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RESEARCH

The Effect of the Use of Cutting Zone Minimum Quantity Lubrication and Wiper Geometry Inserts on Titanium Ti6Al4V Surface Quality After Turning

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A B S T R A C T

Due to their poor machinability, the machining of titanium alloys without a machining fluid is practically impossible. One of the fluid feeding methods, which is also eco-friendly, is minimum quantity lubrication (MQL). This paper presents the results of research into the dry and MQL-assisted machining of alloy Ti-6Al-4V. In the literature on the subject, there are studies on the influence of MQL on tool life, cutting forces, and the most commonly used roughness parameters Ra and Rz. In this paper, MQL's impact on the values of parameters Rq, Rt, Rp, Rv, Rsk, and Rku is shown. In addition, the possibility of improving the surface quality of the selected titanium alloy using wiper geometry inserts combined with MQL is assessed. The exemplary images of the surface, machined using tools of conventional and wiper geometry, in dry and MQL conditions are also shown. Thanks to the wide range of the measured and analysed roughness parameters the results presented in this paper provide a basis for a comprehensive assessment of the geometric and functional features of the surface of alloy Ti-6Al-4V after dry and MQL-assisted turning.

1. INTRODUCTION

The safety of transport means is a major consideration having a bearing on their manufacturing processes. Safety factors in aviation are more exacting than, e.g., the ones in the motor industry. Another important consideration is the economic one. Each one-kilogram reduction in aircraft weight substantially reduces fuel consumption while increasing the flying range. Therefore the materials used in aviation must exhibit better properties than those of the materials used in the production of other means of transport and at the same time they must be lightweight. The development of aviation assumes a reduction in CO_2 and NO_2 emissions and noise. Consequently, novel materials meeting the above requirements are sought, which necessarily entails the development of technologies of processing such materials and producing reliable parts out of them.

Titanium alloys are materials used for both aircraft structures and engines. Because of their low thermal conductivity, high hardness and strength, low longitudinal modulus of elasticity, a strong tendency towards strain hardening, and high chemical reactivity, titanium alloys are classified as poorly machinable materials. Lubrication and cooling methods are used to restrain the temperature at the cutting edge-stock contact and so to improve the machinability of titanium alloys. The most important methods are conventional flood cooling, pressure fluid feeding, cryogenic cooling, oil mist fluid feeding, and hybrid methods [1]. Each of these methods offers huge advantages and increases the effectiveness of titanium alloys machining. Unfortunately, they have also drawbacks and limitations. Therefore their use depends on the industry's production means and the specific quality, cost, and productivity requirements.

Since the effectiveness of the dry machining of titanium alloys is low, it can be employed only with the use of tools made of durable materials or covered with appropriate antiwear coatings. Such materials are polycrystalline cubic boron nitride (PCBN), polycrystalline diamond (PCD), and sintered carbides with chemically applied coatings (e.g., TiN, Al_2O_3, TiCN) or with physically applied coatings (e.g., TiN, TiAlN CrAlSiN, TiAlSiN). Especially coatings with a chromium addition increase blade durability [2]. An alternative to machining without a cutting fluid is flood cooling. Compared with dry machining, it has been found to significantly improve surface quality, reduce total blade wear by 30%, minimize diffusive and adhesive wear, and substantially reduce the adhesion of chips to the blade's face, increasing productivity [3,4]. Even better results are achieved when the cutting fluid is fed under pressure. Then chip/tool contact duration decreases, and the chips are more effectively broken [5]. Blade durability increases by 75% in comparison with flood cooling machining. As a result, cutting speed can be increased twofold and cutting temperature is more effectively lowered. Unfortunately, no positive changes in machined surface roughness and the cutting forces are observed [1]. However, according to [6], surface roughness can be reduced by properly matching the cutting fluid and the feeding pressure.

Since environment protection is a very important consideration, an environment-friendly way of assisting the machining of titanium alloys is sought. One of the investigated ways is cryogeny. This entails a very large temperature difference between the blade and the cooling medium, whereby the temperature in the cutting zone drops sharply and cooling becomes more effective. The large difference in temperature results in local modifications of the mechanical properties of the workpiece and changes in the structure of the surface layer [7]. The disadvantage of this type of cooling is the necessity to provide special tooling and adaptation of the machine tool. It has to be suitably upgraded and adapted so systems will not freeze in extremely low temperatures. An alternative can be minimum quantity lubrication or MQL combined with cryogenic cooling.

The classic MQL technology consists of feeding a very small amount of lubricating oil into the machining process using compressed air. In this method, the oil flow rate is estimated to range from 10 to 200 ml/h [8,9]. Minimum quantity lubrication reduces friction between the cutting tool and the workpiece, whereby it can extend tool life [10,11]. MQL contributes to sustainable production since it is a much more eco-friendly method as the liquids used in it do not need to be recycled [12]. Other advantages of using MQL are lower energy consumption, greater flexibility of the process, easier chip recycling, and better surface quality [13]. In [14], a comparison of the milling of cylindrical Ti-6Al-4V alloy in flood cooling, MQL, and dry conditions was presented. Coated and uncoated inserts were used in the tests. Conventional cooling reduces mechanical abrasive wear most. The use of MQL eliminates adhesive wear and the associated edge chipping. An improvement in blade durability owing to the use of MQL in comparison with dry machining was noted in [15]. Wear on the tool flank surface decreased by about 27%. It was also found that MQL reduces surface roughness. On the other hand, dry micro-milling results in fewer burrs. The efficiency of minimum quantity lubrication can be increased using cutting fluid additives. An example might be the studies in which MoS_2 nanoparticles were added to jojoba oil. It was found that jojoba oil alone satisfies the cutting fluid requirements for the machining of Ti-6Al-4V alloy. In comparison with dry machining, the cutting force can be reduced by 30.21%, surface roughness by 10.3%, and blade wear by 31.58%. Thanks to a small MoS_2 addition (0.1%), the above indices improve by 34.39%, 40.67%, and 47.37%. A particularly strong effect was obtained in titanium surface finish [16]. Blade wear after machining titanium in dry conditions, and under MQL, with rapeseed oil alone, and rapeseed oil enriched with graphene was studied in [17]. Thanks to the use of oil mist, the shear angle increases and friction decreases, whereby the chip/tool contact is shorter and the blade life longer. Pure rapeseed oil slightly reduces the surface roughness, but only after adding graphene, the roughness drops to 58-68% compared to dry cutting.

