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Influence of GnP additive to vegetable oil on machining performance when MQL-assisted turning Alloy 718

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Abstract

The current study demonstrates through experiment the effect of solid lubricant assisted minimum quantity lubrication (MQL) on the machining performance when turning Alloy 718 with cemented carbide tools. A powder of nanosized (~30 nm) graphite nanoplatelets (GnP) was dispersed (0.2% vol.) in a vegetable oil-based lubricant "ECOLUBRIC E200L" and used in MQL-assisted machining. The effect of cutting conditions on the machining performance parameters such as forces, tool wear, surface finish, and vibrations generated was studied. Results demonstrate a significant improvement of the machining performance when MQL-assisted turning of Alloy 718 with GnP-modified oil in terms of tool life, surface finish and process stability.

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Keywords: turning; Alloy 718; MQL; modified vegetable oil; graphite nanoplatelets (GnP); tool wear; surface finish; vibrations

1. Introduction

Cutting fluids are an indispensable constituent of machining processes when acting as coolant/lubricant and influencing the chip formation processes in the cutting zone. Application of the fluids results in the improvement of machining accuracy and surface finish, an extension of tool life, as well as chips disposal from the working zone. On the other hand, employing cutting fluids causes a hazardous impact on the environment and human health. Whereas it is difficult to completely avoid the use of the coolants in machining operations, a conceivable way for resolving

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the problem is a dramatic reduction of their amount in the process in combination with replacing harmful components the fluids are comprised of. The most promising solution to these requirements is a minimum quantity lubrication (MQL), and its modifications such as minimum quantity cooling lubrication (MQCL) in combination with cryogenic technique, etc. [1-3]. The techniques may be improved by a utilization of mineral oils modified by micro- and nano-dispersed materials such as MoS_2, CaF_2, Al_2O_3, CuO etc. and graphite, as well as by the use of vegetable-based oils instead of mineral ones [2, 4, 5].

All aforementioned is an urgent problem for machining difficult-to-machine materials like stainless steels, titanium alloys [2, 6], and nickel-based superalloys [3, 7, 8], and are usually accompanied by a significant consumption of coolant [6-8]. The cutting fluid consumption rate can potentially be decreased by means of a MQCL technique in the case of at least comparable process performance with those for a conventional cooling. With regard to the latter, experimental data, unfortunately, differ considerably for different studies. In general, the diversity can be explained by numerous grades and types of workpiece and tool materials, coolants, as well as specifics of experimental setups.

Practically, the MQL techniques are not widespread in the industry despite the fact that the method is well known for decades. This is an evidence of, at least, the complex nature of the MQL-assisted machining process, which depends on many factors and process parameters. The mechanisms of the process are not studied deeply enough, and existing researches are mainly case studies.

The current study is one more attempt to look at the process of MQL-assisted turning of the age-hardened superalloy Alloy 718 using pure and modified with graphite nanoplatelets (GnP) vegetable-based oil. The article reports the results of the experimental study, which is aimed at the assessment of the performance of machining Alloy 718 with coated cemented carbide (CC) tools. Detailed analysis is presented on the influence of lubricant type and cutting conditions on tool wear, tool life, surface finish, and the dynamic interaction between tool and workpiece, as well as process stability during machining.

2. Materials and methods

2.1. Test setup and machining conditions

All machining tests are performed on a Boehringer Göppingen VFD engine lathe with a motor power of 30 kW and spindle speed rated up to 1800 rpm. The workpiece material was a bar of ∅70×250 mm. Alloy 718 was in the solution treated and aged conditions (~46 HRC). Continuous longitudinal turning tests were done with micro-grain coated CC tools of type DNMG 150608-MF1, grade CP200 (SECO Tools AB) suitable for finishing and semi-finishing machining. The tool provides a chipbreaker with rake angle 14°6′, cutting edge radius 25 μm, and chamfer angle 0°. Inserts have PVD coating of a ceramic layer of (Ti-Al)N over a primer layer of TiN, offering high resistance to wear. The toolholder was of a PDJNR 2525 M15 Jet type geometry with a system of internal passages to provide MQL lubricant at rake and flank faces during machining (Figure 1a, b). The inclination and clearance angles of the insert-toolholder system are λ = -6° and α = 6°, respectively, for all cutting geometries. The toolholder with fixture was clamped to a dynamometer and mounted on the toolpost.

