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Study of tribo-chemical lubricant film formation during application of nanolubricants in minimum quantity lubrication (MQL) grinding

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ABSTRACT

This paper presents the study of mechanism of nanolubricant impingement in minimum quantity lubrication grinding. To study the role of nanolubricants (a new class of advanced lubricants integrating multicomponent chemistries) during workpiece-tool interaction, surface-grinding tests were performed on ductile iron workpieces using an aluminium oxide wheel under varied infeed conditions. The process performance in terms of force ratio, specific energy, and *G*-ratio has shown substantial improvement when using nanolubricant. Formation of tribo-chemical films of *Mo–S–P* chemistry complex on the workpiece surface was identified as the mechanism responsible for these improvements.

1. Introduction

At the microscopic level, the complex workpiece-tool interaction in abrasive grinding can be simplified to a combination of micro cutting and intensive rubbing that contributes to chip removal and high-magnitude frictional losses, respectively. Grinding fluids are often applied for flood or minimum quantity lubrication (MQL) to aid lubrication (friction reduction), alongside cooling effect and chip removal [1,2]. For flood as well as MQL processes, the efficacy of friction reduction and the ability to withstand extreme pressure at the machining interface through lubrication is critically dependent on the continuous penetration of the lubricant into the interface between abrasive grains and workpiece asperities, and thereafter, decomposition of the lubricant into anti-friction, anti-wear, and extreme pressure (EP) bearing chemical species in the form of tribo-chemical films. Intensive seizures at the cutting grain-workpiece interface results in little or no access to the lubricants. Furthermore, grinding with conventional vitrified aluminum oxide wheels has been reported to generate very high surface temperatures – reaching up to 400 °C and 106 °C for MQL and flood conditions, respectively [3], and high energy-partition, ranging from 60 to 85% [4]. Such elevated temperatures can partially vaporize liquid lubricants before reaching the grinding zone. These events result in excessive heat accumulation due to lubricant depleted interfaces of abrasive grain-workpiece asperities. Hence, advanced lubrication strategies for MQL to sustain during production, and deliver continuous and stable tribo-chemical films at the abrasive grain-workpiece asperities' micro interfaces, better lubricant package is required. To address this need for lubrication of micro interfaces, the authors have nanomanufactured a nanolubricant system package integrating inorganic lubricant particles with organic molecular friction-polymer precursors [5] for ready delivery and a higher residence time at the micro interfaces [6,7].

The nanolubricant architecture consists of organic molecules with extreme pressure bearing phosphide groups intercalated with chalcogenide *hcp* structured MoS_2 nanoparticles (<100 nm).

Due to their nanosize it is anticipated that these nanolubricants can navigate in the asperities' interfaces and deliver lubricating glassy tribo-chemical films for the desired extreme pressure conditions. The following process mechanisms were hypothesized for application of the nanolubricant to benefit MQL grinding:

1. Spatial delivery at the grinding interface: aided by the pressurized and directed aerosol delivery technique of MQL, nanolubricant particles will anchor on the network of sites of pores/voids on the grinding wheel and workpiece, as well as the capillary networks on the abrasive wheel resulting in assured penetration into the grinding zone.
2. Ability of nanolubricant to deform into sacrificial tribo-chemical films: aided by the extreme pressure and shear-induced relative motion of the abrasive grain and workpiece, organic molecules intercalated with MoS_2 nanoparticles will deform plastically across their weakly bonded crystallographic *c*-axis and deliver desired chemistries.
3. Catalysed by the thermo-mechanical conditions of the grinding zone, the resultant nanolubricant delivered tribo-chemical films will adhere to the mating material to form stable, anti-friction EP films of organo-metallic chemistry, delivering superior performance in MQL-assisted grinding.

The present research focuses primarily on understanding and evaluating the hypotheses stated above and the related mechanisms under various grinding process conditions for understanding the role of nanolubricants in grinding operations.