A comparative study of cooling through MQL and by various cryogenic methods showed that tool flank wear could be reduced by 54%, 42%, and 24%, in comparison with the dry milling of titanium, through the use of respectively CO_2 snow, N_2, and MQL, [18]. MQL's drawback can be a lower heat removal capacity and a tendency towards lubricant evaporation, whereby friction reduction is not so highly effective [19]. Even when MQL at sub-zero temperatures is used, the heat removal is threefold lower than in cryogenic cooling with CO_2 [20]. According to [21], MQL can be used in titanium alloy machining only at low cutting speeds because, at higher speeds, the oil evaporates. Therefore, the possibility of using hybrid methods, e.g., a combination of MQL and very low temperatures, is under examination. In [22], the effectiveness of cryogenic cooling with nitrogen, cooling by a combination of nitrogen and MQL, and cooling by a combination of Raque Hilsh Vortex Tube (RHVT) and MQL is compared regarding dry milling. Tool flank wear in N_2 + MQL conditions was found to be lower than in the case of N_2, RHVT + MQL, and dry machining. Since a combination of nitrogen and MQL provides both cooling and tool/chip contact lubrication, in the opinion of the authors of [22], this method ensures the best roughness. Moreover, due to this combination, the chips are shorter and have fewer sharp edges and smoother surfaces. In [23], it was demonstrated that both MQL and a combination of MQL and cryogenic cooling result in very efficient heat removal and in a reduction in friction, whereby tool life is extended even thirtyfold in comparison with flood cooling-assisted machining. MQL was found to ensure the lowest surface roughness. The authors of [23] think that roughness *Ra* of 0.2 μm can be obtained even at higher cutting speeds. Also in [24], it was shown that cryogenic cooling extends blade life more than MQL does, while MQL improves much more the quality of the machined surface. MQL lubrication also has a positive effect on the parameters of the 3D texture. It has been shown in [25] that during the processing of 17-4PH steel in MQL conditions, the *Sa* surface texture parameter is reduced by 43%, the *Sz* parameter by 48%, and the *Sq* parameter by 40% compared to dry machining.

The literature review shows that it is necessary to cool and lubricate the cutting zone to ensure effective machining of titanium alloys. However, one cannot definitely conclude that one of the methods can increase all the machinability indices. Therefore further research on innovative cooling and lubrication methods in the machining of titanium is needed. The authors of this paper undertook an attempt to comprehensively assess how MQL affects the quality of the machined surface of titanium Ti-6Al-4V after turning. Not only *Ra* (most often found in the literature sources on titanium machining) but several other parameters were subjected to analysis. Such a broad analysis can reveal the effect of lubrication on not only surface smoothness, but also on the surface texture and its in-service properties. This is of vital importance, particularly in aviation where titanium alloys are very often used.

2. TESTING CONDTITIONS

Tests were carried out on titanium alloy Ti-6Al-4V, which is a two-phase alloy with predominant close-packed hexagonal structure α and body-centered cubic structure β. The main alloying additives are aluminum (stabilizing phase α) and vanadium (stabilizing phase β). The alloy preserves its strength even at elevated temperatures. Furthermore, it is characterized by high strength, high corrosion resistance, and high fracture toughness, owing to which it is used in aviation. The alloy is a constituent of turbine blades, nozzles, piston rings, and gas turbine combustion chambers. It is also used in the chemical industry, the petrochemical industry, the biomedical industry, and even in the nuclear industry.

The tests were carried out on a CNC lathe TUR 560 MN (fig. 1) made by Automatic Lathes Factory PLC in Wroclaw. The machine tool was equipped with a Siemens SINUMERIK 810 Manual Turn control and an AC system. An Accu-Lube MiniBooster MB II HDC feeder (fig. 2 and 3) was used to produce oil mist. The device is used for both internal and external lubrication. It has two cutting fluid tanks from which the fluid is pumped via hoses to nozzles.

Fig. 1. Lathe TUR 560 MN used in tests.

Fig. 2. Oil mist producing and feeding device-general view.

The amount of the fluid fed is controlled by a valve and a pump speed governor. Two nozzles were used in the tests, and the cooling-lubricating agent was drawn from one of the tanks. Figure 3 also shows the inside of the feeder. Oil mist was fed via two hoses to the tool flank and the tool face. During the tests measured flow rate fed to the cutting area of the oil medium. A total of 125ml/h of fog was delivered through 2 nozzles. Oil LB 8000, recommended for light and heavy machining, was used. Its composition is based on fatty alcohol. The oil is non-toxic and environmentally safe. Its other advantage is that it does not leave stains or deposits on the machined surface. The properties of the oil used are shown in Table 1.

Fig. 3. Oil mist producing and feeding device-inside view.

Table 1. Properties of oil LB 8000 used for minimum quantity lubrication of cutting zone during tests

Ignition temperature [°C]	Solidification temperature [°C]	Viscosity at 40°C
310	-17	37

A profilometer Mitutoyo SV series 3200 (fig. 4) was used to measure surface roughness. A diamond stylus with a cone corner radius of 2μm and an angle of 60° was used for the measurements. The tip pitch amounted to 800 micrometers. Measurements were made on an elementary section equal to 0.8 and a measuring section of 4 mm. Three measurements of each of the obtained surfaces were made. The FORMTRACEPACK measurement software was used. The profilometer was equipped with a 3D measuring table with a resolution of 0.05μm and the McCube Ultimate software for 3D analysis.

Fig. 4. Profilographometer Mitutoyo SV series 3200 used for surface roughness measuring

An SCGCR2020K09 turning tool and 2 kinds of cutting inserts designated CCMT 09 T3 04-MF 1025 and CCMT 09 T3 04-WF 1025 were used in the tests. The former insert's geometry with a corner radius of 0.4mm was conventional. The latter insert had a smoothing wiper geometry. According to the manufacturer, the inserts are intended for small diameter exterior finish turning, long and slender objects, and interior machining. The cutting inserts were made of sintered carbide. The two inserts had a TIALN+TIN coating deposited via PVD. Due to carbide grade and coating, they can be used for the machining of ISO M stainless steels and ISO S superalloys.