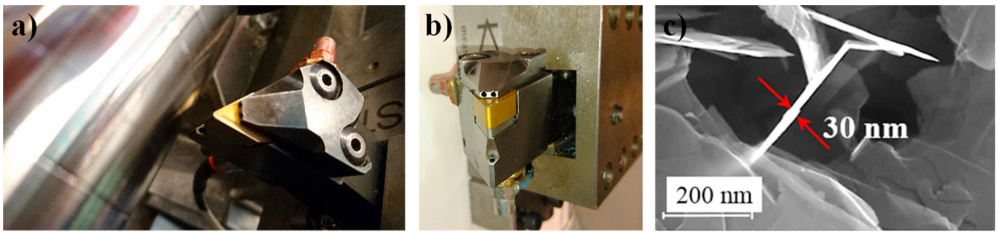

Figure 1. Setup for MQL-assisted turning (a, b) and SEM of graphite nanoplatelets (GnP) particles (c).

Cutting conditions were selected to correspond with the range from finishing to medium turning operations, where DOC was kept constant for all tests and equal to a_p = 0.3 mm. Feed rates and cutting speeds were selected as follows: f = 0.08, 0.125, 0.16 mm/rev; v_c = 40, 50, 60 m/min. This range was selected to mainly cover the range of conventional cutting speeds recommended by the tool manufacturer. The machining tests were performed at dry conditions using pure and modified by GnP rapeseed oil as a cooling/lubricating media for MQCL-assisted turning.

2.2. Cooling/lubrication conditions

The rapeseed oil (ECOLUBRIC E200L) was delivered by Accu-Svenska AB (Sweden). Some characteristics of the oil can be found in [2]. Nanoadditives (GnP) were produced by sonication of thermally expanded graphite (TEG) in a 10% (vol.) alcohol solution (1 g of TEG per 120 ml of solution) during 24 hours in an ultrasonic dispenser with a power of 350W. SEM image of GnP particles is illustrated in Figure 1c. The average size of particles was around 1 µm in diameter and 50 nm in thickness. A modification of oil was performed by adding 0.2% (vol.) of the graphite suspension into the pure oil and persistently stirring using a magnetic stirrer for 10 min. The oil-GnP suspension remains stable around 20 days with insignificant sedimentation.

Original and modified oils were supplied by MQL Ecolubric Booster System provided by Accu-Svenska AB. The flow rate of lubricant mist was set up at 15 ml/h, supporting the idea of the minimum environmental impact, whereas the air pressure was kept constant at 0.5 MPa.

2.3. Measurements and analysis

The data acquired from both types of tests are acceleration spectra of the tooltip and the cutting forces in three mutually perpendicular directions. Tool wear and wear morphology, surface quality, and the morphology of the machined surfaces were also determined. The measurement and reconstruction of worn cutting edges were performed by an optical 3D measurement system – Alicona InfiniteFocus Real3D.

A three-axis piezoelectric dynamometer Kistler 9129AA was used to measure cutting forces. Vibrations in three orthogonal directions were measured using three accelerometers (B&K, type 8309, frequency range up to 60 kHz). Spectra of cutting forces and accelerations were acquired, amplified and recorded simultaneously at sampling rates of 1 kHz and 120 kHz, respectively. FFT analysis was used to extract signal characteristics in the frequency domain.

Surface finish parameters were measured with the portable roughness tester Mahr MarSurf PS10 after each pass at least five times along the workpiece in a feed direction.

3. Results and discussion

The main reasons for applying a coolant/lubricants in machining are as follows: heat dissipation and/or redistribution in the cutting zone among tool, workpiece, chips, and environment; lubricating the interfaces of tool, chips and workpiece surfaces results in reduced heat generation and decreased adhesion between tool and workpiece materials.

