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On the analysis of chip shaping after finishing turning of Ti6Al4V titanium alloy under dry, wet and MQL conditions

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ABSTRACT

The shape and type of chip give general information about the cutting process. This paper presents the results of testing the shape and type of chips of Ti6Al4V titanium alloy after it finishes turning. The process was carried out under dry, wet and MQL (Minimum Quantity Lubrication) conditions at variable cutting speeds and feed rates and a constant depth of cutting. For planning the tests, the PSI (Parameter Space Investigation) method was used, which allows the experiment to be carried out while minimizing the number of experience points. It was found that the cutting speed and feed affect the type and shape of the chip, and clear differences were observed between dry and wet cooling conditions, and MQL conditions. During turning, the intensity of the cutting speed and feed influence on the chip compression ratio was changed. It was similar for dry and wet cooling conditions but smaller for MQL conditions. The purpose of this research is to analyze the chip shaping when Ti6Al4V titanium alloy finishes turning under dry, wet and MQL cooling conditions.

1. INTRODUCTION

Metals and their alloys play an important role as biomaterials used in reconstructive surgery, especially in the field of orthopedics. The materials used in medicine include stainless steels, titanium alloys, cobalt based alloys, magnesium alloys. 316L stainless steel, CoCrMo alloy, Ti6Al4V titanium alloy are commonly used materials [1].

Ti6Al4V titanium alloy has favorable mechanical properties, and in the human body environment it exhibits inert properties and very good corrosion resistance, that makes it a biocompatible material [2,3]. This material is characterized by low thermal conductivity, low modulus of elasticity and high chemical reactivity. The properties of the Ti6Al4V titanium alloy cause that during cutting a high temperature occurs in the cutting zone, which contributes to faster wear of the tool and adversely affects the quality of the surface machined. Therefore, low cutting speeds are usually used when turning [4-6]. Although the Ti6Al4V titanium alloy is a widely known material, it belongs to the difficult-to-cut materials group with a complicated process of chip formation [7-9].

The process of chip formation when titanium alloys turning attracts a lot of interest in the world of science, and difficulties in processing these materials caused that modeling and simulating studies are carried out [7,10-13], as well as experimental researches. In machining processes, the shape and type of chips contain detailed information about the physical mechanisms, as well as the cutting process and workpiece features. However, chip geometry and dimensions are usually difficult to measure and evaluate. Typically, the chip arrangement and chip morphology provide information on the material's machinability in the cutting process. The geometry of titanium alloys chips depends on the cutting parameters. The largest differences in chip geometry occur at high feed rates as well as at increased cutting speeds [14]. The methodology characterized the chip in the process of turning Ti6Al4V titanium alloy in dry conditions was presented and the influence of cutting speed and feed on the change of its geometry was analyzed. A smaller feed value reduces the chip length. On the other hand, the higher feed

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value promotes the occurrence of the serrated shape of the chip. The largest geometric differences occur in the case of chips obtained with higher feeds, and increasing the distance between the top and the valley of the chip was observed at increased cutting speed.

In [15], turning of the Ti6Al4V titanium alloy was carried out under dry conditions and cryogenic cooling. The use of cryogenic cooling provided better performance, reduced tool wear, improved machined surface quality and increased chip breakage compared to dry machining.

In turn, in [16] the phenomenon of shaping the chip when Ti6Al4V titanium alloy turning process under high-pressure cooling was investigated. An increase in the intensity of the occurrence of the serrated shape of the chip and its average thickness was observed in relation to traditional cooling. In addition, the use of high-pressure cooling reduced the chip size and the better surface quality of the material being processed.

In [17], the conditions for heat exchange outside the contact zone were considered. Under these conditions, it is not possible for the chip to contact the rake surface. The use of nanofluids facilitated the formation of fragments of continuous chips with a smaller radius of curling thanks to the reduction of the temperature gradient. This was confirmed in [18], where dry machining of Ti6AL4V resulted in a high frequency of chip breaking, and the use of nanoliquids facilitated the creation of semi-continuous and less coiled chips.

