The effect of different MQL supply strategies into the cutting zone on the tool wear when turning of Ti-6Al-4V alloy

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Abstract. Titanium alloys, especially Ti-6Al-4V alloy, are widely used in industry due to their good mechanical properties, such as high specific strength and excellent corrosion resistance. However, titanium alloys are also difficult-to-cut materials. Metalworking fluids are employed in the machining process to improve the machinability of titanium alloys. In recent years much attention has been paid to the use of the minimum quantity lubrication (MQL) techniques in the machining of the titanium alloys. In this study, the tool wear and its influence on the components of cutting forces have been investigated for different MQL supply strategies into the cutting zone - MQL via external nozzle and MQL via tool holder were investigated. The obtained results were compared with dry turning. It was concluded that the mechanism of tool wear is very similar for each cutting condition, however, it was also noted that the tool life is 28% and 68% longer for the MQL via external nozzle and MQL via tool holder, respectively, compared with the dry cutting conditions.

1. Introduction

Titanium alloys are often used in the aerospace industry, the chemical industry, and medical engineering primarily due to their two properties: high specific strength and excellent corrosion resistance [1]. However, the same properties make them also difficult-to-cut materials. The main problems in the machining of the titanium alloys are intensive tool wear and high cutting temperatures, which can reach beyond 1000°C at the tool-chip interface, due to low thermal conductivity and high chemical reactivity [2,3].

In order to improve the machinability of titanium alloys metalworking fluids are utilized in the machining process. The most common method of transfer of the heat generated during the cutting process is flood cooling. However, the conventional metalworking fluids are non-biodegradable and toxic in nature [4,5]. On the other hand, dry machining shortens the tool life especially in high-speed cutting [6]. Therefore minimum quantity lubrication (MQL) techniques are used to reduce friction at the tool-chip and tool-workpiece contact zones and results in lower cutting temperatures [5]. In the MQL technique, a small quantity of lubricant is supply into the tool-workpiece interface by a compressed air flow [7].

Raza et al. [8] compared the effect of six different cooling and lubrication strategies on the tool wear during turning of Ti-6Al-4V. The uncoated carbide cutting tool was used. The following cutting
conditions were evaluated: dry machining, flood cooling, cryogenic machining (with liquid nitrogen), cooled air lubrication, vegetable oil MQL machining, and vegetable oil + cooled air / MQCL machining. It was found that the MQL and MQCL technique with the use of vegetable oil could be a sustainable alternative to synthetic cooling in terms of tool wear and surface roughness.

Rahim and Sasahara [7] investigated the tool wear and surface integrity during drilling of Ti-6Al-4V alloy in dry and MQL cutting conditions. For the MQL tests, the synthetic ester and palm oil were used. It was found that the tool life increased by 306% in comparison to dry cutting. It was also found that the implementation of the MQL technique improved the thrust force and torque and thus reduced power consumption.

Rahim and Sasahara [9] investigated the effect of palm oil as MQL lubricant in high-speed drilling of Ti-6Al-4V. The effects were compared to the air flow, MQL with synthetic ester and flood conditions. The MQL with palm oil and synthetic ester exhibited comparable performance with the flood conditions and much better comparing with dry cutting in the term of tool life. The cutting forces for MQL with palm oil were lower than that produced in MQL with synthetic ester and almost equal to the flood conditions.

Deiab et al. [10] analyzed the tool wear, energy consumption, and surface roughness during turning of Ti-6Al-4V under six different cutting conditions: dry machining, flood cooling, cooled air lubrication, vegetable oil MQL machining, cryogenic machining, and vegetable oil + cooled air / MQCL machining. The cold-pressed rapeseed oil was used for the MQL and MQCL cutting conditions. It was found that the vegetable oil as a lubricant in MQL and MQCL technique is a sustainable alternative to synthetic cooling in terms of tool wear, cutting energy consumption, and surface quality.

Khan and Maity [11] investigated the influence of cutting conditions on the cutting forces, tool wear, friction coefficient, chip morphology, and surface roughness during turning of commercially pure titanium (CP-Ti) grade II. The cutting conditions selected for the test were dry cutting, flood cooling, and MQL with vegetable oil. Under MQL machining the tool wear was lower by 57% and 34% comparing with dry and flood conditions, respectively. Also, the cutting force was lower for the MQL cutting in comparison to dry and flood cutting conditions (46% and 16%, respectively).

The aim of the study was investigation of the effect of different MQL supply strategies on the tool wear when turning of Ti-6Al-4V. MQL via external nozzle and MQL via tool holder were analyzed. Moreover, changes in the cutting force components as a result of blade wear were determined. The obtained results were referenced for dry turning.

2. Materials and methods
The Ti-6Al-4V alloy was used as the workpiece material in this study. The mechanical properties are given in the Table 1.

| Table 1. Mechanical properties of Ti-6Al-4V alloy |
|-----------------------------------------------|
| Density, kg/m³ | 4430 |
| Young’s modulus, GPa | 114 |
| Poisson’s ratio | 0.33 |
| Ultimate strength, MPa | 1170 |
| Yield strength, MPa | 1100 |
| Melting point, °C | 1660 |
| Thermal conductivity, W/(m·K) | 6.7 |

The machining tests were conducted on the NEF 600 lathe. The cutting insert and tool holder used for the tests were VBG160404-M3 HX and SVJBL2525M16 JET, respectively. Values of cutting
The cutting parameters were as follows: cutting speed $v_c = 120$ m/min, feed $f = 0.1$ mm/rev, and depth of cut $a_p = 0.25$ mm. Table 2 summarizes the experimental setup and cutting parameters.