These effects suppose an attenuation of adhesive and diffusive wears mechanisms related to chemical reactions in the cutting zone, as well as an abrasive impact on the tool surfaces, to a lesser extent. It is well known that the decrease in friction and adhesion interactions in the cutting zone influences the chip formation mechanism, resulting in decreased contact length between the tool rake face and chips. At these conditions, it is more reasonable to study not only mean or RMS values of forces and vibrations, but also an evolution of their variation in time. Hence, the variations in the contact length and chip segment size should affect the system behavior in a frequency domain. The formation of the adherent layer on the tool edge should be reflected on the tool dynamic behavior and on the machined surface finish. In addition to R_a and R_{max} values, the deviation between experimental and theoretical surface profiles also indirectly characterizes the processes in the cutting zone.

3.1. Cutting forces

Figure 2 shows an evolution of the mean value of cutting forces over machining time at different feed rates at cutting speed 50 m/min (behavior of cutting forces at other cutting speeds is similar to those presented in the figure).

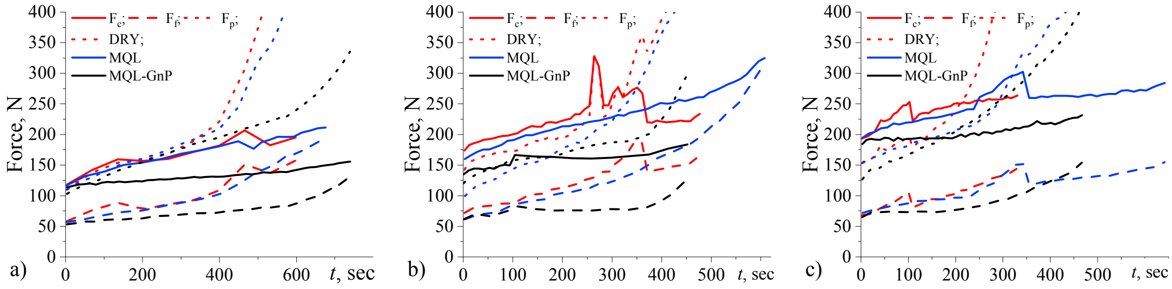

Figure 2. Cutting forces vs. time at different lubrication strategies: a) f = 0.08 mm/rev; b) f = 0.125 mm/rev; c) f = 0.16 mm/rev.

The forces are characterized by an increasing trend due to tool wear development in combination with instability related to a breakage of the cutting edge. At the beginning of the process, force values are similar when machining at dry and MQCL conditions at all feed rates, whereas the machining with GnP-modified oil decreases the forces with an increase in feed rate of up to 15%. Considering the used tool geometry and cutting conditions, this may indicate the reduction of friction in the cutting zone in the vicinity of the tool nose, where cutting and passive force components are more sensitive to a change in friction conditions. The negligible difference between dry machining and using a pure oil lubrication is probably related to specifics of insert's coating material [10, 11], although the effect of cooling/lubrication is clearly seen and intensifies with increased speed. The average values of force variation around its mean value during machining at different cutting test conditions are shown in Figure 3.

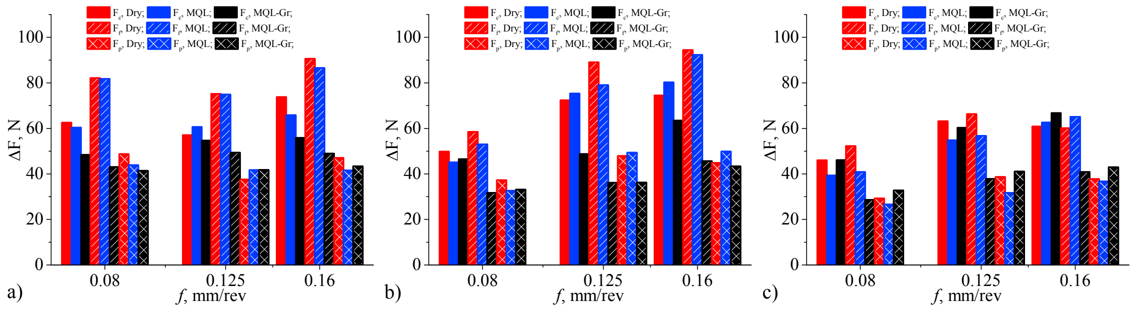

Figure 3. Average values of cutting force variation at different cooling conditions: a) v_c = 40 m/min; b) v_c = 50 m/min; c) v_c = 60 m/min.

