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Influence of Minimum Quantity Lubrication Using Vegetable-Based Cutting Fluids on Surface Topography and Cutting Forces in Finish Turning of Ti-6Al-4V

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ABSTRACT

Titanium alloys are included in the group of difficult-to-cut materials. The use of different methods to reduce the temperature of the machining zone is one of the factors influencing the performance of the machining. The most commonly used method is flood cooling. On the basis of recent research, the conventionally used cutting fluids can cause some health problems for machine operators. Moreover, it was found that they can cause some problems for the environment during storage and disposal. Therefore, in recent years, the aspects of the use of biodegradable fluids and the reduction of the number of metalworking fluids used in machining processes have received much more attention. In this study, the effect of the application of three different vegetable oil-based cutting fluids was evaluated for minimum quantity lubrication (MQL) in finishing the Ti-6Al-4V titanium alloy on surface topography and cutting force components. The same tests were conducted for dry cutting conditions and the results were compared with those after machining with MQL. It was found that the best surface roughness was obtained with the use of the mixture of 50% vegetable oil and 50% diester (1PR20) under all the cutting parameters considered. The biggest differences in the values of the *Sa* and *Sz* parameters can be noticed for the lowest feed rate. For the feed rate $f = 0.1$ mm/rev, the *Sa* parameter values were approximately 32% and 24% lower for MQL with 1PR20 compared to MQL to LB2000 and dry cutting conditions, respectively. In terms of cutting force components, the lowest values were obtained for the MQL with 1PR20 machining. The values of the main cutting force were about 15% lower compared to the MQL with LB2000 cutting conditions for all the cutting parameters considered.

Keywords: minimum quantity lubrication, MQL, vegetable oil, cutting fluids, Ti-6Al-4V, titanium alloy.

INTRODUCTION

Due to the strength-to-weight ratio, also in high temperatures, excellent corrosion resistance, and low modulus of elasticity, titanium and its alloys found wide applications in many industries, such as aerospace, medical, petrochemical, and marine [1].

However, the same properties also make titanium and titanium alloys classified as difficult-to-cut materials. High cutting temperature and intense tool wear are the main problems that occur during the machining of titanium alloys [2]. To improve machining performance, the cutting temperature is reduced by coolant supply to the machining zone. The conventional way of cooling the machining zone is flood cooling.

The main functions of metalworking fluids are lubrication and cooling. Moreover, they reduce the build-up edge, protect both machined elements and machine parts against corrosion, and facilitate the removal of chips from the machining zone [3]. On the other hand, conventionally used cutting fluids can cause some health problems for machine operators, such as dermatitis [4], work-related asthma [5] and cancer at several sites (e.g. skin, esophagus, stomach) [6]. In addition, conventional metalworking fluids can cause some problems for the environment during storage and disposal, and special physical, chemical, biological or physical treatment is often needed to remove hazardous components from the metalworking fluid used [7].

Therefore, as an alternative to flood cooling conditions, the minimum quantity lubrication (MQL) method is increasingly being used. The metalworking fluid flow rate under minimum quantity lubrication conditions is between 5 and 50 ml per hour, therefore, MQL is considered as a loss lubrication system. Safety aspects should receive special attention, in the case of machining under MQL cutting conditions, because the cutting fluid is completely distributed in the working area as mist and vapors. Therefore, pastes, oils, fatty alcohols, and esters are in use today [8].

Some studies on cutting fluids based on vegetable oils used under MQL conditions are published in the literature [9].

Rahim and Sasahara [10] handled an Inconel 718 drilling experiment under MQL cutting conditions with the use of synthetic ester and palm oil. The tools used for the tests were indexable carbide drills coated with AlTiN. Palm oil used in MQL cutting conditions outperformed the synthetic ester. It was concluded that longer tool life, lower cutting temperature, cutting force, and torque for palm oil were achieved because of the high percentage of unsaturated fatty acids in the carbon chain and increased formability of the high lubrication strength film at the tool-workpiece or tool-chip interface.

Gunjal and Patil [11] investigated the performance of three metalworking fluids during the turning process of hardened AISI 4340. The vegetable-based oils used in the tests were: soybean oil, coconut oil and canola oil. The inserts used for the experiment were PVD carbide inserts coated with AlTiN. In terms of tool life, the best results were obtained for canola oil, which may be due to the higher heat transfer coefficient and density. It was also concluded that the surface roughness of the material is not significantly affected by the application of different cutting fluids.

