Research on Effect of Cryogenic Coolants on Machinability Characteristics in Machining Ti-6Al-4V

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Abstract: In this research, Ti-6Al-4V was machined under dry cutting conditions and cryogenic cooling environment, on cutting tool and workpiece material, surface performance, and cutting force were studied. However, all cases observed a positive influence of cryogenic machining on selected aspects after turning Ti-6Al-4V. Turning process is carried out for five different cutting speeds (35, 40, 55, 70, 80 m/min) while 0.15 mm/rev cutting feed out and 0.5 mm cutting depth are to be constant. It was found that Cryogenic cooling can decrease cutting temperatures, increase tool life, improve the roughness of the cutting surface and the residual stress of the surface, improve the wear resistance and corrosion resistance of the cutting surface.

1. Introduction
Titanium alloy (Ti-6Al-4V) is widely used in aerospace, automobile manufacturing due to high specific strength, good corrosion resistance and low density [1, 2]. However, due to the low thermal conductivity of titanium alloys, the heat generated during the cutting process is not easily transmitted [3], the temperature in the cutting area increases, and the tool wear is rapid, leading to an increase in the cost of titanium alloy. This will affect the residual stress on the machined surface of the workpiece and the machined surface quality of the workpiece.

The most effective way to improve the machining performance in cutting materials is to reduce the cutting temperature. There are some methods to decrease the cutting temperature and the cutting force.

One way is to add the fluids liquid during the cutting process. The main purpose of adding cutting fluids between the tool, chip, and workpiece in metal cutting is to reduce the cutting temperature.

Cryogenic cooling technology application in machining operation plays an essential role in the cutting industry. Cryogenic cooling can increase tool life, decrease cutting temperatures, reduce the roughness of the cutting surface and the residual stress of the surface, improves the wear resistance and corrosion resistance of the cutting surface. DHAR et al. [4] studied the cooling in high cutting speed turning of aisi4037 steel. The results showed that liquid nitrogen could reduce the cutting temperature by more than 10%. Pereira et al. [5] investigated cryogenic cooling on a turning machine of asp23 high-speed steel bar. It showed that the tool life increased more than 60%. Elanchezhian et al. [6] carried out an experiment on Ti6Al4V alloy with a grinding wheel under different cooling conditions. Due to the significant reduction of processing area temperature, the surface roughness of liquid nitrogen cooling grinding was reduced by 38%.
The main objective of the present work is to experimentally investigate the effect of cryogenic cooling with liquid nitrogen (-196 °C) on cutting forces and surface roughness during turning Ti-6Al-4V.

2. Experimental setup and procedure

Machining experiments were carried out cak3665 CNC lathe; as shown in Fig.1, the maximum speed of the spindle can be set up to 3000r/min. The workpiece specimens were in the form of round bar of 14 mm diameter and 200 mm long. The material used through this work was Ti-6Al-4V. The cutting tools used in the experiment were cemented carbide CCGT 09T3040UMH13A, the back angle of the tool is 7° and the rake angle of the tool is 0°, the radius of the arc is 0.04mm. The chemical composition and the mechanical and thermal properties of Ti-6Al-4V workpiece materials used in the experiments are shown in Tables 1 and 2. Liquid nitrogen is stored in a high-pressure cylinder (DURA-CYL 160 HP self-pressurized cylinder, CHART Industries, MVE model) with a security value. The pressure gauge and valve can help to detect and control the pressure. A high vacuum insulated pipe carries the liquid nitrogen from the cylinder to the cutting zone. The position and the direction of the nozzle (diameter of 3 mm) concerning the cutting zone were optimized after several rough turning trials. Under cryogenic cooling, LN2 is passed on the cutting zone by a nozzle at 20 bar pressure, as shown in Fig.1.

Table 1 Chemical composition of titanium alloy Ti-4AL-6V workpiece (mass fraction, %)

|   | Ti | Al | V | C  | Fe | O    | N   |
|---|----|----|---|----|----|------|-----|
| Bal| 5.5-6.8| 3.5-4.5| ≤0.1| ≤0.3| ≤0.2| ≤0.05 |

Table 2 Physical and thermal properties of Ti-4Al-6V workpiece.

|                  | Hardness (HB) | Tensile strength (RM) | Yield strength (Ry) | Elongation (%) | Modulus E Gpa | Shear strength | Poisson's ratio (v) |
|------------------|---------------|-----------------------|--------------------|----------------|---------------|-----------------|--------------------|
|                  | 320           | 920MPa                | 860MPa             | 10%            | 108           | 760MPa          | 0.33               |
Table 3  Machining parameters and their levels.

| Level | Cutting condition  | Cutting speed (m/min) |
|-------|--------------------|----------------------|
| 1     | Dry cutting        | 35                   |
| 2     | Cryogenic cooling  | 40                   |
| 3     |                    | 55                   |
| 4     |                    | 70                   |
| 5     |                    | 80                   |

3. Results and discussion

3.1. Cutting force

Fig. 2 shows the plot of cutting force versus cutting speed in the cryogenic and dry cutting conditions. The turning process is carried out in five different cutting speeds while 0.15 mm/rev cutting feed rate and 0.5 mm cutting depth under dry turning and cryogenic cooling conditions as shown in Table 3. The results show that cutting force is found to decrease with cutting speed increases in both machining conditions. The feed force $F_x$ in liquid nitrogen under cryogenic cooling ranged from 64 N to 89 N compared with 68 N to 94 N in dry turning. The main cutting force $F_z$ ranged from 182 N to 210 N in the cryogenic cooling compared with 170 N to 197 N in dry turning. The cutting $F_Y$ was ranged from 88 N to 103 N compared with 79 N to 98 N in dry turning. The change of $F_Y$ and $F_Z$ versus cutting speed in cryogenic are greater than those in dry cutting, parallel to the data obtained by some researchers [7,8].

