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Influence of graphite nanoadditives to vegetable-based oil on machining performance when MQCL assisted hard turning

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Abstract

The current study demonstrates through experiment, the effect of solid lubricant assisted minimum quantity cooling lubrication (MQCL) when turning tempered (~60 HRC) alloyed steel Uddeholm Caldie with cemented carbide tools on the process performance. In MQCL application, nanosized graphite nanoplatelets (GnP) solid lubricant powder was dispersed (0.2% vol.) in rapeseed oil based lubricant "ECOLUBRIC". The effect of cutting parameters at dry machining and with MQCL lubrication on the machined surface finish, tool forces, tool wear and vibrations generated were studied.

Keywords: hard turning; Uddeholm Caldie; MQCL; modified vegetable oil; graphite nanoplatelets (GnP); tool wear; surface finish; vibrations

1. Introduction

Cutting fluid is an indispensable constituent of machining processes performing the functions of coolant/lubricant and influencing on the chip formation processes in the cutting zone. Application of the fluids results in improvement of machining accuracy and surface finish, an extension of tool life as well as in a chips disposal from the working zone. On the other hand, it is well known that cutting fluids have a hazardous impact on the environment and human health. Whereas it is difficult to completely get rid of the coolants in machining, a conceivable way for resolving the problem is a dramatic reduction of their amount in the process together with a replacement of harmful components the fluids are comprised of. A promising solution to the requirements is a minimum quantity lubrication (MQL) and its modifications in combination with cryogenic technique, etc. [1]. The techniques may be improved by a use of mineral oils modified by micro- and nanodispersed materials as well as by utilization of vegetable oils instead of mineral ones [2].

All mentioned is an urgent problem for machining difficult-to-machine materials that usually requires a significant amount of coolant. However, consumption rate of cutting fluids can be potentially decreased by means of MQL technique in case of at least a comparable process performance with those for a flood cooling. Regarding latter, experimental data, unfortunately, differ quite much for different studies that, in general, can be explained by specifics of experimental setups and conditions.

A practice shows that MQL-wise techniques are not still widespread in the industry even though the method is well known for decades. This is an evidence of, at least, complex nature of MQL assisted machining process and many of studies have mainly a character of case-studies as most of them in the field of metal cutting.

The present study is a one more attempt to look inside the process of MQL assisted turning the chromium-molybdenum-vanadium alloyed tool steel Uddeholm Caldie with use of pure and modified with graphite nanoplatelets (GnP) vegetable-based oil. The article reports the results of the experimental study aimed at the assessment of the performance of machining advanced high strength steel (AHSS), with coated cemented

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carbide tools. Detailed analysis of the influence of lubricant type and cutting conditions on tool wear, tool life, surface finish, and process dynamics and stability during machining is presented.

2. Materials and methods

2.1. Test setup and machining conditions

All 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 tempered Caldie steel (~60 HRC) (Uddeholm, Sweden). Continuous longitudinal turning tests were done on the steel rods ∅70×350 mm with micro-grain coated CC tools of type DNMG150608-MF1, grade TH1000 (SECO Tool AB) appropriate for finishing and medium machining. The tool provides a chipbreaker with rake angle 14°6′, cutting edge radius 25 µm, and chamfer angle 0°. TH1000 TiSiN-TiAlN nanolaminate PVD-coated grade enables manufacturers to productively tackle a wider variety of ISO H5-H10 applications as well as maintain long tool life when machining hardened steels, from 50-62 HRC, hard surfaced components and superalloy materials. A toolholder was of PDJNR 2525 M15 Jet type with a system of internal passages to provide MQL lubricant at a rake and flank faces during machining (Fig. 1 a). The inclination and clearance angles of the insert-toolholder system are λ = -6° and α = 6° for all cutting geometries, respectively.

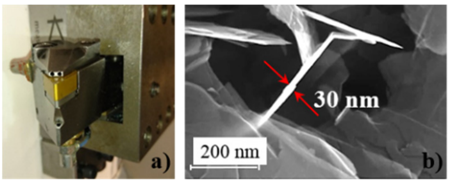

Fig. 1. (a) Setup for MQL assisted turning; (b) SEM image of GnP particles.