A cylindrical element with an diameter of 50 mm and a length of 300 mm was prepared for the experimental tests. Each cutting test was performed with a cutting length of 15mm. Finish turning cut depth a_p=0.25 mm was used in the tests. Cutting speed and feed rate were selected following the manufacturer's recommendations, and their ranges were extended to widen the interval of tested cutting conditions. Three cutting speeds: v_c = 35, 70 and 110 m/min and five feed rates: f = 0.08, 0.13, 0.17, 0.21 and 0.27mm/turn were adopted. A wide range of application parameters made 60 turning tests (30 dry and 30 with MQL), and as obtained to measure and analyze the surface were 60.

3. TEST RESULTS

The analysis of the test results was divided into parts. The analyzed roughness parameters were grouped so that they would describe similar surface features. Figures 5-10 show the effect of MQL and the smoothing inserts on the amplitude parameter values. The most commonly used parameter in the industry, *Ra* that is the mean arithmetic deviation of the profile from the mean line (figures 5-7), and *Rq* (figures 8-10), the mean square deviation of the profile from the mean line, were chosen for the analyses.

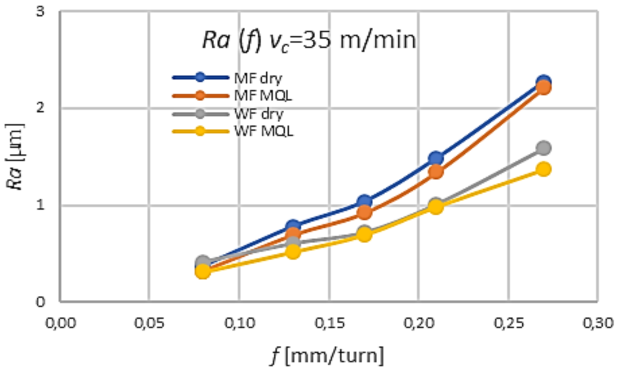


Fig. 5. Effect of feed rate and oil mist on parameter *Ra* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

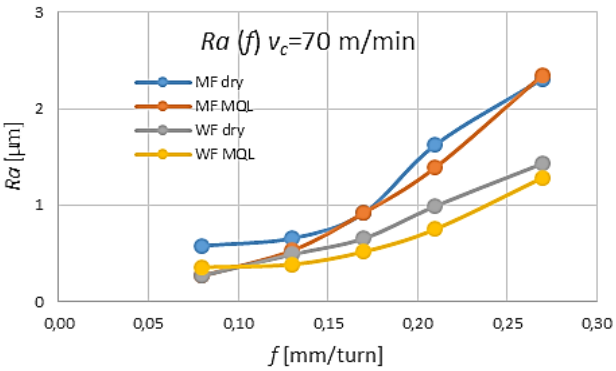


Fig. 6. Effect of feed rate and oil mist on parameter *Ra* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

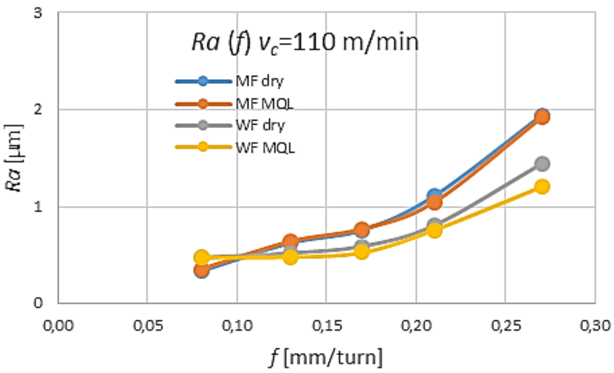


Fig. 7. Effect of feed rate and oil mist on parameter *Ra* in alloy Ti6-Al-4V turning at cutting speed v_c=110 m/min.

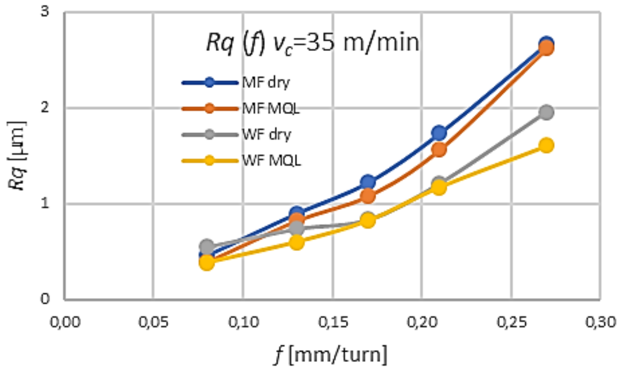


Fig. 8. Effect of feed rate and oil mist on parameter *Rq* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

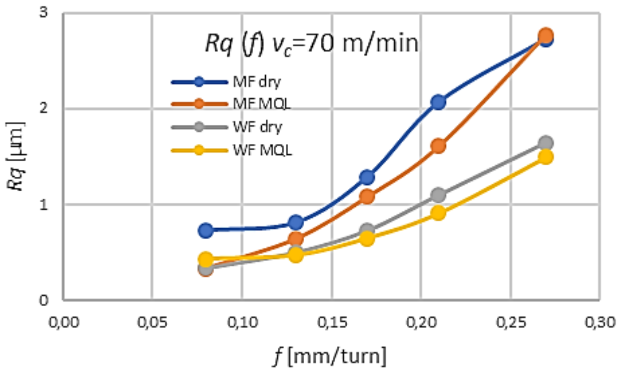


Fig. 9. Effect of feed rate and oil mist on parameter *Rq* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

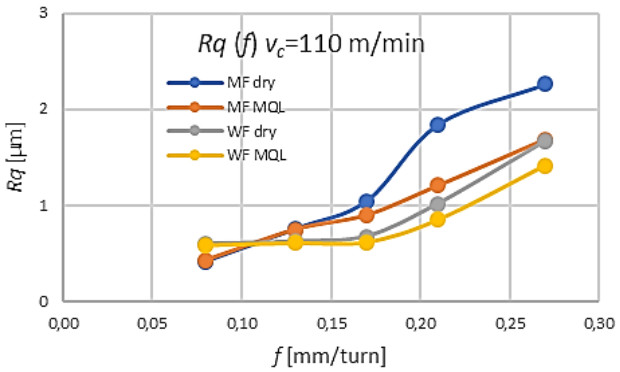


Fig. 10. Effect of feed rate and oil mist on parameter *Rq* in alloy Ti-6Al-4V turning at cutting speed v_c=110 m/min.