Ghuge and Mahalle [12] studied the performance of Blassocut-4000, coconut oil, groundnut oil, sunflower oil and soybean oil in the AISI 4130 MS turning process in terms of surface roughness and cutting temperature. Among the cutting fluids examined, the best results were achieved for soybean oil. In another study, Ghuge and Mahalle [13] compared the performance of soybean oil, sunflower oil, and Blasocut-4000. The reduction of cutting forces has been noticed for both vegetable-based oils compared to Blasocut, however, a decrease in grater was observed for soybean oil.

Raza et al. [14] studied the flank wear of uncoated carbide tool in the turning process of titanium alloy (Ti-6Al-4V) in different cutting conditions: vegetable oil + cooled air (MQCL), MQL with vegetable oil (ECOLUBRIC E200), cooled air lubrication, cryogenic machining (with liquid nitrogen), flood cooling, and dry machining. In terms of tool wear and surface roughness , MQCL and MQL with application of vegetable oil as a cutting fluid can really be a good alternative in the case of sustainable machining.

Shyha et al. [15] analyzed the impact of working conditions, four different vegetable oils, and cutting tool materials on tool flank wear and surface roughness in the Ti-6Al-4V turning process. The cutting fluids used for the tests were the following: Super Synth 4, Coolant NE250 H, Vasco 1000, and Hocut 3450. The results were compared to machining with the use of a mineral oil-based cutting fluid. The main contributing factor for *Ra*, with Percentage Contribution Ratio (*PCR*) of 44.5%, was cutting tool material. No significant effect of the variation in cutting fluid was observed.

Rahim and Sasahara [16] compared the effects of different machining conditions when drilling Ti-6Al-4V with the use of an AlTiN coated indexable carbide drill. The investigated cutting conditions were flood cooling, air blow, and MQL with synthetic ester and palm oil. The performance of MQL with synthetic ester and palm oil, as well as with flood cooling conditions, was comparable, in terms of tool life. MQL with palm oil produced almost the same workpiece temperatures and cutting force as flood conditions, lower than MQL with synthetic ester.

Deiab et al. [17] analyzed the effects of vegetable oil + cooled air (MQCL), MQL with vegetable oil, cooled air lubrication, cryogenic machining (with liquid Nitrogen), flood cooling, and dry machining on surface topography, energy consumption and flank wear of uncoated carbide tool when turning Ti-6Al-4V. Taking into account surface roughness, cutting energy consumption, and tool wear, it can be summarized that MQL and MQCL conditions can be a good alternative to synthetic cooling in the case of sustainable machining.

Khan and Maity [1] studied the influence of the cooling technique and cutting speed on

Table 1. Summary of the basic properties of the workpiece material [20]

Properties	Density	Poisson's ratio	Modulus of elasticity	Tensile strength, ultimate	Tensile strength, yield	Melting point
Units	kg/m^3	-	GPa	MPa	MPa	°C
Value	4430	0.33	114	1170	1100	1660

surface roughness, tool wear, machining temperature, and cutting force in finish turning of Cp-Ti grade 2 under MQL, flood and dry cutting conditions. Vegetable oil was used as cutting fluid in MQL. The MQL method resulted in the lowest tool wear, power consumption, cutting forces, and cutting temperature. Among the three cutting conditions tested, MQL machining gave the best results in terms of surface finish.

Haq et al. [18] conducted an experiment of face milling D2 tool steel under MQL and nano fluid MQL (NFMQL) cutting conditions. The effect of flow rate, depth of cut, and feed on the cutting temperature was investigated. In the MQL conditions, deionized water was used. A 2% wt. concentration of Al_2O_3 in the deionized water was used under NFMQL cutting conditions. In both cases, the flow rate was 200-400 ml/h. It was concluded that the use of the NFMQL method results in a 25% reduction of the temperature comparing to the MQL conditions.

Maruda [19] studied the impact of the compressed air pressure on the surface geometric structure in the turning process of AISI 1045 steel under the MQCL (Minimum Quantity Cooling Lubrication) conditions. Air pressure was changed from 1 MPa to 7 MPa. It was found that lower surface roughness parameters can be obtained for low pressure of compressed air.

In this paper the results of turning tests conducted under MQL cutting conditions with three various vegetable oil-based metalworking fluids: rapeseed oil, mixture of 50% vegetable oil and 50% diester, and LB2000 - vegetable-based, biodegradable lubricant for industrial use are presented. The results obtained for cutting force components and roughness of the workpiece surface were compared to the results obtained under dry machining.