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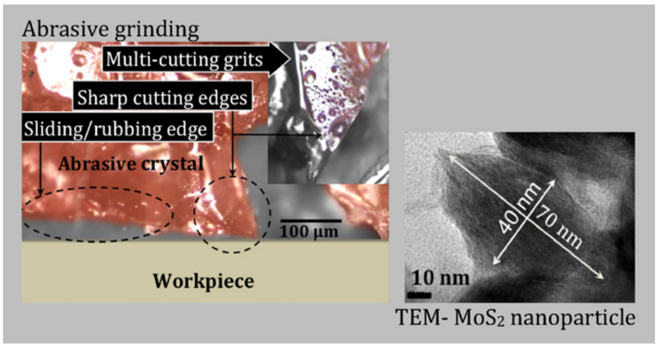

Fig. 1. Optical micrographs of typical abrasive alumina micro grain from grinding wheel (left); TEM image of MoS_2 nanolubricant particle intercalated with organic agents (right).

2. Experiments

ASTM A536 grade 100-70-03 ductile cast iron workpiece test samples (HRC hardness-50) were ground on a mechanically controlled surface grinder (100 kW Magarle, MFP) using vitreous bonded aluminum oxide (Al_2O_3) grinding wheel (32A46-HVBEP, Saint-Gobain/Norton abrasives, 356 μm average grain size; Fig. 1, left). For testing purposes, industry standard surface grinding parameters were used, summarized in Table 1, along with the lubricants selected for testing. Paraffin oil, used as the base oil, finds wide applications as a lubricant in industrial production [5]. Nanolubricants were formulated by homogenizing intercalated MoS_2 nanoparticles (Fig. 1, right), enhanced with additional capping chemistries of triglycerides and phospholipids in base (paraffin) oil. The nanomanufacturing process of the multicomponent lubricant chemistries is discussed elsewhere [5,6]. Hereafter, the nanolubricant formulation will be addressed as *nanolubricants-X%*, where *X* is the concentration of the lubricant additive package in the base oil. For a comparative performance evaluation with nanolubricants, a benchmark paraffin-based lubricant package containing commercial grade MoS_2 microparticles (*APS* 3–5 μm) was also tested.

The ground surfaces of the cast iron workpieces were characterized using the following analytical tools: scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDS) for microstructural and chemical analysis, respectively. These analyses were collectively aimed, not only to determine the microstructural characteristics and elemental composition, but also to determine the chemical integrity of the tribo-chemical lubricant films, and correlate the findings with that of the grinding performance parameters-grinding force ratio, specific energy, and *G*-ratio. This was done in order to develop a process mechanism through experimental analysis for evaluation of the aforementioned hypotheses. Furthermore, grinding surface temperatures from different lubrication conditions were measured through embedded K-type thermocouples in the cast iron workpieces using standard protocols discussed elsewhere in [3].

3. Results and discussion

3.1. Grinding performance parameters

Figs. 2a, b and 3 show measured force ratios (μ), specific energies (*U*), and *G*-ratios (*GR*) from the grinding tests, respectively. These measured parameters are presented as a function of wheel-infeed and lubrication condition.

Under the investigated process conditions (Fig. 2a), flood coolant application returned the highest force ratio values, 0.48 and 0.73, for 10 and 20 μm infeed, respectively. This is a typical observation for conditions that involve the limited penetration of applied lubricant fluids into the high hydrodynamic pressure grinding zone – conditions that are exacerbated by the low lubricating performance of the fluids. Reductions in the values of μ were observed for the pressurized oil-based lubricant delivery through MQL. For 10 and 20 μm infeed, under MQL conditions, base (paraffin) oil gave $\mu = 0.35$ and 0.45, respectively. Microparticles integrated paraffin oil showed a decline in the values of μ under MQL conditions, but not to the extent demonstrated with the use of nanolubricants. Nanolubricant-8 wt.% delivered lowest values of $\mu = 0.19$ and 0.23 for 10 and 20 μm infeed conditions, respectively. On average, these values of μ are 24% lower than the ones measured for 2 wt.%-nanolubricant, and 47% lower than the MQL condition without nanolubricant, which is suggestive of better performance control with a quantitative increase in nanolubricant additive chemistries. In an interesting correlation, the measured values of μ with nanolubricants correspond to well-lubricated blunt abrasive grains in contact with the work-surface [8].