The values of the two parameters increase with the rate of feed. The increase is very similar to a quadratic function. It should be noted that roughness *Ra* and *Rq* as high as 0.5µm could be obtained. The effect of the wiper inserts is visible but not unequivocal. For the lowest feed rate, it is possible to obtain even lower Ra and *Rq* values after turning with a conventional insert. In the feed rate range of 0.13-0.27 mm/turn, the positive effect of the insert's wiper geometry is noticeable. After turning with the wiper insert, the value of parameter *Ra* can decrease by as much as 46% and that of parameter *Rq* by 47%. No significant effect of the cutting speed on surface smoothing with the wiper insert was noticed. However, it can be noted that at the speed of 110 m/min, this effect is weaker, and one can assume that at higher speeds, the wiper inserts would not satisfy the imposed requirements. The positive effect of oil mist is slight. For the insert with the conventional geometry, the value of parameter *Ra* was reduced by maximally 14% and that of parameter *Rq* by 35%. The strongest positive effect of oil mist was noted after turning at high feed rates and cutting speeds. But this applies to only parameter *Rq*. No such wide divergences were found after turning with the smoothing insert. Although, it should be noted that by improving machining conditions through oil mist feeding and the use of special inserts, it is possible to obtain roughness *Ra* of 1.3-1.5 µm even at a feed rate of 0.27 mm/turn.

Since parameters *Ra* and Rq are mean profile deviations from the mean line, the effect of oil mist on their values can be little noticeable. A reduction in friction in the zone of secondary strains at the chip/face contact and in the zone of tool flank action on the machined surface may result in a reduction in the number of single roughness valleys and peaks, which will not be fully reflected in the values of parameters *Ra* and *Rq*. Therefore the authors decided to analyze parameters: *Rt* – the maximum roughness height measured within the roughness traversing length (figs 11-13) and parameter *Rz* – the largest profile height within the roughness sampling length (figs 14-16).

The values of parameter *Rz* at the lowest feed rate used do not depend on the insert geometry and the cooling method. The effect of these factors increases with the rate of feed and slightly with the cutting speed. At the feed rate of 0.27 mm/turn, the wiper insert can reduce roughness by 40% in dry machining and by 43% in oil mist machining. The positive effect of lubrication is particularly strong at the cutting speed of 110 m/min. The values of parameter *Rz* decrease by as much as 37% in comparison with dry machining. Such a strong positive effect of MQL and cooling at high cutting speeds is undoubtedly due to the huge impact of cutting speed on blade durability. The speed of 110m/min exceeds the range of the speeds recommended for the cutting inserts used. By assisting machining with oil mist, one can extend this range and so increase the efficiency and productivity of alloy Ti-6Al-4V turning.

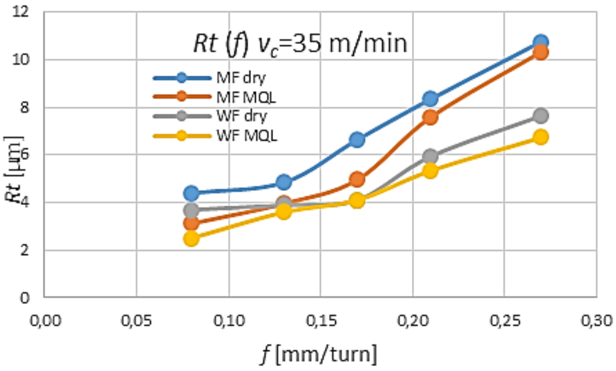


Fig. 11. Effect of feed rate and oil mist on parameter *Rt* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

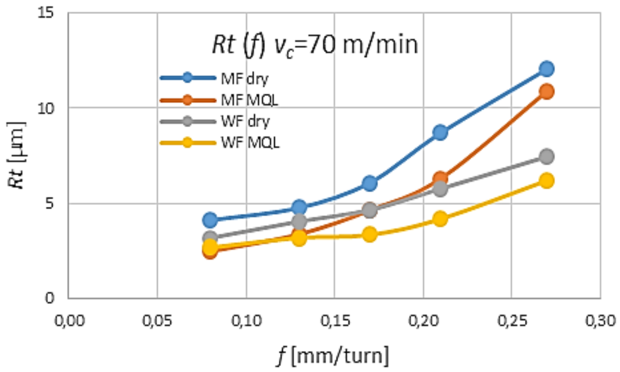


Fig. 12. Effect of feed rate and oil mist on parameter *Rt* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

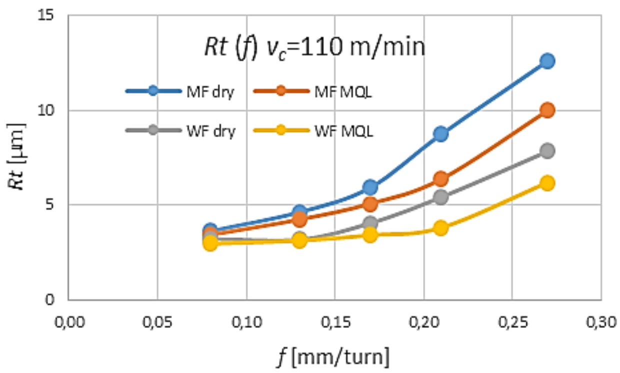


Fig. 13. Effect of feed rate and oil mist on parameter *Rt* in alloy Ti-6Al-4V turning at cutting speed v_c=110 m/min.

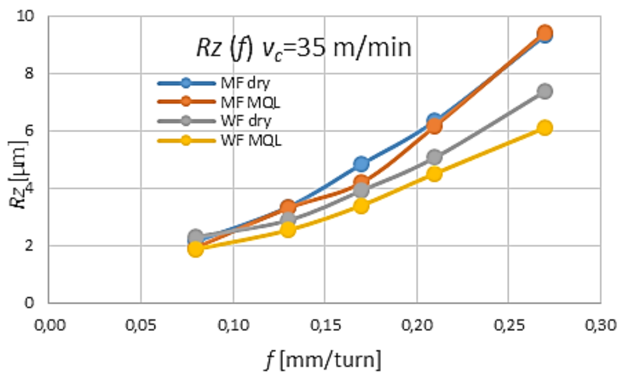


Fig. 14. Effect of feed rate and oil mist on parameter *Rz* in alloy Ti-6A-l4V turning at cutting speed v_c=35 m/min.