EXPERIMENTAL SETUP

Table 1 presents the mechanical properties of the Ti-6Al-4V titanium alloy – the workpiece material used for the tests.

The study used an uncoated cutting tool with a positive entering angle of 93° and an angle of 35° corners. The depth of cut a_p was at constant level and equal to 0.25 mm. Tests were performed for three levels of feed rate and cutting speed. Table 2 presents the summary of the cutting parameters and the experimental setup.

The tests were conducted with the application of the MQL method. The mist was fed from the rake face via internal cooling channels in the tool holder showed at the Figure 1 (diameter of the nozzle was 1.6 mm at a distance of 12 mm from the cutting zone). Three cutting fluids were used: LB2000 – vegetable-based biodegradable lubricant for industrial use, rapeseed oil and the mixture of 50% vegetable oil and 50% diester (marked as 1PR20). The properties of the cutting fluids are summarized in Table 3. The MQL parameters are as follows: cutting fluid flow rate 30 ml/h and air pressure 7 bar.

Table 2. Summary of cutting parameters and experimental setup

Description	Component	Description
Experimental setup	Cutting tool	VBGT160404-M3 HX
	Tool holder	SVJBL2525M16 JET
	Machine	NEF 600 lathe
	Cutting conditions	dry, MQL
	Workpiece material	Ti-6Al-4V
	Cutting fluid in MQL conditions	LB2000 rapeseed oil vegetable oil + diester
Cutting parameters	Depth of cut a_p, mm	0.25
	Cutting speed v_c, m/min	80, 120, 160
	Feed rate *f*, mm/rev	0.1, 0.2, 0.3

Table 3. Properties of cutting fluids

Fluid	Viscosity at 40 °C, mm^2/s	Density g/cm^3
1PR20	37	0.94
LB2000	35	0.92
Rapeseed oil	33	0.91

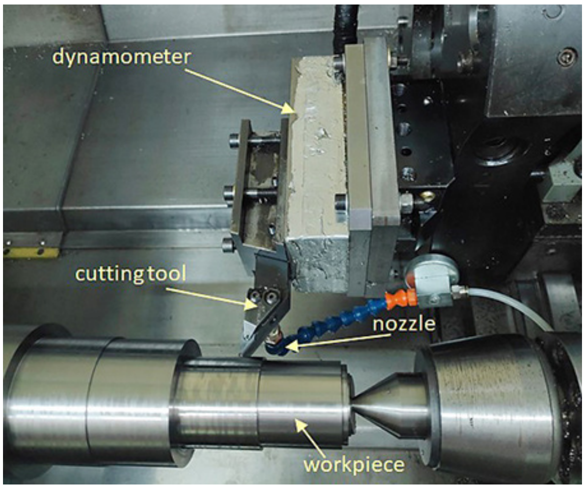

Fig. 1. Test stand configuration based on NEF 600 lathe

RESULTS

Surface roughness

The *Sa* and *Sz* parameters were measured. The results of the measurements are shown in Figure 2 and Figure 3. The obtained results showed a significant influence of the feed and a slight influence of the cutting speed on the roughness parameters. These dependencies are reflected in the literature [21, 22]. Moreover, it was showed that type of lubricating liquid also affects the surface roughness. The lowest roughness parameters were obtained for the 1PR20 oil, while the relatively highest roughness values were achieved for the lowest cutting speed and the LB2000 oil. Differences in the roughness parameters (in the case of the *Sa* parameter up to 80%) can be caused by the change in tribological conditions in the tool-workpiece contact. Depending on the type of oil, larger differences in surface roughness parameters occurred in the range of lower cutting speeds. Taking into account the constant flow rate of the metalworking fluid, a significant influence of tribological conditions on surface roughness can be confirmed. The amount of oil delivered efficiently to the cutting zone per unit of removed material volume decreases at higher cutting speeds. Relatively small values of roughness parameters during dry machining are the result of a change in the contour of the cutting tool edge due to greater wear intensity - the measuring lengths were 6 mm. This translates into a reduction of the roughness parameter in the first phase of cutting; however, the high temperature in the contact zone causes a change in the wear mechanisms and the risk of critical damage to the blade.