Measured values of specific grinding energy (Fig. 2b) showed direct correlation to the previously noted conditions of sliding

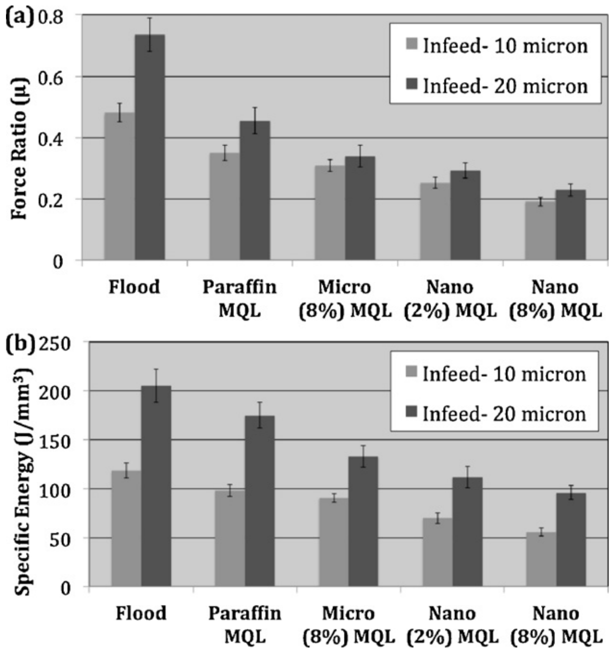

Fig. 2. (a) Force ratio (μ) and (b) specific grinding energy (*U*) obtained during grinding of cast iron (average values of 100 measurements, error bars represent standard deviation).

Table 1
Surface grinding parameters (left) and lubricant description (right).

Grinding parameters	Lubricant description
Wheel speed – 30 m/s	Nanolubricant (2 wt.%) – MQL
Work speed – 0.06 m/s	Nanolubricant (8 wt.%) – MQL
Depth of cut – 10, 20 μm	Paraffin oil containing MoS_2
Grinding passes – 100	microparticles (8 wt.%) – MQL
Flow rate-MQL – 2.5 ml/min	Pure paraffin (base) oil – MQL
Flow rate-flood – 8450 ml/min	Water-based grinding fluid – flood

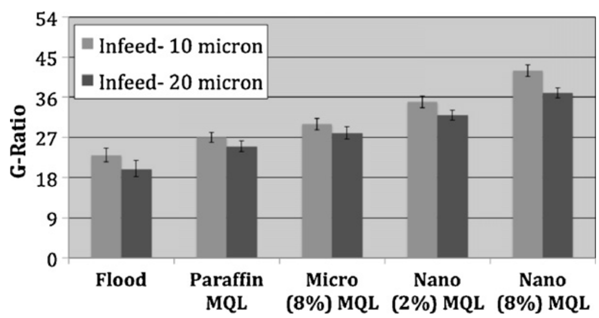

Fig. 3. *G*-Ratio values obtained after 100 grinding passes (average value of 3 measurements, error bars represent standard deviation).

friction represented by force ratio (Fig. 2a; overall the energy values were found higher than the normal values and will be optimized in future work). Grinding with 8 wt.%-nanolubricant consumed 56 and 96 J/mm^3 of specific energy for 10 and 20 μm wheel-infeed, respectively. On average, this measures as a 53% and 44% decrement in energy consumption, in comparison to the cases of grinding with flood application and MQL with paraffin (base) oil, respectively. Paraffin lubricant containing microparticles showed a moderate reduction in energy consumption, where $U_{10\ \mu m\text{-}infeed}$ = 91 J/mm^3 and $U_{20\ \mu m\text{-}infeed}$ = 133 J/mm^3, although not as effective compared to nanolubricants. It is proposed that the observed decrease in energy consumption with nanolubricants is due to their unique ability to penetrate the grinding wheel-workpiece interface and lubricate the blunt edges of abrasive grains (Fig. 1, left), which in effect reduces sliding frictional losses. In abrasive machining, the total specific grinding energy finds significant contribution from sliding, and additionally from chip formation and plowing components [4].