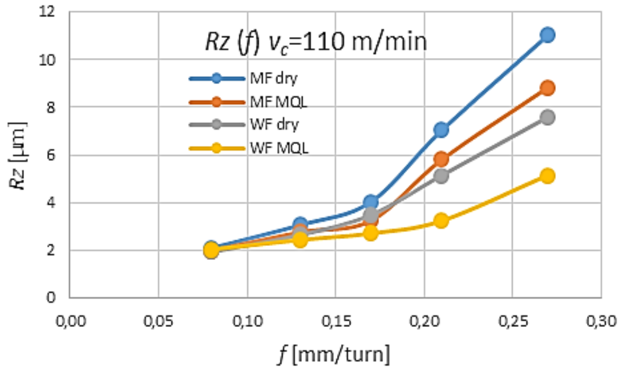


Fig. 16. Effect of feed rate and oil mist on parameter *Rz* in alloy Ti-6Al-4V turning at cutting speed v_c=110 m/min.

An analysis of the parameter *Rt* measurement results shows some differences in comparison with the parameter *Rz* measurement results. A slight positive effect of the smoothing inserts (amounting to 23%) and MQL (amounting to as much as 20%) is noticeable already at the feed rate of 0.08 mm/turn. At the feed rate of 0.27 mm/turn, this effect increases up to 38% and 31%, respectively. Also, in the case of this parameter, MQL results in the biggest improvement in surface quality at the speed of 110 m/min.

As it became apparent that the use of wiper insert geometry and oil mist improves surface roughness quality measured by both amplitude parameters *Ra* and *Rq* and vertical parameters *Rt* and *Rz*, the authors decided to check which part of the roughness profile (the valley or the peak) is more affected. Figures 17-19 show graphs of parameter *Rp*, and figures 20-22 show graphs of parameter *Rv* versus feed rate for all the cutting speeds used.

An analysis of the graphs shows a much stronger effect of MQL on the values of parameter *Rv* than those of parameter *Rp*, especially at speeds of 70 and 110 m/min. For these speeds and the conventional insert, even higher *Rp* values were obtained after machining with lubrication, whereas for the smoothing inserts, the values of the parameters were similar. The value of parameter *Rv* decreases by as much as 40%. It is an interesting observation since it would seem that the assistance of machining with oil mist will eliminate roughness peaks. It was found that the blade wear reduced by decreasing friction results in fewer surface valleys and cracks, which in dry machining can arise due to cutting edge chipping and blunting. A stronger effect of the smoothing inserts is visible for parameter *Rp*. This is so because the wiper geometry affects first of all roughness elevations, smoothing them and reducing their height. The wiper inserts remove roughness elevations so effectively that the oil mist contribution in this regard is not noticeable (no effect of MQL on *Rp* was noted). At the highest feed rates, used it can happen that the surface machined with lubrication will show a higher value of this parameter than when dry machined. Cutting speed has no significant bearing on how machining conditions affect the peaks or valleys of the roughness profile.

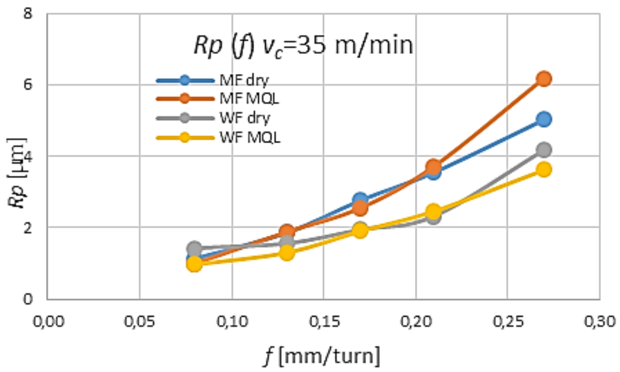


Fig. 17. Effect of feed rate and oil mist on parameter *Rp* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

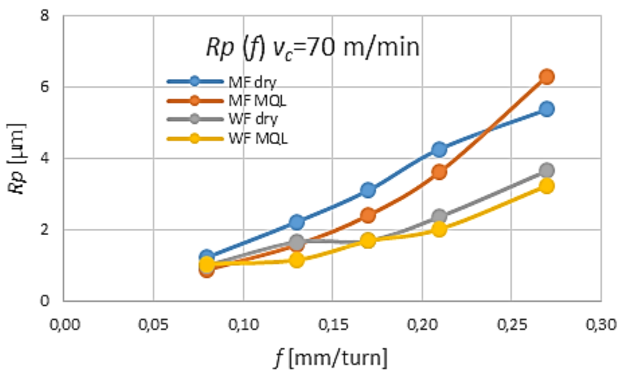


Fig. 18. Effect of feed rate and oil mist on parameter *Rp* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

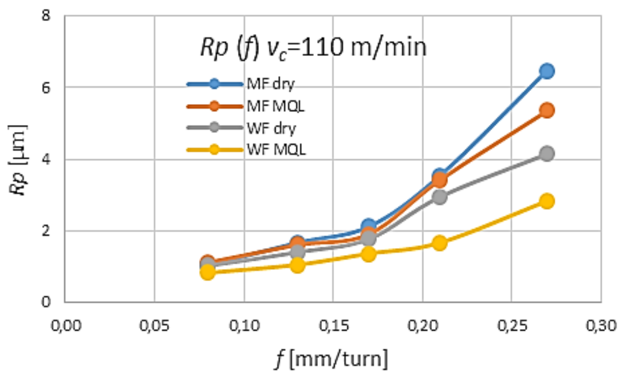


Fig. 19. Effect of feed rate and oil mist on parameter *Rp* in alloy Ti-6Al-4V turning at cutting speed v_c=110 m/min.