Titanium alloy has high chemical activity due to the thermal conductivity of titanium alloy is very small. Cryogenic machining tends the cutting heat generated in the cutting area resulting in significant-high temperature, which increases the hardness of the titanium alloy.

Figure 2  Measured cutting force vs. cutting speeds in cryogenic and dry milling: (a)$F_X$; (b)$F_Z$; (c)$F_Y$ force.
3.2. Surface roughness
The roughness can affect the machined surface’s wear resistance, corrosion resistance and affect the fatigue strength. Roughness can also affect the residual stress on the machined surface of the workpiece and the machined surface quality of the workpiece [9]. It is important to study the effect of liquid nitrogen cooling and cutting parameters on the surface roughness, which can help to explore the methods to improve the surface properties of Ti-6Al-4V workpieces. Machining experiments were carried out on surf test SJ-410 roughness tester. In order to reduce the error of test data, different cutting parameters were selected, and the average of the different points is taken as the effective date of the surface roughness measurement results.

Fig. 3 and table 4 show the value of surface roughness (Ra) during turning Ti-6Al-4V with cemented carbide cutting tool insert under dry turning and cryogenic cutting conditions. It was showed from the experimental results; the roughness values decreased with the increased cutting speed in both dry and cryogenic conditions. Ra value in Fig. 4 for the 0.5 mm cutting depth, feed rate of 0.1 mm/rev, and carried out cutting speed of 55 m/min under cryogenic cooling was 2.205 µm. Ra value at the same cutting conditions was 2.934 in dry turning. Ra value showed with cryogenic cooling provided 28% improved in roughness value compared to dry turning. Under cryogenic cooling was found by about 8% 28% reduction and improved surface roughness values over dry turning. This is because cryogenic cooling reduces the cutting temperature at the cutting zone, lower cutting forces, and no weld adhesion of the chip.

Table 4  Surface roughness (Ra) value with changing cutting speed.

| Cutting speed $V_c/(m/min)$ | Ra/µm | % Change in Ra |
|---------------------------|-------|----------------|
| Dry cutting               |      |                |
| 35                        | 3.150 | 2.904          | 8               |
| 40                        | 2.862 | 2.348          | 18              |
| 55                        | 2.934 | 2.105          | 28              |
| 70                        | 2.259 | 1.764          | 22              |
| 80                        | 1.832 | 1.394          | 23              |

| Cryogenic cooling         | Dry cutting |

Figure 3  Surface residual stress diagram of workpiece.
3.3. **Chip morphology**

During the cutting process, chip breaking can cause many problems, such as damage to the machined surface and tool wear. The most common way to improve chip breaking is to select the tool parameters that are easy to chip breaking and use the chip breaking groove. Cryogenic cooling can change the material’s mechanical properties, thus changing the chip breaking effect in the cutting process. To study the effect of low-temperature cooling on chip breaking effect, Ti-6Al-4V workpiece was machined under cooling conditions compared with dry.

Fig.4 shows the chip breaking while turning Ti-6Al-4V with cemented carbide cutting tool insert under dry turning and liquid nitrogen cooling. It can be seen from the chip shape comparison in Fig.4(a-b) was evident that there is a reduction in primary serrated teeth, secondary serrated teeth.

Fig.4(a) shows the chip formed in dry cutting of Ti-6Al-4V. The chip shaped in dry cutting is a long chip, which is not easy to break. The long-curved chip is easy to wrap on the tool; it can destroy the machined surface and affect surface integrity after cutting. The low temperature using liquid nitrogen has a more significant effect on chip form due to reducing the adhesion between the tool and chip. Fig.4(b) shows the chip formed in cryogenic cooling. The chip shape obtained by low temperature under liquid nitrogen is obviously different from the dry cutting conditions, and it is a relatively short chip. When the cutting speed is high in liquid nitrogen cooling, the chip breaking is still very smooth.

![Figure 4 Chip morphology under cooling conditions comparison with dry](image_url)
4. Conclusion
The turning operations of Ti-4Al-6V with cemented carbide cutting tool insert were performed under dry turning and liquid nitrogen as a coolant in cryogenic turning. The main conclusions are as follows:

1. Cutting force decreases with increasing cutting speed. However, the main cutting force increases, but the feed force has a more significant reduction, which is conducive to improving the stability of the process system. The change is more obvious, when cutting speed exceeds 40m/min.

2. The cryogenic application using liquid nitrogen was found by about 8% – 28% reduction in surface roughness values over dry turning.

3. In dry cutting and cryogenic cooling conditions, the low temperature under liquid nitrogen can effectively reduce the ductility of the chip since it is smooth and easy to break.

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