In [19], Ti6AL4V titanium alloy was turned under three different cooling and lubrication conditions: dry, wet and MQL. The analysis of the influence of the type of cooling and lubrication on tool nose wear and surface roughness was fulfilled. During dry machining the wear of the rake face was greatest, while during wet and MQL turning, larger differences in wear of the flank were observed. Due to the increase of serrated chips caused by the machining fluid, changes of cutting forces values were observed, which resulted in vibrations and surface roughness increasing.

The chip-forming mechanics is an important element affecting the course of the turning process, while the chip formed presents the external phenomena occurring in it. In the turning process, the tool surface is in continuous contact with the material being processed, hence the occurrence of long and tangled chips. They often entangle the cutting tool, which leads to its faster wear and can cause scratches on the machined surface, as well as entangle the chuck, causing the lathe to stop [20].

The purpose of this research is to analyze the chip shaping when Ti6Al4V titanium alloy finishes turning under dry, wet and MQL cooling conditions.

2. EXPERIMENTAL PROCEDURE

Ti6Al4V titanium alloy with a chemical composition (%, according to the ISO 5832-3): O <0.20, V = 3.5, Al = 5.5, Fe <0.30, H <0.0015, C <0.08, N <0.05, Ti = the rest was processed. Its mechanical properties were: modulus of elasticity 110–114 GPa, tensile strength 960–970 MPa, yield point 850–900 MPa, fatigue strength 620–725 MPa.

The tests were carried out using a DMX MORI CTX510 machining center.

The turning was carried out with a constant cutting depth of 0.5 mm that corresponds to finish turning conditions, and also with variable cutting speeds of 37.5 – 125 m/min and feed rates of 0.05 – 0.4 mm/rev.

The cutter was used with a CoroTurn SDJCR 2525M 11 holder and a CoroTurn DCMX 11 T3 04-WM 1115 insert made of GC1115 tungsten carbide with (Ti,Al)N + $(Al,Cr)_2O_3$ coating applied by PVD method. Cutting edge geometry was: tool cutting edge angle $\kappa_r = 93°$, rake angle $\gamma = 18°$, tool clearance angle $\alpha = 7°$, nose radius $r_\varepsilon = 0.4$ mm, width of tool rake face $b_{\gamma n} = 0.1$ mm.

The investigations were carried out under dry, wet cooling conditions (emulsion based on Castrol Alusol SL 51 XBB emulsifying oil with 7% working concentration) and MQL (mixture of air and ECOCUT MIKRO 20 E oil). The Lenox 1LN micronizer was used to produce the oil mist, the air flow was 5.8 l/min and the oil flow was 39.4 ml/h.

An important factor that characterizes the features of the chip-forming process is the chip thickness ratio K_h. It allows determining the rate of chip displacement along the rake face, and is also used to calculate different factors of the chip formation zone, cutting forces etc. [21].

The values of the chip thickness ratio were determined by the equation [22]:

$$K_h = \frac{h_{ch}}{h_D} \tag{1}$$

where: h_{ch} – chip thickness, h_D – undeformed chip thickness.

When both the main cutting edge and the edge of the nose work simultaneously the values of the K_h ratios and the average values of an undeformed chip thickness can be calculated using the formulas described in [23].

The chip thickness h_{ch} was measured five times using an electronic caliper with an accuracy of 0.01 mm.

For the tests planning, the PSI (Parameter Space Investigation) method was used, which allows planning the experiment while minimizing the number of experimental points located in fixed locations in a sequential manner. The sequence consists in placing the test points in a multidimensional space in such a way that the points of their scattering are arranged on the X_1 and X_2 axes respectively and they should be in equal distances to each other (Fig. 1) [24].

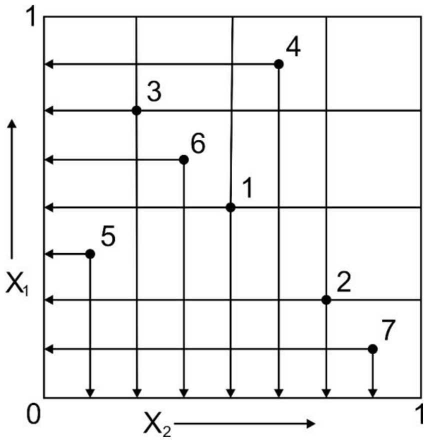


Fig. 1. The location of experimental points on the X_1 and X_2 axes in multidimensional space in accordance with the PSI method.