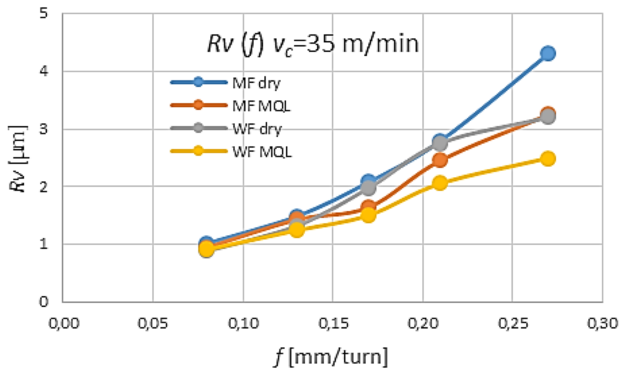


Fig. 20. Effect of feed rate and oil mist on parameter *Rv* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

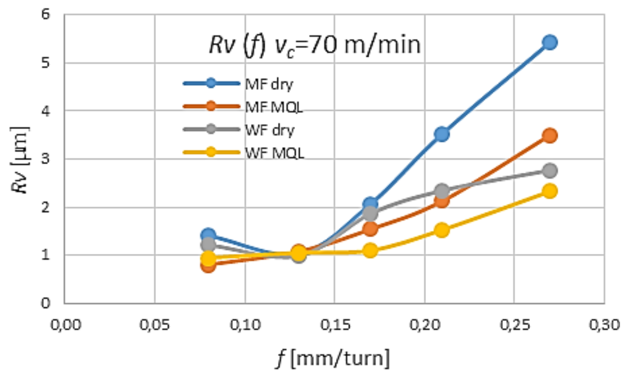


Fig. 21. Effect of feed rate and oil mist on parameter *Rv* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

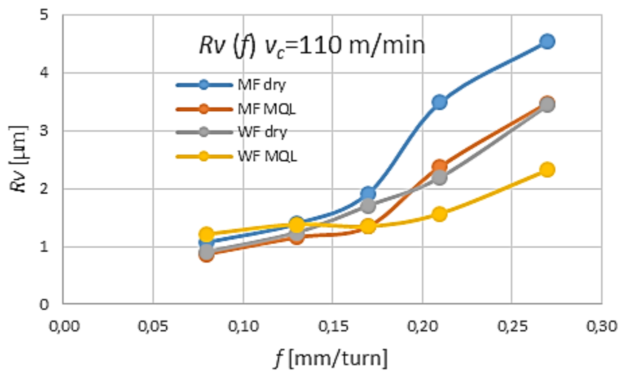


Fig. 22. Effect of feed rate and oil mist on parameter *Rv* in alloy Ti-6Al-4V turning at cutting speed v_c=110 m/min.

The above analyses are supplemented with an analysis of statistical parameters. The *Rsk* parameter was analyzed, which is a profile asymmetry coefficient expressing the skewness of the distribution of ordinates. It has an averaging character and can assume positive values for structures with numerous peaks and negative values for surfaces with predominant valleys. The further this parameter is distant from zero, the more nonuniform the distribution of the material. The another analyzed parameter *Rku* is a measure of the amplitude density curve's acuteness, also referred to as a flattening coefficient. It has a limit at *Rku*=3. Below this limit the asperities are longer and the peaks are more filled with the material, while above this limit they become sharper and shorter.

Analysis of parameters *Rsk* and *Rku* show that assisting turning with oil mist results in some stabilization of the titanium Ti-6Al-4V surface texture shaping process. Thanks to MQL, the effect of cutting parameters on parameters *Rsk* (figs 23-25) and *Rku* (figs 26-28) disappears – their values do not change significantly as the feed rate and the cutting speed increase.

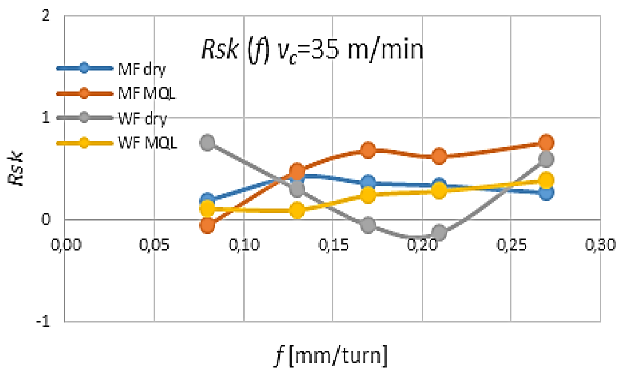


Fig. 23. Effect of feed rate and oil mist on parameter *Rsk* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

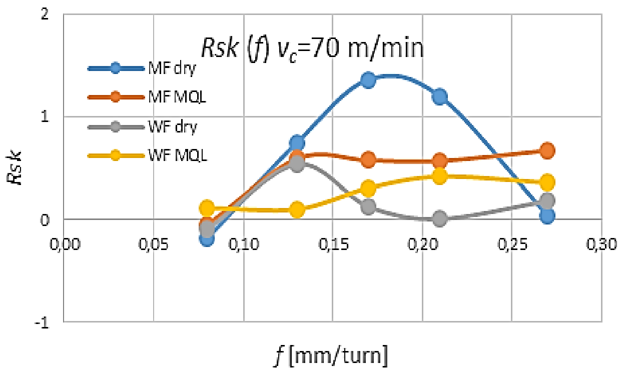


Fig. 24. Effect of feed rate and oil mist on parameter *Rsk* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

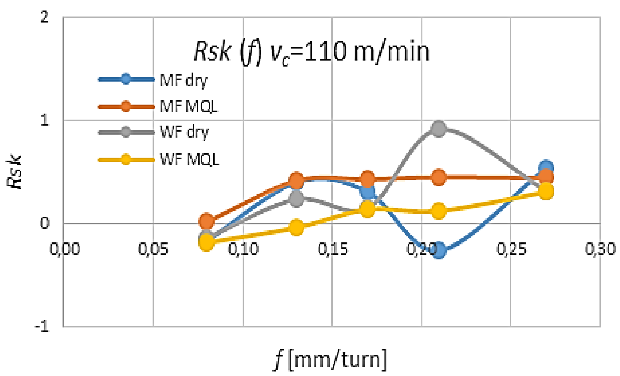


Fig. 25. Effect of feed rate and oil mist on parameter *Rsk* in alloy Ti-6A-l4V turning at cutting speed v_c=110 m/min.