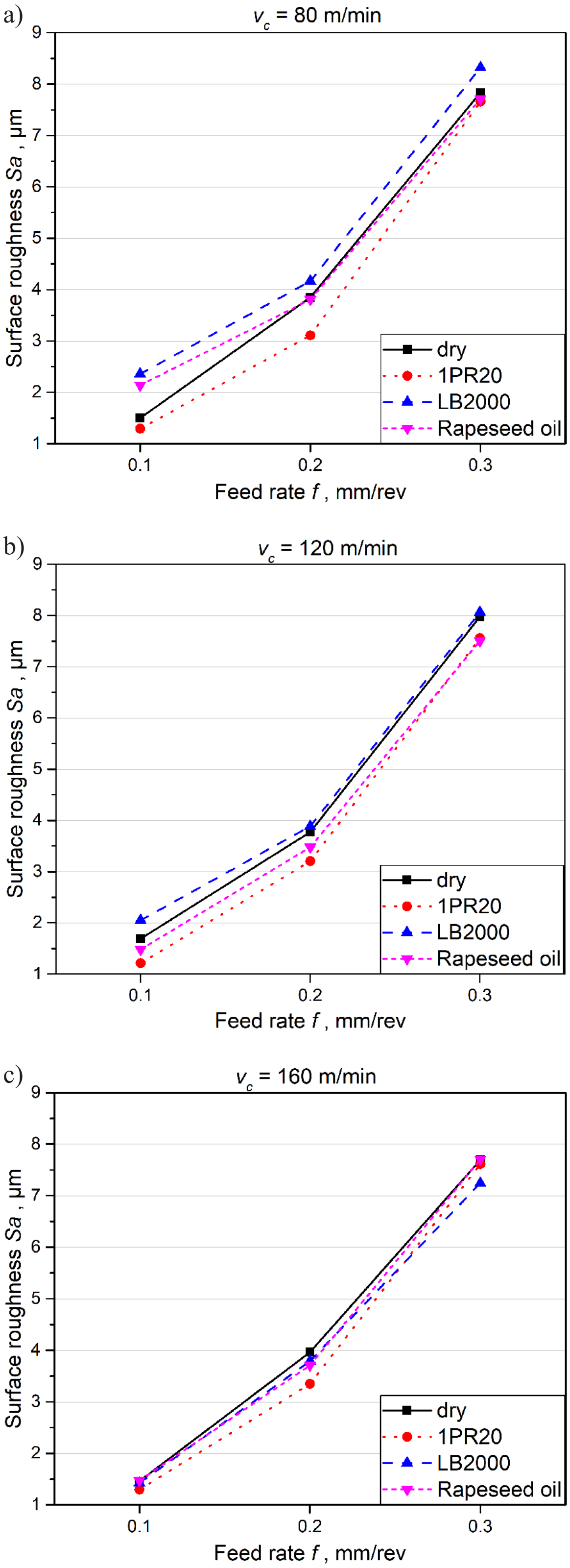

Fig. 2. Dependences of the surface roughness S_a on the feed rate *f* for a) v_c = 80 m/min, b) v_c = 120 m/min, c) v_c = 160 m/min