Fig. 3 shows the measured values of *G*-ratio, a parameter that translates grinding wheel wear. The lowest values with flood application ($GR_{10\ \mu m\text{-}infeed}$ = 23 and $GR_{20\ \mu m\text{-}infeed}$ = 20) correspond to high volumetric wear of abrasive grains during grinding. In comparison, MQL with 8 wt.%-nanolubricant delivered *G*-ratio values of 42 and 37, an average reduction of 45% in volumetric wheel wear. These *G*-ratio values are higher than those obtained from grinding using paraffin (base) oil as the lubricant ($GR_{10\ \mu m\text{-}infeed}$ = 27 and $GR_{20\ \mu m\text{-}infeed}$ = 25). This demonstrates the superior ability of the novel nanolubricant as an effective anti-friction and anti-wear lubrication delivery system at intricate micro interfaces between grinding wheel and workpiece asperities.

3.2. Evaluation of lubrication in the grinding zone

Fig. 4 shows the peak grinding surface temperatures from different lubrication conditions. Flood application condition showed the lowest surface temperature of 96 °C. A temperature lower than the boiling point (100 °C) suggests convective bulk cooling of the workpiece by the applied water-based grinding coolant. MQL grinding using paraffin (base) oil yielded 288 °C as the peak surface temperature, higher than its flash temperature of 215 °C. Application of 2 and 8 wt.%-nanolubricants reduced peak temperature to 175 °C and 160 °C, respectively. To understand the mode of heat transfer, thermal conductivity values of paraffin (base) oil, and 2 and 8 wt.%-nanolubricant were measured using the hot wire method. The values were found to be 0.146, 0.150, and 0.165 W/m K, respectively. No notable differences in the thermal conductivities could be observed for nanolubricant added paraffin oil. It confirms that the observed steep decline in peak surface temperatures during the application of nanolubricants, over paraffin (base) oil in MQL, is not due to enhanced convective heat transfer, but a result of the previously noted significant reduction in friction-induced heat generation during grinding.

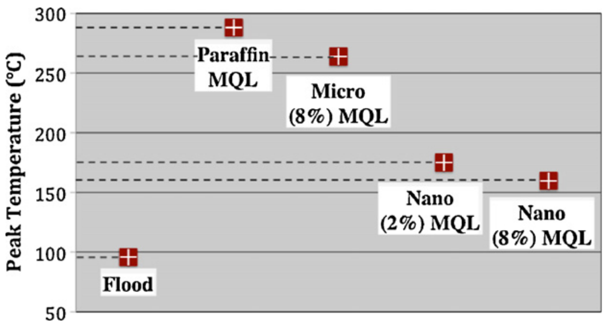

Fig. 4. Peak surface temperatures obtained during grinding of cast iron with 10 μm-wheel infeed.

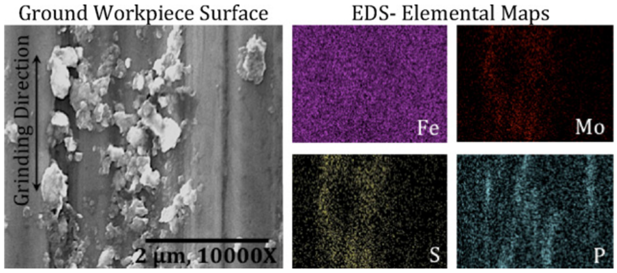

Fig. 5. SEM–EDS microanalysis of ground workpiece surfaces lubricated with 8 wt.%-nanolubricant.