Cutting conditions were selected to correspond the range from finishing to medium turning operations where DOC was kept constant for all tests a_p = 0.2 mm. Feed rate and cutting speeds were selected as follows: f = 0.08, 0.125, 0.16 mm/rev; v_c = 60, 80, 100 m/min. The range covers conventional cutting speeds recommended by tool manufacturer. The machining tests were performed at dry conditions and with use of a pure and modified with GnP vegetable 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 [1]. Nanoadditives (GnP) were produced by a sonication of thermally expanded graphite (TEG) in a solution (1 g of TEG per 120 ml of 10% (vol.) alcohol solution) during 24 hours in an ultrasonic dispenser with a power of 350W. SEM image of GnP particles is illustrated in Figure 1 b. The average size of platelets was around 1 µm and 50 nm in thickness. A modification of oil was performed by adding 0.2% (vol.) of the GnP suspension into the pure oil with a persistent stirring by a magnetic stirrer during 10 min. Oil-GnP suspension remains stable around 20 days with an insignificant sedimentation.

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

2.3. Measurements and analysis

The data acquired from all types of tests are acceleration of the tooltip and cutting forces in three mutually perpendicular directions. Tool wear and wear morphology and surface quality were also determined. The study of worn cutting edges were performed by an optical (Alicona InfiniteFocus Real3D) and electron (Tescan Mira3 High Resolution Schottky FE-SEM) microscopies.

A three-axis piezoelectric dynamometer Kistler 9129AA was used to measure cutting forces. Acceleration signals are acquired with use of B&K sensors (type 8309, frequency range up to 60 kHz). Force and acceleration spectra were amplified and recorded simultaneously at sampling rates of 1 kHz and 120 kHz, respectively. Signal processing was performed using Matlab.

The surface finish parameters are measured with a portable roughness tester Mahr MarSurf PS10 after each pass at least 5 times along the workpiece in a feed direction.

3. Results and discussion

Application of coolants/lubricants in machining results in a change of a heat dissipation or/and redistribution in the cutting zone between tool, workpiece, chips, and environment; lubrication of interfaces between tool, chips and workpiece surfaces resulting in a reduced heat generation and a decrease of adhesion between tool and workpiece materials. These effects also 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 a friction and adhesion interactions in cutting zone influences on the chip formation mechanism resulting also in a decrease of the contact length of the tool rake and chips and its variation during machining. 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.

3.1. Cutting forces

An evolution of the mean value of cutting forces over time at different feed rates at cutting speed 100 m/min is shown in Fig. 2. The forces are characterized by an increasing trend due to tool wear development. Feed components of cutting forces at the beginning of turning are similar independently on the lubrication strategy and cutting conditions. Components in cutting and passive directions differ quite much with increase of both feed rate and speed as well as lubrication. The increase of feed rate does not affect forces when using oil-GnP lubricant due to decreased friction in the cutting zone. Other lubrication strategies are characterized by a sensitivity of forces to cutting conditions where a feed has a considerable influence. The cooling/lubricating effect of pure oil on the force behavior (10-25%) is more visible with increase of cutting speed. The utilization of GnP in MQL assisted machining results in the decrease in cutting forces up to 38%.

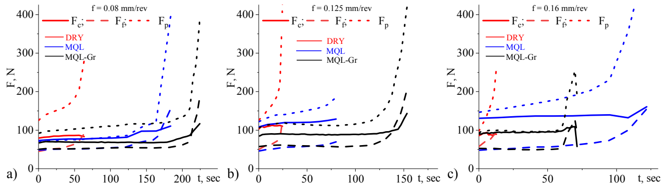

Fig. 2. Cutting forces at v_c = 100 m/min (a) 0.08; (b) 0.125; (c) 0.16 mm/rev.

The average values of force variation around its mean value during the machining time at different cutting test conditions is shown in Fig. 3.

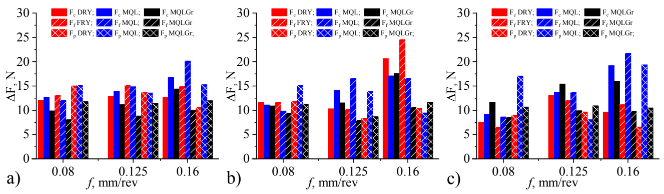

Fig. 3. Force variation (a) v_c = 60 m/min; (b) 80 m/min; (c) 100 m/min.