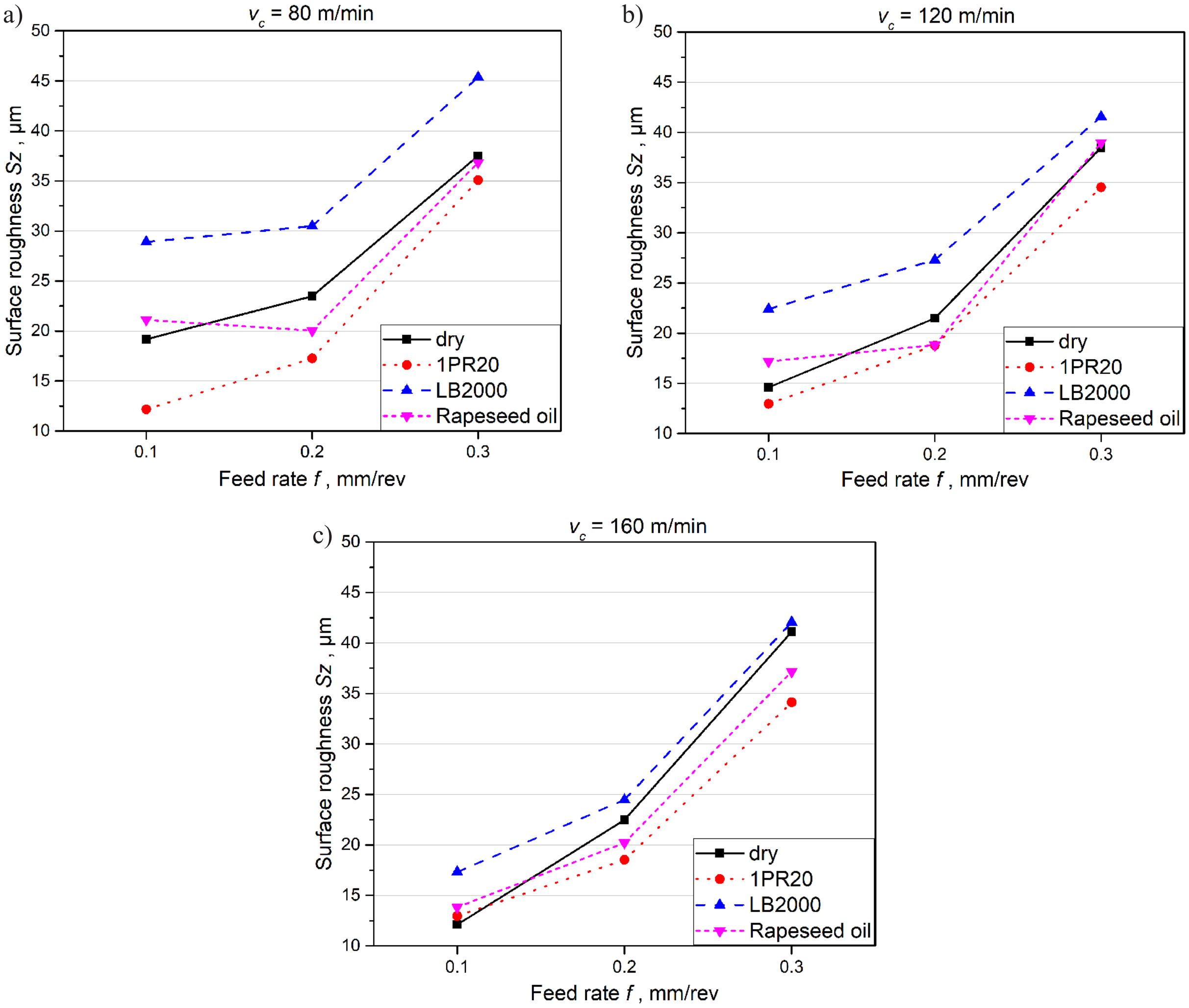

Fig. 3. Dependences of the surface roughness S_z on the feed rate f for a) v_c = 80 m/min, b) v_c = 120 m/min, c) v_c = 160 m/min

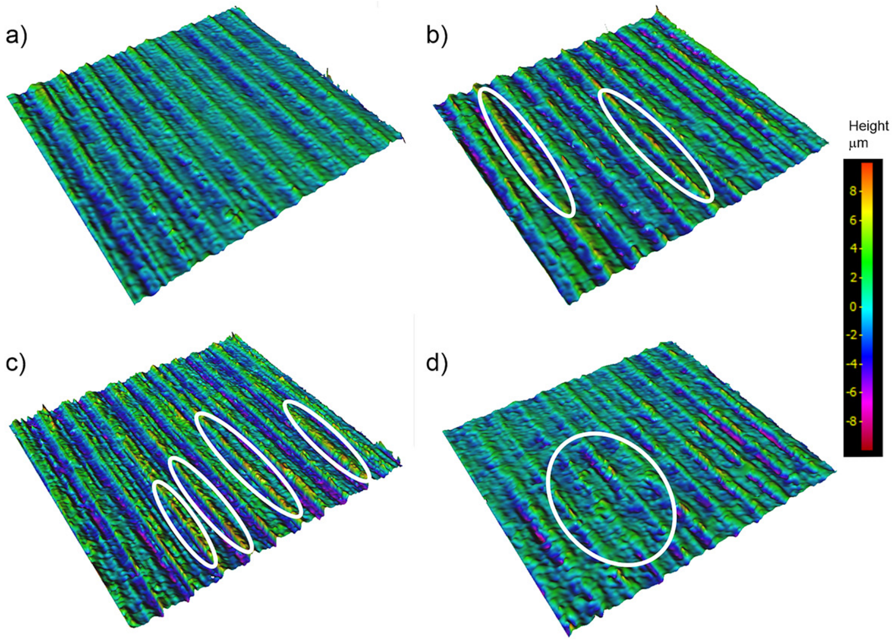

Fig. 4. Surface topography after the machining with the feed rate *f* = 0.1 mm/rev and cutting speed v_c = 80 m/min a) with 1PR20, b) with rapeseed oil, c) LB2000, d) in dry conditions