The coordinates of experimental points were calculated based on the algorithm presented in [24] and are shown in tab. 2, where $X_{min} = 0$ and $X_{max} = 1$.

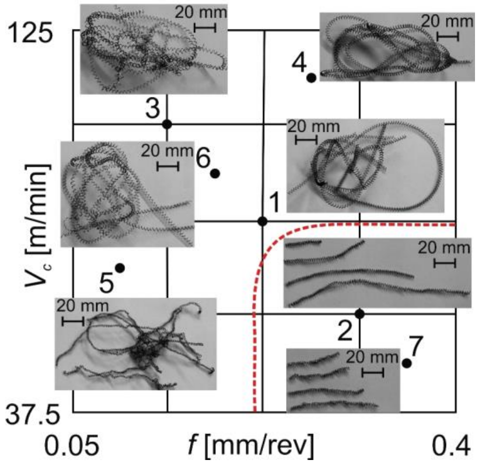
Table 2. Coordinates of experimental points

Experimental points	Variables	
	X_1	X_2
1	0.5000	0.5000
2	0.2500	0.7500
3	0.7500	0.2500
4	0.8750	0.6250
5	0.3750	0.1250
6	0.6250	0.3750
7	0.1250	0.8750

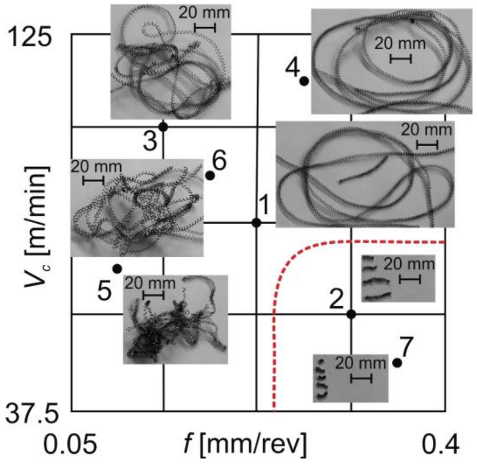
The number of 7 experienced points on each axis is satisfactory for performing statistical calculations, which were carried out using the Statistica 13 software.

3. RESULTS

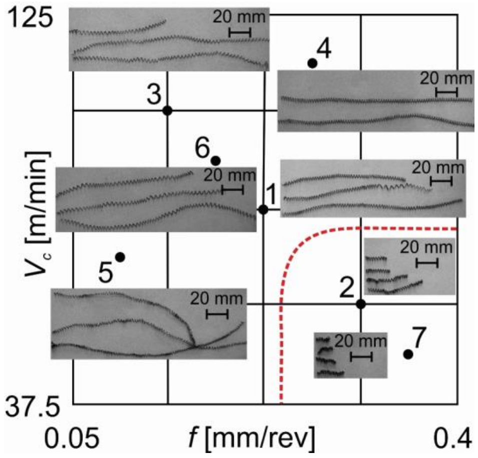
Fig. 2 presents changes in the shape and type of chips depending on the type of cooling and variable cutting parameters: speed and feed, according ISO 3685.



a)



b)



c)

Fig. 2. Changes in the shape and type of chips obtained in the 7 PSI test points, depending on the method of cooling: a) dry; b) wet; c) MQL.

During dry and wet machining, tangled chips were obtained at test points 1, 3-7. In turn, long spiral chips were observed at the same points under MQL cooling conditions. While dry cutting at test points 2 and 7, short and long spiral chips were obtained. However, short spiral chips were obtained at the same points under wet cooling and MQL conditions.

Differences in chip shapes are caused by the simultaneous effects of plasto-elastic deformation in the chip-forming zone and changes in the heat exchange conditions in the zone of cutting. The features of these processes depend on the simultaneous influence of the properties of the material processed, cooling conditions, wedge geometry, composition of the coating used and many other factors.

For each cooling method, the same division limit was outlined, which in Fig. 2 is marked with a red dashed line. It occurred in the cutting speed range of 37.5 – 80 m/min and feed rate of 0.25 – 0.4 mm/rev.