The figure shows that cutting and feed force components are subjected to variation due to the chip formation process, whereas the passive component is stiffer and influenced by a formation of flank wear land. Moreover, the force variation amplitude of the cutting component is dependent on the adhesive processes on the flank in addition to chip and segment formation mechanisms. The influence of lubrication when machining with pure oil is mostly significant at low values of feed rates and almost has no effect at other cutting conditions as compared to dry machining. This evinces a more significant effect of oil as a coolant and, to a lesser extent, as a lubricant.

GnP additive has much more of a considerable impact on the process within the range of cutting speeds 40-50 m/min within the range of all feed rates. The comparable results at a feed of f = 0.08 mm/rev is probably related to a presence of tool edge radius and chamfer size of around 0.1 mm. The increased speed hinders the graphite nanoparticles from penetrating the cutting zone. The effect of graphite at higher cutting speeds (60 m/min) is visible on the force variation amplitude in a feed direction due to a partially open radial part of the tool nose, which is accessible for lubrication.

3.2. Tool wear

The tool wear mechanisms of uncoated CC tools and those coated with CVD and PVD of different compositions when turning Alloy 718 are well studied [9, 10]. Therefore, only some results are presented in the subsection. Since the influence of lubricants is mostly visible at lower cutting speeds, Figure 4 illustrates 3D images (difference between sharp and worn tools) of tools at v_c = 40 m/min and f = 0.08 mm/rev, where the length of cut is comparable for all used lubrication strategies. The pictures have the same color scale of depth.

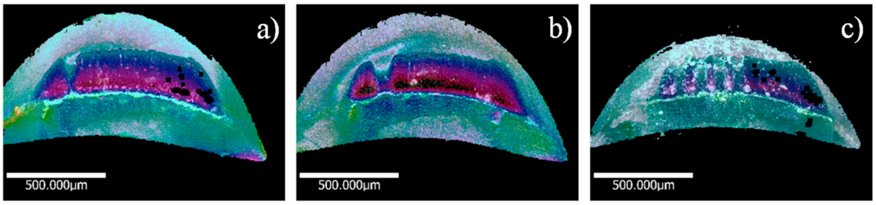

Figure 4. 3D images of worn tools at v_c = 40 m/min, f = 0.08 mm/rev: a) dry; b) pure rapeseed oil; c) oil modified with 0.2% GnP.

Figure 4 proves the conclusions of the authors [9, 10] about the diffusion and abrasion as main wear mechanisms in combination with cutting edge chipping, rake flaking, notch formation, and adhesion. In [9] it is shown that the formation of grooves, as seen in Figure 3c, is typical for initial formation of flank wear land. This concludes that GnP particles in oil prevent/retard the flank wear development. The evolution of flank wear land size versus length of cut is depicted in Figure 5.

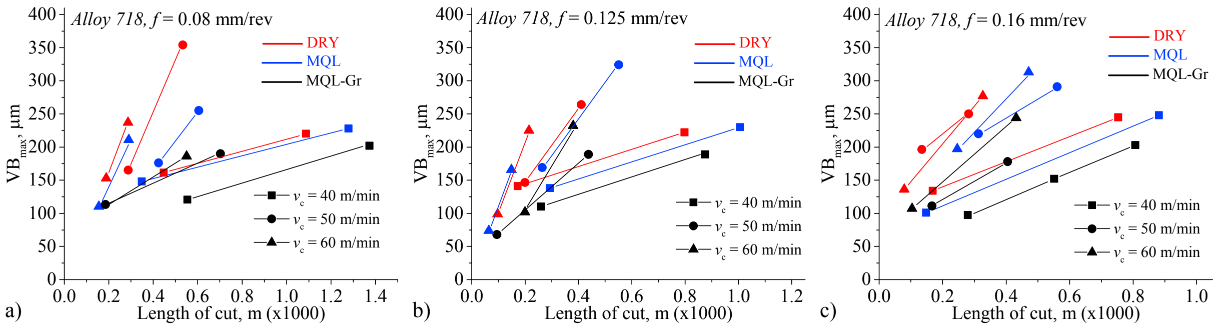

Figure 5. Flank wear vs. length of cut at different cutting and cooling conditions: a) f = 0.08 mm/rev; b) f = 0.125 mm/rev; c) f = 0.16 mm/rev.