Figure 4 shows the topography of the machined surface. The interaction of plastic-elastic stresses and the change in tribological conditions in the cutting zone are visible as an outflow. The surface morphology after turning under MQL conditions with the 1PR20 lubricant did not show any significant irregularities (Figure 4a). In the case of the remaining oils (Figure 4b-c), the plastic-elastic interaction causes an outflow in the area of the peaks, which determines the higher roughness parameters. In the case of dry machining (Figure 4d), the treated surface was characterized by smaller elevations (which is confirmed by a change in the contour of the cutting edge), but also by the occurrence of larger disturbances in the surface morphology.

Cutting force

Cutting force components have been measured with a Kistler three-dimensional piezoelectric dynamometer. Dependences of the main cutting forces F_c on the cutting speed v_c are shown at the Figure 5. The values of the main cutting force increased with increasing feed force and decreased with increasing cutting speed in all cutting conditions. The lowest values were for machining with 1PR20 fluid and the highest values were for the LB2000. The difference was about 15%.

Figure 6 shows the dependences of the passive force on the cutting speed for three values of the feed rate. An increase in passive force can be observed with an increase in feed rate. The dependence on the cutting speed is not as clear as in the case of the main cutting force and strongly depends on the value of the feed rate. However, the curves of the passive force as a function of the cutting speed are very similar for all cutting conditions for each feed rate value. Passive force values were very close for cutting with LB2000 and rapeseed oil, and higher than for dry cutting conditions and cutting with 1PR20 fluid.

In the case of feed force, the dependency on the feed rate value is almost imperceptible (Fig. 7). Additionally, in the case of feed force, the lowest values were for machining with the 1PR20 fluid.

The results regarding the influence of cutting parameters and the type of cutting fluid during turning under MQL conditions on the components of the cutting force mostly confirmed the conclusions from the analysis of roughness parameters regarding the significant influence of tribological conditions. These conditions determine the differences (up to 15% in terms of cutting force F_c) in terms of force components for various cutting fluids. Again, a mixture of 50% vegetable oil and 50% diester (marked as 1PR20), showed the