The mathematical models to calculate K_h are shown below:

- dry cutting

$$K_h = -1.005 - 12.7334f + 0.0879V_C + 33.0083f^2 - 0.0141fV_c - 0.0005{V_c}^2 \tag{2}$$

- wet cutting

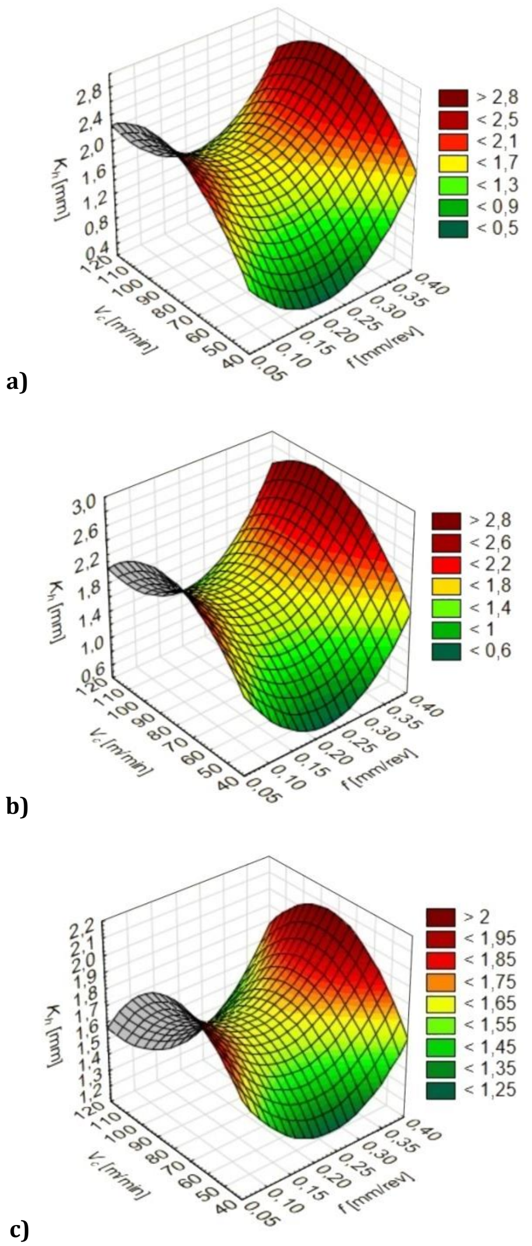
$$K_h = -0.0857 - 15.5629f + 0.0743V_C + 33.3816f^2 + 0.0172fV_c - 0.0004{V_c}^2 \tag{3}$$

- MQL cutting

$$K_h = -0.9118 - 6.6723f + 0.0362V_C + 13.071f^2 + 0.0118fV_c - 0.0002{V_c}^2 \tag{4}$$

where: V_c - cutting speed in m/min; f - feed in mm/rev.

Fig. 3 presents the changes in the chip thickness ratio depending on the type of cooling and the cutting speed and feed.



a)

b)

c)

Fig. 3. Changes in the chip thickness ratio K_h depending on the cutting speed and feed rate and the method of cooling: a) dry; b) wet; c) MQL.

On the basis of the results obtained, it is possible to determine the influence of the cutting speed and feed on the chip thickness ratio under dry, wet and MQL cooling conditions. When machining under MQL conditions, the chip thickness ratio decreased compared to dry and wet machining. In the tested cooling conditions, lower K_h values of occurred in the range of medium feeds and lower cutting speeds, while higher values were observed in the range of lower and higher feeds and average cutting speeds.

The results of the combined effect of the processing conditions on the chip thickness ratio can be used, in particular, to create numerical models of the cutting process, as K_h values are one of the main factors of this process.

4. CONCLUSION

The research was devoted to the analysis of the influence of cutting speed, feed and dry, wet and MQL cooling conditions on the features of chip formation after finishing turning of Ti6Al4V titanium alloy. Based on the results obtained, it was established that:

- when turning under dry cooling conditions there were entangled ships, long and short spiral chips; under wet conditions tangled and spiral short chips, and under MQL conditions spiral long and short chips;
- clear differences in the shapes of the chip between dry and wet machining, and MQL were observed;
- The chip thickness ratio when turning in MQL conditions was smaller in comparison with dry and wet turning;
- The cutting speed and feed rate affect the chip thickness ratio after finishing turning of Ti6Al4V titanium alloy.

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