Results show a significant difference in the force variation when lubricating with original oil and may imply a difference in tool wear development as compared to other lubrication strategies. An application of GnP shows comparable or less ΔF values at low and moderate speeds and feed rates. Since the force variation value depends on processes in the cutting zone such as adhesion and friction on the rake and flank, chip segment formation and tool wear, a consideration of tool wear specifics at different lubrication strategies is quite important.

3.2. Tool wear

SEM images of worn cutting edges at v_c = 60 m/min and f = 0.125 mm/rev at dry, oil and GnP-oil lubrication conditions are shown in Fig. 4. Machining with GnP-oil lubrication is characterised by a maximum crater formation on the rake – white spot is a base CC material – that is, evidently, related to a higher contact pressure on the cutting edge due to the less contact area – red line.

In general, the worn area also contains a delamination and damage of coating, chipping of the cutting edge, flaking and notch formation near h_{1min} and h_{1max} areas. The areas with a lack of coating is partially filled in with a workpiece material. More detailed analysis has shown that the damage and delamination of coating and flaking on the rake face is caused by a plastic deformation of the cutting edge. This fact also explains the steep increase in passive component of cutting forces before the total tool damage [4].

The utilization of original oil for MQL lubrication (Fig. 4 b) shows better effect on a wear debris disposal and minimum of tool damage [3]. At the same time, GnP decreases the contact area and friction between rake and chips but causes the higher impact on the cutting edge.

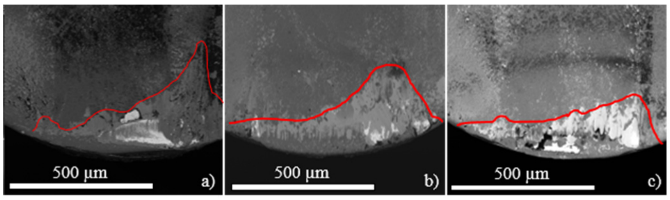

Fig. 4. Tool wear (a) dry; (b) MQCL oil; (c) MQCL oil-GnP.

The dependencies of wear on the flank face of the tool on the test conditions are shown in Fig. 5.

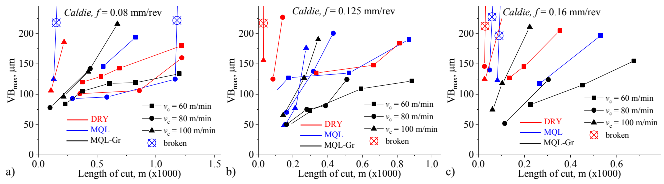

Fig. 5. Flank wear (VB_{max}) at (a) 0.08; (b) 0.125; (c) 0.16 mm/rev.

Fig. 5 shows that tool life quite good correlates with cutting forces behavior. Utilization of original oil has a comparable or better tool life at higher speeds and feed rates used. The application of GnP modified oil shows the improvement of tool life almost at all test conditions excepting the case at v_c = 80 m/min and f = 0.08 mm/rev. The mentioned is probably related to a presence of chipbreaker that, in combination with a reduced contact area, results in a negative effect on tool life. The similar phenomenon occurs when machining with pure oil at the lowest feed rate (Fig. 5 a).

3.3. Process dynamics and stability

Fig. 6 shows the evolution in time of RMS values of accelerations at different cutting conditions.

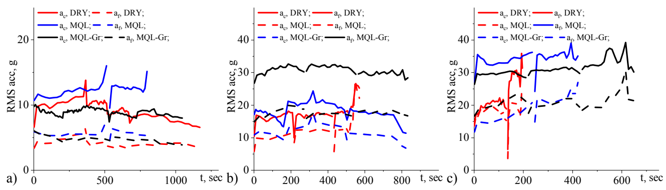

Fig. 6. Accelerations at v_c = 80 m/min (a) 0.08; (b) 0.125; (c) 0.16 mm/rev.

Mean value of vibrations amplitude at different cutting and lubrication conditions are presented in Figure 7. The difference between RMS values of accelerations is little at lower feed rate. Considering a similar behavior of mean values of cutting forces (Fig. 2) and their variations (Fig. 3) this may imply the similarity in dynamic interaction between tool, workpiece and processes in cutting zone.

The increase of cutting speed and feed rate to 0.125 mm/rev results in significant increase of vibration intensity when machining with GnP-modified oil where the vibrations for dry turning and with pure oil are resemble. The increase of feed rate to 0.16 mm/rev and at higher cutting speeds leads to the 2-fold increase of vibration amplitude for both cases of lubrication with original and modified oils.