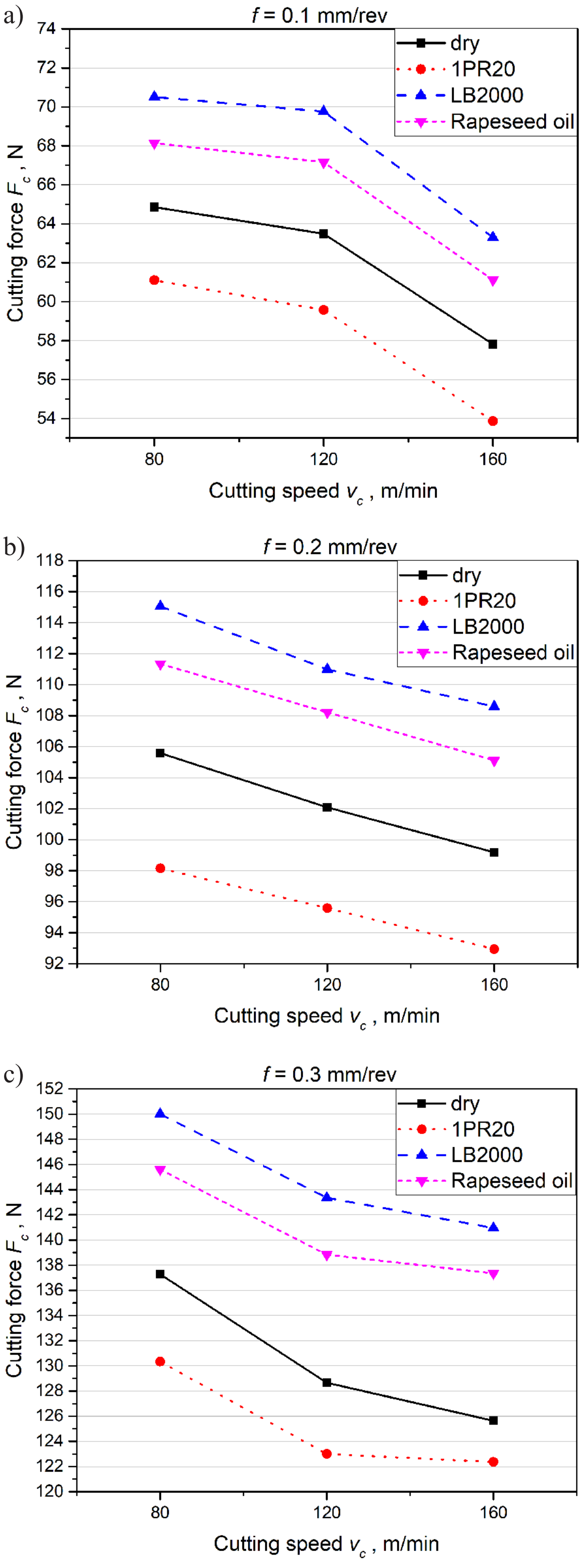

Fig. 5. Dependences of the main cutting force F_c on the cutting speed v_c for a) $f = 0.1$ mm/rev, b) $f = 0.2$ mm/rev, c) $f = 0.3$ mm/rev

best results. The extreme occurring in Figure 6 in the scope of passive force indicates the influence of the cutting speed on the conditions of material decohesion. In the case of turning Ti-6Al-4V alloy under MQL conditions, the use of speeds greater than 120 m/min adversely affects the passive force. The results of dry machining confirm an increase in temperature and a reduction in the

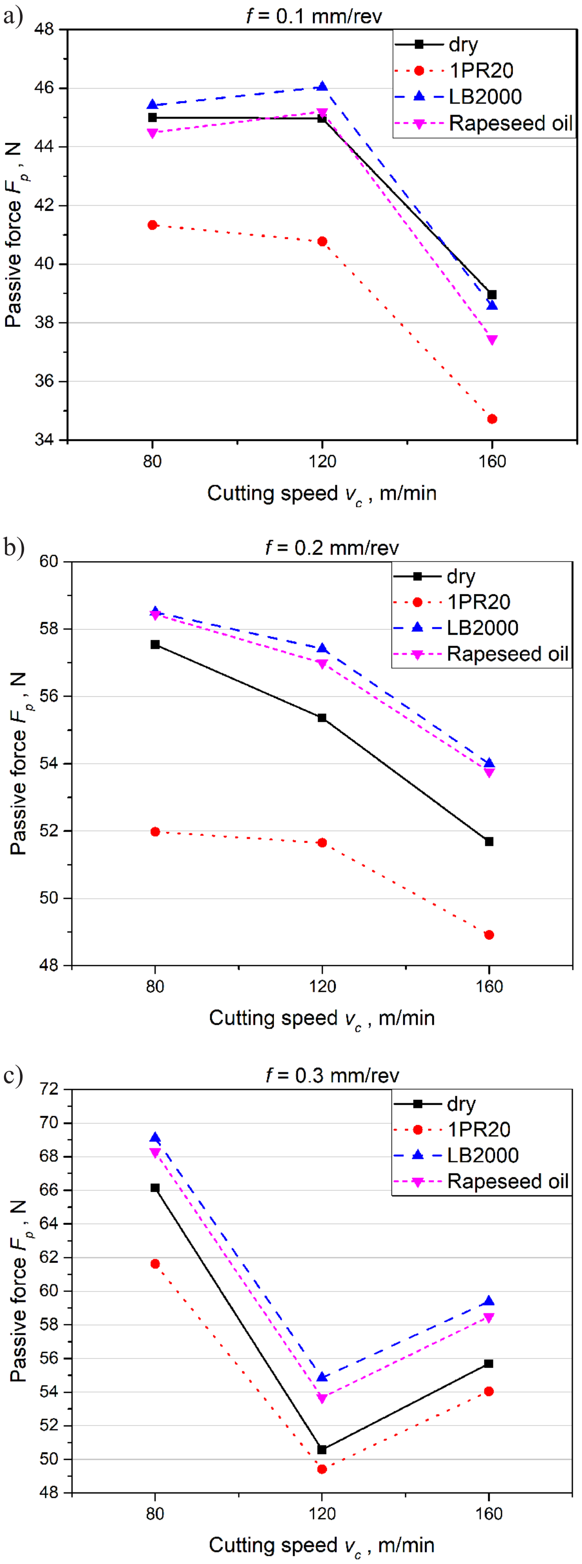

Fig. 6. Dependences of the passive force F_p on the cutting speed v_c for a) $f = 0.1$ mm/rev, b) $f = 0.2$ mm/rev, c) $f = 0.3$ mm/rev