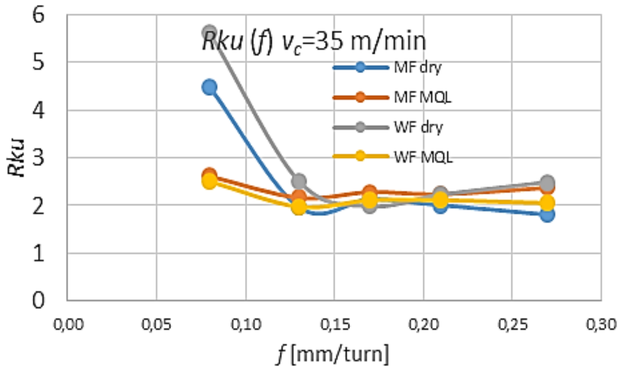


Fig. 26. Effect of feed rate and oil mist on parameter *Rku* in alloy Ti-6Al-4V turning at cutting speed v_c=35 m/min.

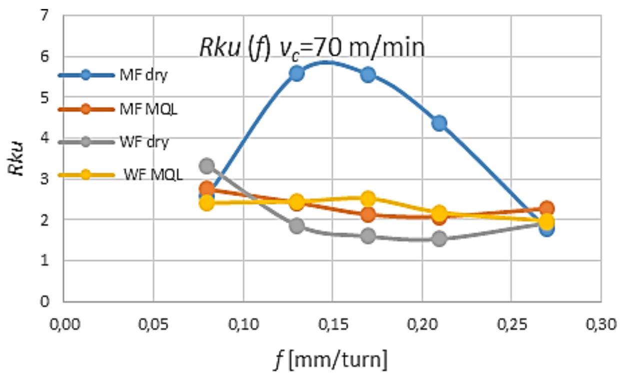


Fig. 27. Effect of feed rate and oil mist on parameter *Rku* in alloy Ti-6Al-4V turning at cutting speed v_c=70 m/min.

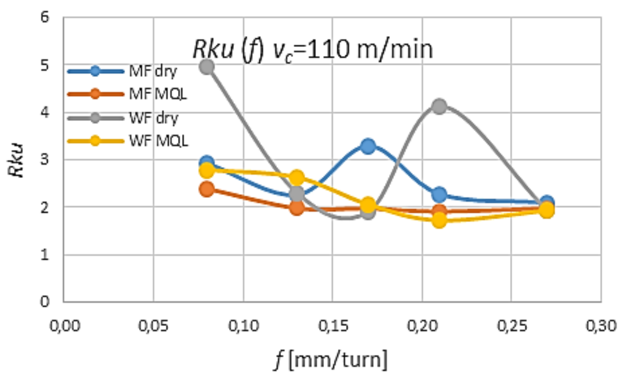


Fig. 28. Effect of feed rate and oil mist on parameter *Rku* in Ti6Al4V turning at cutting speed v_c=110 m/min.

Whereas in the case of dry machining, parameters *Rsk* and *Rku* assume random values and their correlation with the cutting parameters cannot be established. Therefore when assessing the smoothing inserts, only the parameter values after MQL-assisted turning were taken into account. It was noted that when the wiper blades were used, *Rsk* would assume values approaching zero or even negative values.

This is consistent with the observations of parameters *Rp* and *Rv* and provides further evidence that wiper blades smooth elevations. No effect of insert geometry on parameter *Rku* was noticed. The parameter assumes values lower than 3 after turning with each of the inserts in minimum quantity lubrication conditions. Consequently, the machined surfaces have no slender elevations.

The analyses of roughness profiles were supplemented with observations of the measured 3D surfaces (figs 29 and 30). Figure 29 shows surfaces after turning at feed rate *f*=0.08 mm/turn. The character of the tool marks changes slightly when oil mist lubrication is used, and also when smoothing inserts are used. This confirms the results of the 2D measurements. Figure 30 shows the surfaces after turning at feed rate *f*=0.27 mm/turn. After turning with the wiper inserts, one can see a marked change in surface texture and a considerable reduction in the height of roughness elevations. There is also a noticeable reduction in the number of single peaks and roughness pits on the surfaces obtained after turning with oil mist assistance.

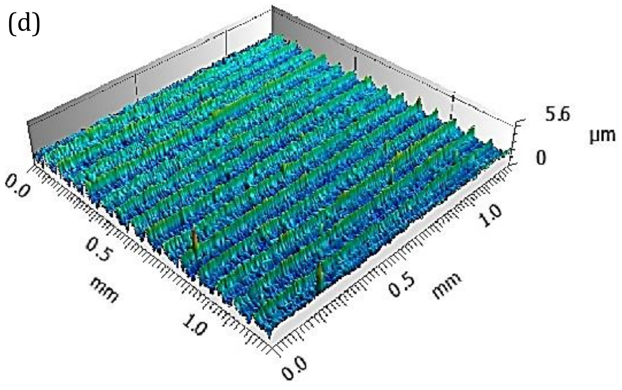
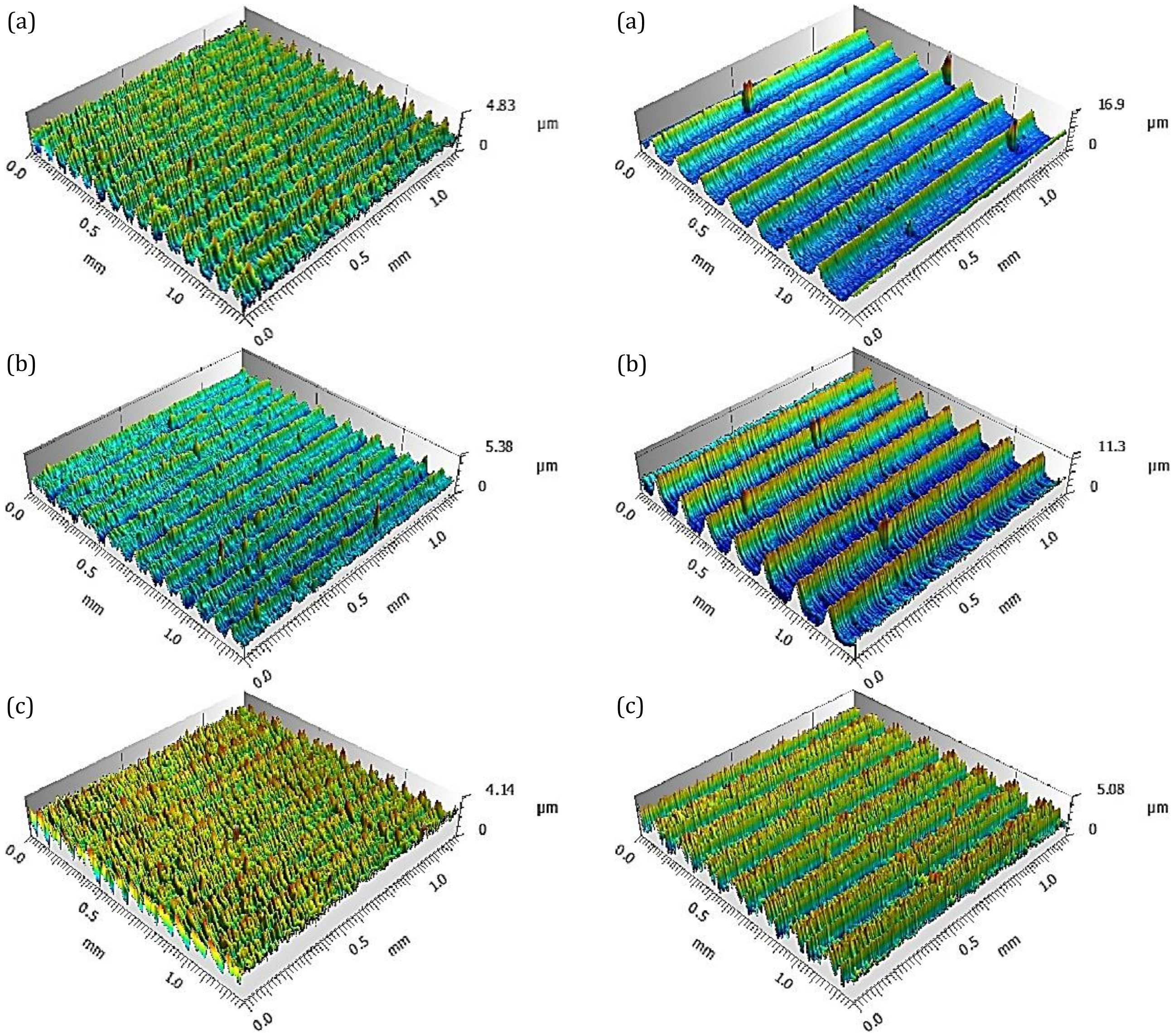


