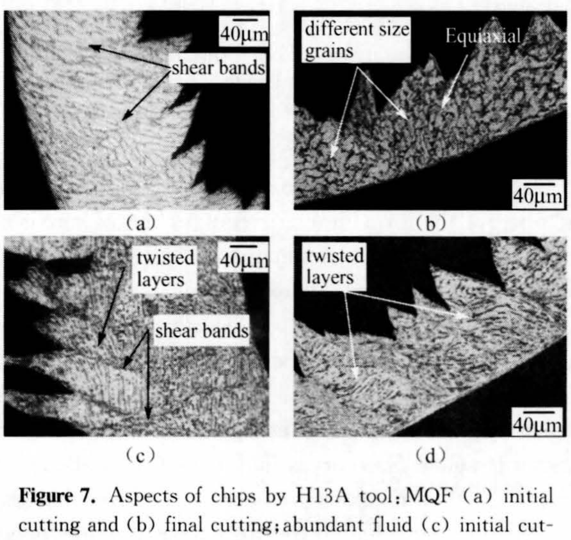

Figure 7. Aspects of chips by H13A tool: MQF (a) initial cutting and (b) final cutting; abundant fluid (c) initial cutting and (d) final cutting

There was some spread of micro-cracks in the α grains, due to the high degree of deformation of the chip. The chips of the last test MQF (Figure 7(b)) apparently showed less shear angle, and consequently a lower degree of deformation, the structure is equiaxal. In the chip of Figure 7(c) and 7(d), the microstructure is composed primarily of lamellar twisting. The action of the fluid probably induced the formation of these structures due to the higher strain rate and the lower temperature.

4. Conclusions

The use of machining with MQF is characterized as an alternative to machining of titanium alloys, because of several advantages of the economy in the use of cutting fluid. However, the dimensional variations caused by tool wear with respect to cutting fluid in abundance, and the formation of built-up edge-cut need to be further studied. In fact, the use of MQF decreases the friction between the workpiece and machining tool with respect to the abundant fluid interfaces by achieving chip-tool and piece-tool with ease. This is due to the higher pressure at which the fluid is applied.

It was noted that the application of cutting fluid in large quantities leads to the formation of a microstructure different from dynamic recrystallization, with elongated grains and deformed in most cases perpendicular to the direction of the primary shear bands. Such chips have reached a higher level of deformation, in general, which may be related to the greater range of cutting fluid, and also the greater feed length (Lf), which was used for the machining fluid. With a higher feed length, it is likely that the heat generated in machining is greater, and the combination with high levels of deformation promoted the recrystallization of the microstructure of thin lamellae and twisted.

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