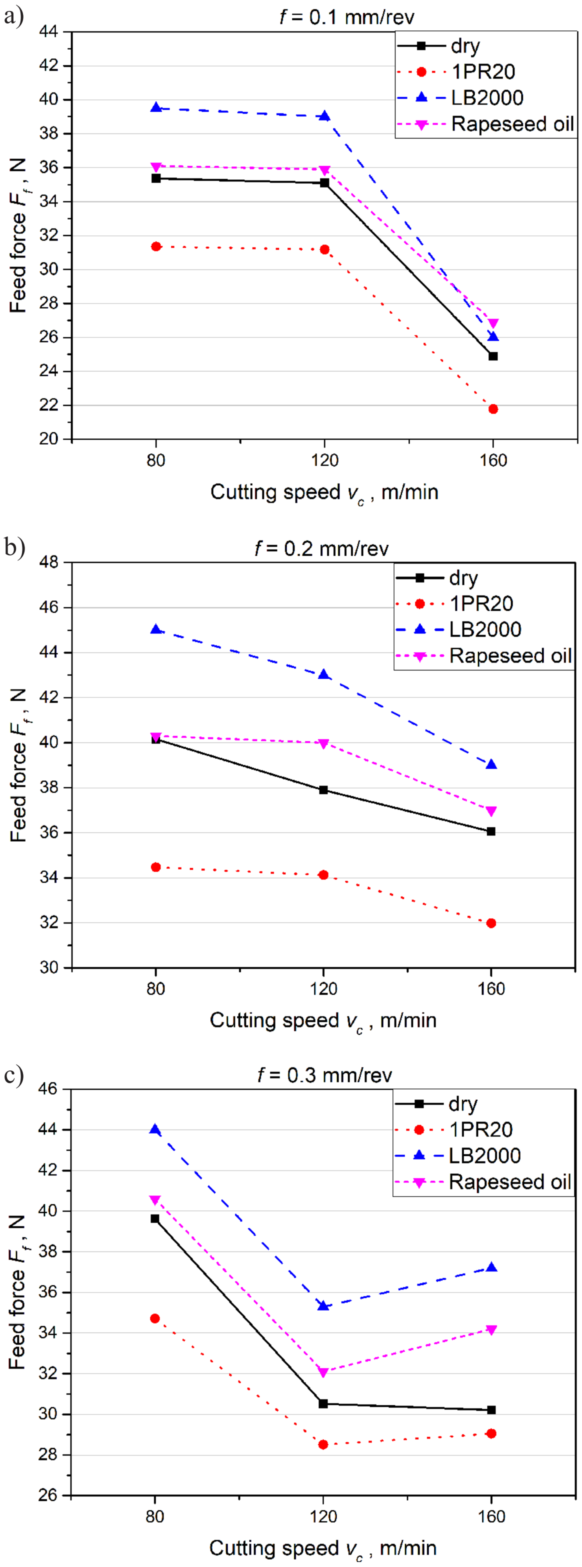

Fig. 7. Dependences of the feed force F_f on the cutting speed v_c for a) $f = 0.1$ mm/rev, b) $f = 0.2$ mm/rev, c) $f = 0.3$ mm/rev

yield stress of the workpiece. Unfortunately, this has a negative effect on the technological condition of the surface layer and the intensity of wear of the cutting insert.

CONCLUSIONS

The influence of the type of metalworking fluid and cutting parameters on the surface topography and cutting force components has been studied in the finish turning of the Ti-6Al-4V titanium alloy. In summary, it was observed that:

- The type of cutting fluid and the feed rate have a significant influence on the surface roughness parameters.
- The lowest roughness parameters were obtained for the 1PR20 oil, while the relatively highest roughness values were achieved for the lowest cutting speed and the LB2000 oil. The values of the parameters the parameters Sa and Sz after cutting under MQL conditions with LB2000 were up to 80% and 130% higher, respectively, compared to the parameters after cutting with 1PR20.
- Obtained values of the cutting force components were the lowest for cutting with 1PR20 cutting fluid. The values of cutting force, passive force, and feed force were approximately 15%, 10%, and 25% higher, respectively, for cutting with LB2000 cutting fluid compared to cutting with 1PR20 cutting fluid under MQL cutting conditions.

In conclusion, it can be said that, among the investigated cutting fluids, the best results, in the case of surface roughness parameters and cutting force components, can be achieved with the use of 1PR20 cutting fluid under MQL cutting conditions.

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