Representative SEM micrograph of ground workpiece surface lubricated with 8 wt.%-nanolubricant is shown in Fig. 5. EDS microanalysis rendered the characteristic elemental (chemical) distribution of the tribofilm formed on the surface. Analysis of platelets observed in SEM micrograph of the nanolubricant-lubricated work surface confirms the presence of molybdenum (Mo), sulphur (S), and phosphorus (P). These plate-like layers of *Mo–S–P* chemical complex are tribofilms derived in a sacrificial process from the nanolubricant additive chemistries when entrapped at tool-workpiece interfaces. Similar microanalysis indicated the presence of weak sulphide and dominant oxide layers on the flood-lubricated work surface, and smeared oil traces on the paraffin-lubricated workpiece wear tracks. Optical images of a section of the abrasive wheel applied in nanolubricant assisted MQL grinding (Fig. 6a) show retention of entrapped nanolubricant, ready for delivery in the micro-porosities/reservoirs network. This implies and assures the readily available delivery of organic-molecules intercalated with MoS_2 nanoparticles into the grinding zone through the micro-reservoirs (porosity) and the capillary networks of the abrasive wheel. SEM–EDS microanalysis (Fig. 6b) confirmed the presence of elemental Mo and S in the debris retained on the surface of an abrasive grain, which could further aid in reducing the abrasive nature of trapped debris.

3.3. Formation and deformation of tribochemical films in the grinding zone

SEM micrographs of higher magnification in Fig. 7a and b show the microstructure of *Mo–S–P* tribofilms derived from 8 wt.%-nanolubricant during MQL grinding (10 and 20 μm wheel-infeed), where notable results were seen above. Under lower magnification, repeatable formation of microscale plate-like tribofilms was observed from both conditions of grinding. However, the aerial density of surface films deposited on the ground workpieces showed a declining trend as the wheel infeed was increased from

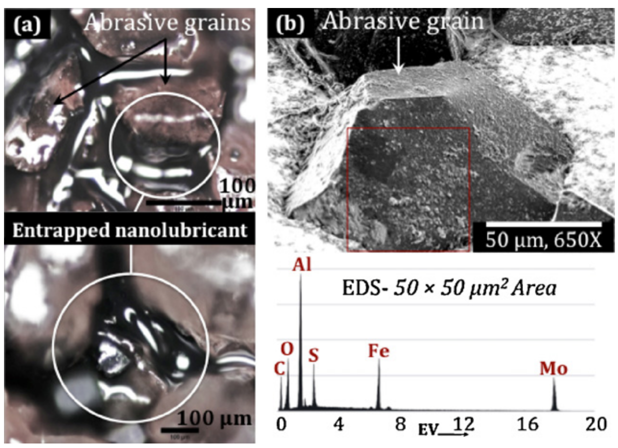

Fig. 6. (a) Optical and (b) SEM–EDS surface examination of post-grinding abrasive wheel lubricated by nanolubricant.

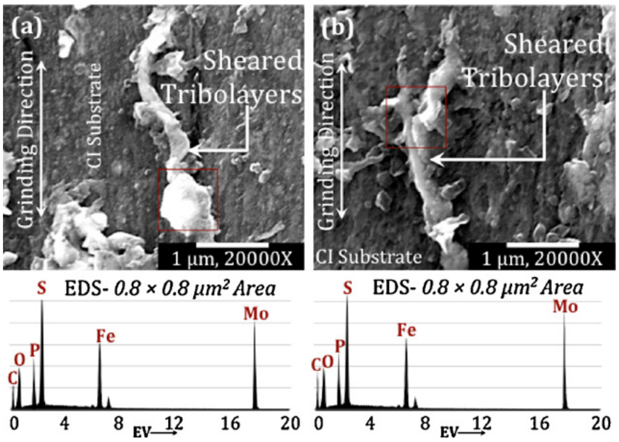

Fig. 7. SEM–EDS microanalysis of nanolubricant tribofilms formed during grinding at: (a) 10 and (b) 20 μm wheel-infeed (CI, cast iron).