Fig. 29. 3D titanium alloy surfaces after: (a) dry turning with conventional insert, (b) MQL-assisted turning with conventional insert, (c) dry turning with wiper insert and (d) MQL-assisted turning with wiper insert, at feed rate of 0.08 mm/turn and cutting speed 35 m/min.



(d)

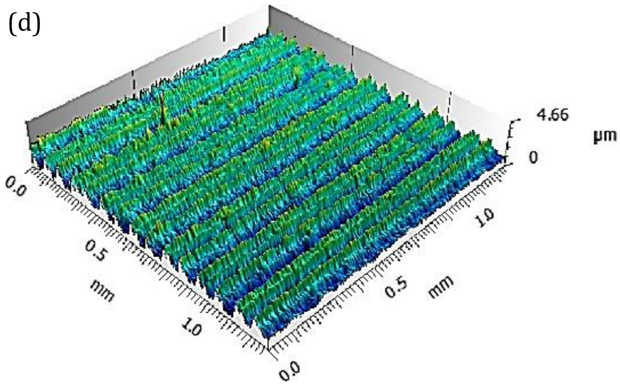


Fig. 30. 3D titanium alloy surfaces after: (a) dry turning with conventional insert, (b) MQL-assisted turning with conventional insert, (c) dry turning with wiper insert and (d) MQL-assisted turning with wiper insert, at feed rate of 0.27 mm/turn and cutting speed 35 m/min.

4. CONCLUSIONS

Owing to their excellent strength at small weight, titanium alloys are readily used in aviation. As they are characterized by enhanced high-temperature creep resistance, they can also be used for engines. Because of their low thermal conductivity and tendency towards strain hardening during machining, they are classified as poorly machinable materials. Titanium alloys are rarely dry machined. Instead, various cooling methods are employed to assist the machining process. One of the methods is cooling and minimum quantity lubrication (MQL). As part of this research, an attempt was undertaken to assess the effect of machining conditions on the quality of the surface after turning. The main conclusions emerging from the research are as follows:

- using smoothing inserts and MQL at a feed rate of 0.08 mm/turn, one can obtain surface roughness Ra of 0.3-0.5μm;
- it is possible to effectively increase alloy Ti-6Al-4V machining productivity at no significant deterioration in surface quality; at feed rate f=0,27 mm/turn roughness Ra of 1.2μm can be obtained;
- at the lowest used feed rate f=0.08 mm/turn, the effect of MQL and the wiper inserts is ambiguous; at higher feed rates, the positive effect of both the factors becomes evident;
- it is possible to reduce the *Ra* parameter after turning with a Wiper insert by up to 46% and the *Rq* parameter by 47%;
- the effect of the oil mist is less. For an insert with traditional geometry, the maximum reduction of the *Ra* parameter by 14% and the *Rq* parameter by 35% was obtained;
- the influence of the tested factors on the *Rz* parameter values increases with the increments of the feed and slightly the cutting speed. The feed of 0.27 mm / rev allows the insert with the Wiper geometry to reduce the Rz roughness by 40% during dry machining and by 43% when using oil mist.
- As a result of the use of oil mist, the number of cracks and valleys in the surface decreases - the reduction of the *Rv* value due to the use of oil mist is even 40%, while smoothing inserts effectively remove roughness elevations and peaks.
- As a result of the assistance of machining with oil mist, the effect of the feed rate on the values of parameters *Rsk* and *Rku* disappears; Therefore, it can be assumed that under MQL, the feed rate affects only the roughness amplitude without affecting the character of tool marks. Consequently, it is easier to forecast the in-service properties of the surface of titanium alloy Ti-6Al-4V after turning.

The obtained test results show that the application of minimal lubrication of the MQL cutting zone allows to obtain good quality Ti6Al4V titanium surface after turning. The next stages of the research should be to check the effect of the oil mist quantity on the surface roughness and to determine the lower limit value of the quantity at which a positive effect of MQL appears. The possibility of using oils other than LB 8000 for oil mist generation should also be checked.

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