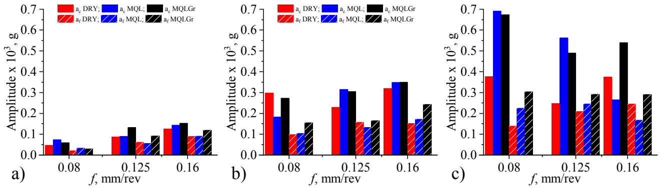

Fig. 7. Vibration amplitude (a) 60; (b) 80; (c) 100 m/min.

Lower values of cutting forces when turning with lubricants in combination with higher level of vibration, as compared to dry machining, implies the change of mechanisms occurring in a contact area: segment size; length, variation and regeneration of adhesion-friction zones on the rake; adhesion and friction on the flank. All these factors influence on the dynamics of the system and should be reflected in frequency domain. Fig. 8 shows FFT spectra of accelerations in cutting direction for a feed rate value f = 0.16 mm/rev at the beginning of the process.

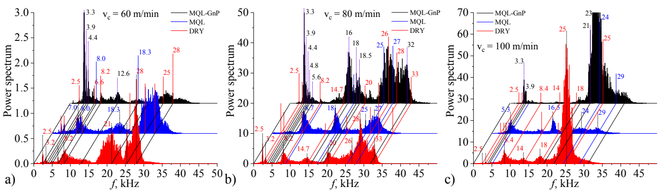

Fig. 8. FFT of vibration signals (a) 60; (b) 80; (c) 100 m/min.

Low-frequency range (<12 kHz) includes three natural frequencies of tool holder 2.5, 3.2 and 8.2 kHz and vibrations of tool post and workpiece. High-frequency (above 12 kHz) – characterizes the adhesive and friction processes in the cutting zone and chips segmentation. FFT at low cutting speed showss a similarity of spectra for dry machining and with original oil one. The presence of GnP additives is determined by several harmonics next to one of the tool natural frequency (3.3-4.4 kHz) that is a result of reduced friction in the cutting zone leading to an increase of ‘effective process stiffness’.

The increase of cutting speed shows the same behavior at low-frequency range. Segmentation frequency is concentrated at 25 kHz for all cases at cutting speed 80 m/min but spectra of MQL machining also show the generation of harmonics in higher frequency diapason 35-45 kHz (not shown in Fig. 8).

FFT’s at maximum cutting speed demonstrate resemblance for dry and GnP-oil machining illustrating a strong excitation at 25 kHz – chip segmentation, as well as origin oil and GnP-oil assisted machining at higher frequency range 35-40 kHz. This illustrates the ambivalent influence of GnP nanoadditives those, on the one hand, reduce friction between chip and tool rake and decrease a contact length of tool-chip interface, on the other, intensifies adhesive processes in the cutting zone.

3.4. Surface finish

Independently on the physics behind the cutting process, the quality of the machined surface is one of the most important characteristics of the performance and define, in combination with other factors, an expediency of application of GnP for MQL assisted machining. Mean values of surface roughness (R_a) along a pass with error bars representing a deviation of the absolute value of R_a are shown in Fig. 9.

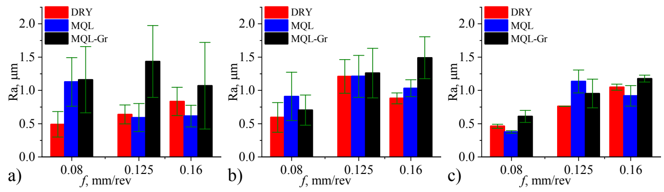

Fig. 9. Surface finish at v_c (a) 60 m/min; (b) 80; (c) 100 m/min.

Results show that R_a value when utilizing GnP-modified oil is very dependent on the amplitude of vibration (Fig. 7) and cutting conditions. As demonstrated low cutting speeds are not recommended to use due to the low surface quality (Fig. 9 a). The increase of the cutting speed shows quite comparable results for all cooling/lubrication strategies tested (Fig. 9 b, c).

4. Conclusions

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

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

– presence of GnP particles results in a significant reduction of friction in cutting zone in combination with cooling effect but inherit the influence of dry machining demonstrating higher adhesiveness at some cutting conditions that affects the surface finish.

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