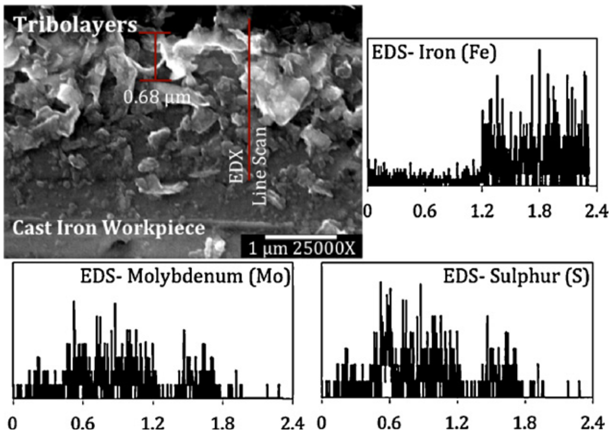

Fig. 8. Cross-sectional microstructure of nanolubricant tribofilm; EDS-line scan confirms the presence of molybdenum and sulphur especially in zones where no iron debris was detected.

10 to 20 μm. This suggests a direct implication of grinding thrust forces on lubrication efficacy and their depletion under extreme loading. From Fig. 7 we observe elongated and sliding-oriented tribofilms, indicating that shear-induced plastic deformation and alignment along grinding direction are the prevailing mechanisms for formation and deformation of the tribofilms during grinding. Sandwiched between the high-strength abrasive grains and the relatively low-strength workpiece are the MoS_2 lamella, integrated with organic molecules, which underwent continuous plastic deformation. In this sacrificial process the resultant plate-like tribofilms were aligned parallel to the direction of relative motion.

To understand this further, the focused ion beam assisted cross-section of the tribofilm was studied using SEM–EDS. Cross-sectional microstructure of tribofilm (Fig. 8) reveals numerous stacked sheared tribofilm layers (of different size and thickness) sliding simultaneously or separately over one another. Sacrificial behaviour (low shear) of tribo-chemical layers allow low-resistance (low friction) sliding of abrasive wearflats against the workpiece and reduce interfacial stress on individual abrasive grains. It is believed that these mechanisms are collectively responsible for a noticeable reduction in friction, energy consumption, and wheel-wear during the grinding tests.

The machining results reported above and their analyses validate the listed hypotheses, including: spatial delivery and navigation of nanolubricant at the grinding interface; ability of nanolubricant to deform and deliver sacrificial tribo-chemical films, resulting in superior machining performance in MQL-assisted grinding. Future research will also study potential environmental and health safety (EHS) issues, and effect of MoS_2 on grinding debris, machine cleanliness, etc. Currently MoS_2 is one of the most common lubricants in industrial applications.

4. Conclusion

This research describes the impinging and lubricating mechanisms of advanced nanolubricants, consisting of organic molecules with phosphide intercalated-MoS_2 nanoparticles ($<$100 nm), in MQL surface grinding of ductile cast iron. Analysis of grinding tests confirmed the effectiveness of the nanolubricants, measuring a decline of 45–50% in force-ratio and specific energy, and a 48–55% decrease in abrasive wheel wear, against grinding with conventional flood cooling and MQL with paraffin (base) lubricant. Measurement of grinding surface temperature showed a reduction in friction-induced heat generation due to nanolubricants. Surface examination of the grinding zone indicated delivery of organic molecular intercalated nanoparticles entrapped in the porous abrasives and the formation of tribo-chemical films of a *Mo–S–P* chemistry complex on the friction surfaces during grinding. Continual shearing and alignment of the sacrificial tribofilm layers derived from nanolubricant in the grinding zone sustained the low-resistance sliding of abrasive wearflats against the workpiece. These tribological mechanisms are correlated with friction, energy, and wheel-wear reduction efficacy of nanolubricants during grinding.

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