The results show the benefits of using GnP-modified oil with respect to lengthened tool life at overall test conditions. Although the used concentration of 0.2% (vol.) of GnP-water suspension in the oil is not optimized, and it is likely possible to improve a tool's life even more, this requires further detailed researches.

Considering the aforementioned change of friction conditions and temperature distribution (e.g., intensity of chemical reactions, diffusion processes, formation of adherent layer) in cutting zone it should be also reflected on the dynamic behavior of the machining system. The study of the interaction between system components 'tool-process-workpiece' was carried out to reveal the specific influence of GnP nanoparticles on the cutting process.

3.3. Vibrations generated and process stability

The results of measurements of tool vibrations (accelerations) are presented below. The approach is similar to the previous procedure, but in the case of accelerations the RMS value is used instead of the average. Figure 6 represents the evolution in time of RMS value of accelerations at different cutting conditions. The dependencies of the average vibration amplitude at different cutting and lubrication conditions are presented in Figure 7.

Results in Figure 6 prove instability when dry machining (intermittency of RMS curves), which is related to the mutual influence of cutting edge damage and adhesion processes in the cutting zone such as a regeneration of the adherent layer on the rake and flank (excitation factor). It is possible to avoid this unstable behavior via MQL-assisted machining, as well as to decrease, to some extent, the intensity of vibrations, especially at lower values of feed rate. However, RMS spectra when machining with GnP-modified oil have higher amplitude compared to the pure oil lubrication process and are similar to dry machining save for the instability.

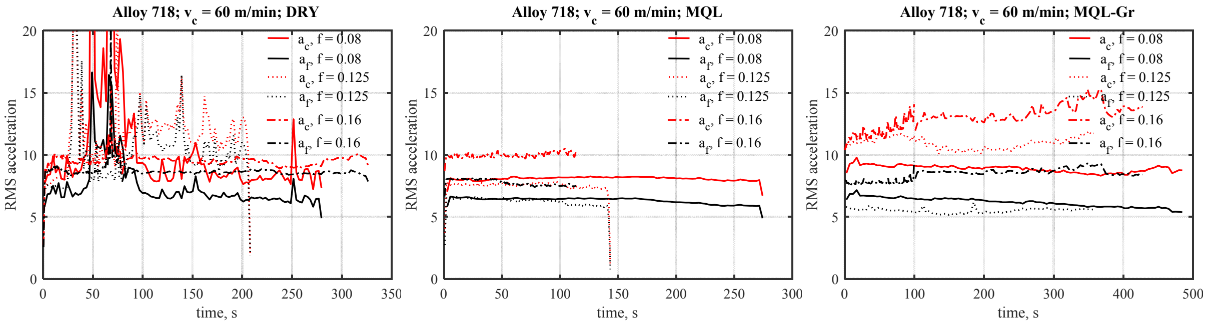

Figure 6. RMS of acceleration signals at different cutting and cooling conditions.

The dependencies of vibration amplitude on cutting and cooling/lubrication strategies (Figure 7) show very good correlation with force variation values shown in Figure 3 at all test conditions for dry machining and when utilizing pure oil as a coolant/lubricant. However, the results for GnP-oil lubricant differ at low cutting speeds, where a probability of the GnP particles of reaching the cutting zone is highest. The vibration amplitude in the last case is more comparable to dry machining conditions than to oil lubrication, especially for feed components of acceleration.

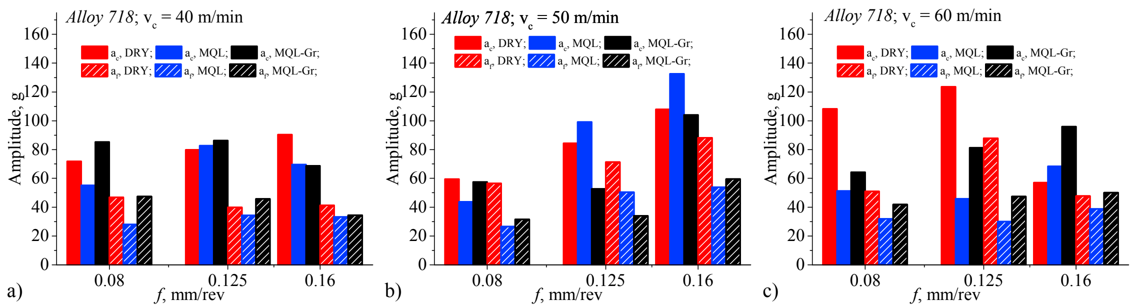

Figure 7. Acceleration signal amplitudes at different cutting and cooling conditions.

