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Technical paper

Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants

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ABSTRACT

An investigation on minimum quantity lubrication (MQL) grinding was carried out with the scope of documenting the process efficiency of oil-based nanolubricants. The nanolubricants were composed of MoS_2 nanoparticles (<100 nm) over coated with organic agents, dispersed in two different base oils—mineral oil (paraffin) and vegetable oil (soybean). Surface grinding tests were carried out on cast iron and EN 24 steel under different lubrication conditions—*MQL* using nanolubricants (varying compositional chemistry and concentration of nanoparticles), pure base oils (without nanoparticles) and base oils containing MoS_2 microparticles (3–5 μm), and *flood* grinding using water-based coolant. Specific energy, friction coefficient in grinding and G-ratio were used as measurands for determining the process efficiency. Results show that MQL grinding with nanolubricants increases the process efficiency by reducing energy consumption, frictional losses at the wheel–workpiece interface and tool wear. The process efficiency is also found to increase with increasing nanoparticle concentration. Soybean and paraffin based-nanolubricant performed best for steel and cast iron, respectively, showing a possible functional relationship between the compositional chemistry of nanolubricant and the workpiece material, which will be the goal of future work.

1. Introduction

Surface grinding is a widely used machining process with the characteristic property of finishing and smoothing of machined surfaces to tight tolerances and dimensional accuracy. The process utilizes hard abrasive crystals bonded in the form of a wheel as the cutting medium. The abrasives plunge and slide against the workpiece during material removal. Negative effects of sliding friction on the output process parameters have been reported by Cai et al. [1] and Srihari and Lal [2]. Sliding frictional losses between the abrasive crystals and the workpiece has been identified as a critical factor in determining the final output of the process. Severe sliding friction results in higher cutting forces, temperatures and abrasive wear by rapid in-process dressing of the wheel, primarily due to fracture at the bond posts. The process, therefore, is characterized by high specific energy consumption (energy per unit volume of material removal) and high grinding zone temperature. To improve process efficiency, lubrication becomes an important requirement of the grinding fluids, along with chip removal and cooling the grinding zone. Despite using high fluid volume, conventional flood method of delivering grinding fluid has been reported to be incapable to penetrate into the high hydrodynamic pressure-grinding zone [3]. The costs associated with the application and recirculation of high volume of fluid adds up to the total production cost and its disposal creates several biological and environmental problems. The use of minimum quantity lubrication (also called near-dry lubrication) has been reported as a technologically and environmentally feasible alternative to flood cooling [3]. MQL combines the functionality of cooling and lubricating the tool-workpiece surfaces with an extremely low consumption of lubricant (three to four orders of magnitude lower than the amount commonly used in flood cooling) [4,5]. However, effective lubrication capability in MQL is continuously affected by the severe thermo-mechanical conditions at the grinding zone. In such conditions, tribological performance of the lubricants can make a transformative difference in energy efficient and sustainable MQL grinding.

To address these challenges of MQL grinding, the authors have designed and developed a nanolubricant solution, which is a unique multicomponent and multilayer nanomaterial system [5,6]. This proposed oil-based nanolubricant is a combination of inorganic hexagonal closed packed (HCP) layered MoS_2 nanoparticles (<100 nm) carrying intercalated as well as overcoated organic molecules of triglycerides and phospholipids. During MQL fluid delivery, the nanolubricant particles can effectively penetrate into the grinding zone due their size, high surface energy and

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excellent dispersibility in carrier medium. It was hypothesized that during the grinding process, the MoS_2 nanoparticles will deform plastically across crystallographic *c*-axis when sheared between wheel–workpiece sliding surfaces and will deliver low-friction lubricating transfer film. This hypothesis was proved experimentally using a metrological approach based on surface grinding and tribotesting studies [4,7]. MQL grinding results showed that the use nanolubricants significantly reduces tangential cutting forces and increases grinding (G)-ratio, compared to commercial metal working fluids [4]. Simulated abrasive tribotesting explained the grinding results when nanolubricants showed to reduce frictional losses between flat facets of abrasive crystals and workpiece by forming composite tribofilm [7].

With this background, the objective of present research is to measure the process efficiency of MQL grinding using oil-based nanolubricants and studying their performance consistency in friction reduction. Specific energy, friction coefficient in grinding and G-ratio were used as measurands for determining the efficiency of process under various conditions, as discussed below.