**Table 2. Experimental setup and cutting parameters.**

| Component           | Description            |
|---------------------|------------------------|
| Workpiece material  | Ti-6Al-4V              |
| Machine             | NEF 600 lathe          |
| Cutting tool        | VBGT160404-M3 HX       |
| Tool holder         | SVJBL2525M16 JET       |
| Cutting speed, m/min| 120                    |
| Feed rate, mm/rev   | 0.1                    |
| Depth of cut, mm    | 0.25                   |

The tests were conducted in two different MQL supply strategies into the cutting zone: MQL via external nozzle (Figure 1), and MQL via tool holder (Figure 2), where the mist was supplied on the rake face of the cutting tool. The obtained results were compared with dry cutting. The cutting fluid used in the MQL was a mixture of 46% of eco-friendly vegetable oil, 46% of diester, 4% of extreme pressure (EP) / anti-wear additives, and 4% of antistatic agent. The volume flow of the cutting fluid was set up at 30 ml/h and the air pressure was set up at 0.7 MPa.

![Figure 1. Configuration of the test stand for the cutting with MQL via external nozzle.](image)
Figure 2. Configuration of the test stand for the cutting with the MQL via tool holder.

Kistler 9257B piezoelectric three-dimensional dynamometer was used to measure of the components of cutting forces. The dynamometer was mounted on the turret of the lathe machine by a VDI holder.

3. Results

3.1. Tool wear

The wear of the cutting tool was measured for specific volumes of material removed until the wear criterion was reached. The wear criterion was 0.2 mm of flank wear - VB indicator. In Table 3, the volumes of the removed material of the workpiece for reaching the tool wear criterion for different MQL supply strategies and dry cutting were presented.

| Volume of removed material, cm³ |
|---------------------------------|
| MQL via external nozzle         | 37.11 |
| MQL via tool holder             | 48.63 |
| Dry cutting                     | 28.97 |

Figure 3 shows the tool wear in the function of the volume of removed material for MQL via external nozzle, and MQL via tool holder and dry cutting conditions.

The use of MQL cooling during finish turning of the Ti-6Al-4V alloy reduced the intensity of the cutting tool blade wear when compared to dry machining. The presence of the lubricant in the cutting zone causes a decrease of the coefficient of friction between tool-chip and tool-workpiece interfaces and therefore the tool life was extended. However the better results were achieved with the application of the MQL via tool holder. In this case, a more precise supply of the lubricant allowed more lubricant to go directly into the cutting zone.
3.2. The influence of the tool wear on the cutting forces

Figures 4 and 6 show relationship of the cutting force in the function of the tool wear VB for MQL via external nozzle and MQL via tool holder cutting conditions, respectively. Figures 5 and 7 present the wear on the flank face respectively, for the same cooling strategies, for the points 1-4 marked at the graphs (Fig. 4, 6).
Figure 5. Photos of the cutting insert at different points of tool wear for MQL via external nozzle.

Figure 6. Cutting force in the function of tool wear VB for MQL via tool holder.
Figure 7. Photos of the cutting insert at different points of tool wear for MQL via tool holder.

In the case of dry machining, a similar relationship of the cutting force in the function of the tool wear VB was observed to that of MQL (Fig. 8). However, research has shown a greater tendency of the workpiece material to adhere to the rake face and flank face of the cutting insert (Fig. 9).

Figure 8. Cutting force in the function of tool wear VB for dry cutting conditions.
It was observed that in the initial stage of machining, the main cutting force $F_c$ is the largest component of the total cutting force. The progressive wear of the tool causes an intensive increase of the passive force $F_p$. With wear at the level of $VB = 0.16$ mm, the passive force becomes dominant, which is unfavorable due to the tendency of titanium alloys to strengthening. For the cutting with the MQL via tool holder the cutting force components values are slightly smaller than for the dry machining and MQL via external nozzle. This is most likely due to the fact that directing the oil mist on the rake face under the chip formed reduce the contact surface of the chip to the cutting tool and therefore reduce the values of cutting force components. Moreover, for each tool wear value the cutting force components values were very similar for analyzed cutting condition.

4. Conclusions
The effect of different MQL supply strategies into the cutting zone on the tool wear and cutting forces has been studied when finish turning of Ti-6Al-4V. MQL via external nozzle and MQL via tool holder were analyzed and referenced with dry cutting. The following conclusions can be drawn:

- Volume of the removed material was 28% and 68% bigger for the MQL via external nozzle and MQL via tool holder, respectively, compared with the dry cutting conditions.
- At the basis of the measurements of the cutting forces and tool wear value it can be said that the mechanism of tool wear is similar for all analyzed cutting conditions.
- Above the tool wear of about 0.16 mm the passive force becomes dominant components of the cutting force.

In conclusion, it can be said that the MQL via tool holder provides the best results from the tested strategies in the term of tool wear.

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