The disagreement in the higher vibration amplitude at lower forces can be explained by a change of energy dissipation mechanism. The change is often associated with resonant phenomena or chatter appearance, but the latter was not observed during the tests. In our case, considering the decrease of friction in the cutting zone and decrease in contact length, the acceleration amplitude increase might be explained by an increase in tool oscillation frequency that, in turn, can be related to change of contact length variation frequency. This explains the higher impact on the behavior of feed component accelerations. In terms of dynamics, this implies the change of process stiffness and damping; therefore, a difference in the system response should be clearly seen in a frequency domain. Figure 8 shows FFT spectra of accelerations in cutting direction for the feed rate value $f = 0.16$ mm/rev, where the excitation is strongest (results for acceleration spectra in feed direction are similar).

FFT spectra show quite a similar behaviour of a dynamic response in the frequency domain in the case of dry machining and MQL-assisted with pure oil conditions. The frequencies excited are situated in a wide frequency diapason of 1.5-5.1 kHz, shifting into a range of 1.7-6.1 kHz with an increase of cutting speed and exciting the frequencies in a wider band. In contrast to previous cases, the machining with GnP-oil lubrication causes a rise of harmonics in the range of 3.0-6.0 kHz and shifting to 3.0-7.1 kHz with an increase of speed. Harmonics excited with frequencies around 2.0, 3.3, 4.7, and 6.9 kHz are related to natural frequencies of the system ‘machine tool-tool-workpiece’ and remain constant at all cutting and cooling conditions. Machining at dry conditions, and with the use of the pure oil, leads to excitation of harmonics of frequencies 2.5 and 3.1 kHz, whereas the GNP-oil lubrication results in generating higher frequency harmonics at 3.8, 3.9 and 4.0 kHz (slight shift of harmonic of 3.3 kHz is caused by a test setup). This proves the assumption about the change of system dynamic parameters when using modified oil as a lubricant.

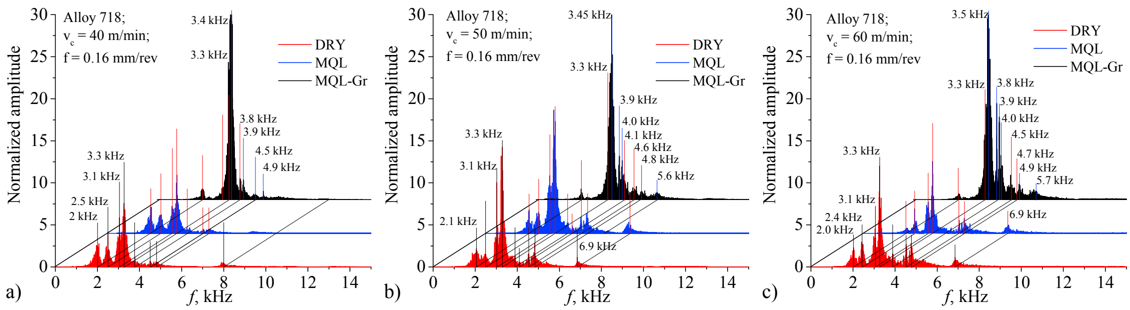

Figure 8. FFT of acceleration signals at different cutting and cooling conditions.

3.4. Surface finish

Independent of the physics behind the cutting process, the quality of the machined surface is one of the most important characteristics of the performance and defines, in combination with other factors, an expediency of application of GnP additives for MQCL-assisted machining. Average values of surface roughness (R_a) along a pass depending on the cutting and cooling conditions are shown in Figure 9. Error bars represent a deviation of the absolute value of R_a.

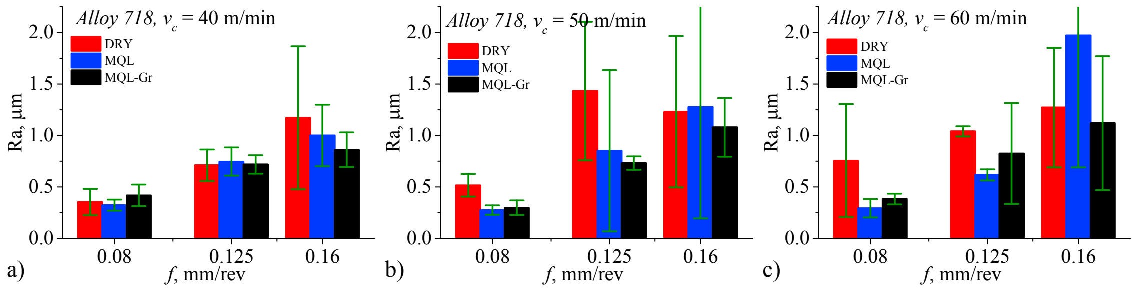

Figure 9. Surface roughness: a) v_c = 40 m/min; b) v_c = 50 m/min; c) v_c = 60 m/min.

Results show that the surface finish, when utilizing the GnP-modified oil, is better or comparable to one for dry machining and with the use of pure oil as a lubricant. The advantage of using the modified oil appears when turning with higher feed rates within overall cutting speed range.

It is known that the average value of surface profile (R_a) is not a parameter entirely describing specifics of surface finish. In order to reveal the specifics of machined surface in more detail a signal-to-noise ratio (SNR) – deviation between experimental and theoretical profiles – was employed for characterization. SNR indirectly characterizes the influence of chip formation processes, adhesion between tool and workpiece materials, vibrations generated, and tool wear development on the surface finish. The results are illustrated in Figure 10. Higher SNR values correspond to better agreement between real and calculated profiles. Error bars show the absolute variation of SNR during the pass.

The results prove the considerable influence of edge roundness and chamfer on the machining with the lowest feed rate, where the surface quality degrades with increased cutting speed. The increased feed rate value shows satisfactory results within the overall cutting speed range used in the tests.

4. Conclusions

The following conclusions can be drawn for summarizing the results of the experiments and analyses:

– GnP additives of 0.2% (vol.) to vegetable-based oil can significantly improve the process performance when MQCL-assisted turning of Alloy 718 in terms of tool life, surface finish and process stability;

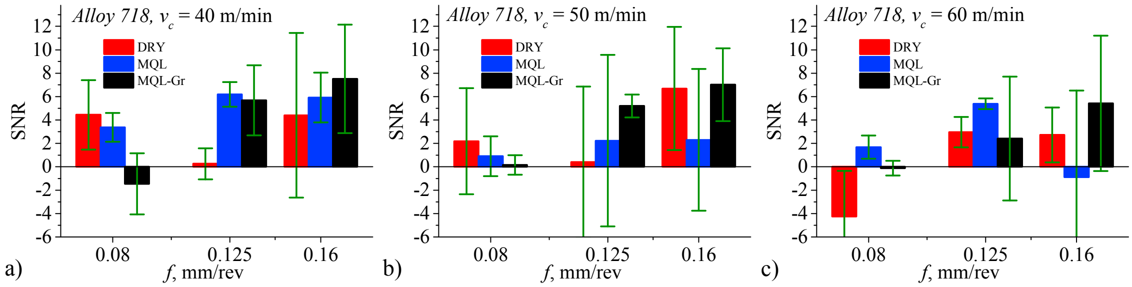

Figure 10. Signal-to-noise ratio of surface profiles at a) v_c = 40 m/min; b) 50 m/min c) 60 m/min

– According to obtained results, the presence of GnP particles results in a significant reduction of friction in the cutting zone in combination with the cooling effect influencing the chip formation process, whereas a pure oil lubrication acts more as a coolant only;

– MQCL-assisted turning of Alloy 718 with vegetable-based oil, both with and without nanoadditives, stabilizes the cutting process. However, the utilization of graphite nanoparticles results in an increase of ‘effective process stiffness’ due to the decrease of contact length on the tool-chip interface and adhesion between tool and workpiece materials, both on the rake and flank.

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