2. Experimental

2.1. Grinding fluids

The nanolubricants were prepared by dispersing the multi-component organic–inorganic nanoadditive (composed of MoS_2 nanoparticles, triglycerides and phospholipids) in base fluids. Paraffin (mineral-based) oil and soybean (vegetable-based) oil were used as the base fluids. Nanomanufacturing of multi-component nanolubricant is discussed elsewhere [4,5,7]. Two nanoadditives were manufactured for testing – *nanoadditive I* and *nanoadditive II* – using canola and soybean oil as the source of triglycerides, respectively. Soybean and canola oil are bio-based lubricants with excellent lubricity, high flash points and polar attraction to metal surfaces. Mineral and vegetable oil-based nanolubricants were formulated by dispersing emulsified *nanoadditive I* and *II* in paraffin and soybean oil, respectively, in two concentrations—2% and 8% by weight. These concentrations were selected based upon previous research [4,5,7]. The nanolubricant formulations were ultrasonicated for 4 h to attain dispersion homogeneity. The resultant multicomponent nanolubricant architecture consisted of inorganic nanoparticles of MoS_2, with intercalated and overcoated molecular layers of organic-triglycerides. High-resolution transmission electron microscopy (TEM, FEI Company-TITAN 80-300 S/TEM) revealed 'elongated coconut' shaped MoS_2 nanoparticles, with numerous atomic shear planes as shown in Fig. 1. Using TEM, the average size of MoS_2 nanoparticles was repetitively measured as 70 nm and 40 nm along major and minor axes, respectively.

Microparticles-based lubricants were selected for comparison. These lubricant formulations were prepared by adding 8 wt.% of emulsified MoS_2 microparticles (3–5 μm) in base oils (paraffin and soybean). Compared to MoS_2 nanoparticles, the dispersibility of microparticles in base oils was extremely poor, despite comparable sonication. For flood grinding comparison, a water-based synthetic metal working fluid (MWF) was used. The synthetic MWF was mixed with water at a ratio of one part concentrate to 20 parts water (5 vol.%). The viscosity and chemistry of base oils are listed in Table 1, while Table 2 provides the summary of lubricants applied in this research.

Table 1
Base oil properties.

Base oil	Viscosity	Chemistry
Paraffin oil	2.4 cSt @ 20 °C	Mineral-based
Soybean oil	75 cSt @ 20 °C	Vegetable-based

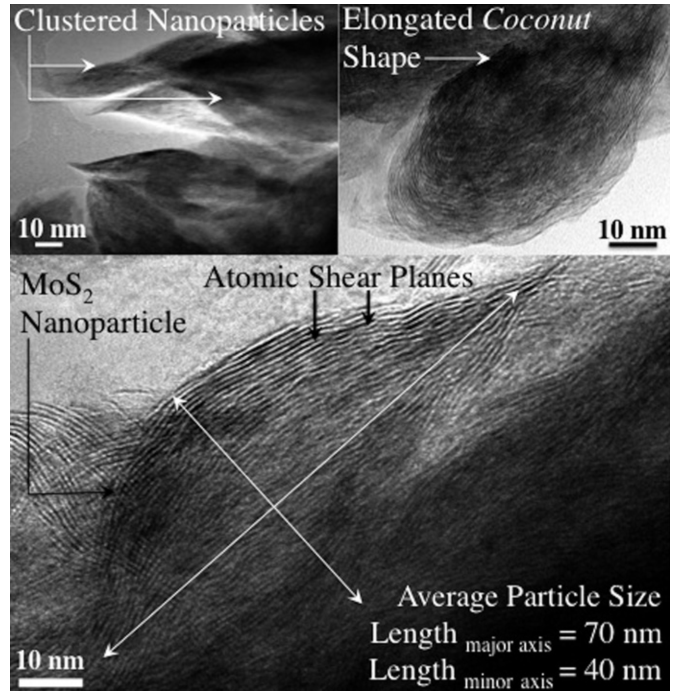

Fig. 1. TEM images of molybdenum disulphide (MoS_2) nanoparticles.

2.2. Grinding and MQL equipment

Straight surface grinding experiments (with no cross feed) were carried out on an instrumented surface grinding machine (Magarle MFP) as shown in Fig. 2(a). An external fluid delivery system (precision dispenser-AMCOL Corp.) was used for MQL grinding as shown in Fig. 2(b).

In this system, the lubricant is suctioned into a pressurized air stream (60 psi) coming from the regulator to the fluid/lubricant reservoir. The lubricant–air mixture is propelled to the grinding zone by air pulses through a tube and nozzle system. The mist was delivered to the cutting zone from the leading end of the grinding wheel (in the direction of its rotation). Grinding process parameters are listed in Table 3. The process parameters and workpiece material were selected based on published literatures and inputs from industrial collaborators.

Table 2
List of lubricants.

Nanolubricants	Fluid Delivery method
Paraffin-based (2 wt.%)	MQL
Paraffin-based (8 wt.%)	MQL
Soybean based (2 wt.%)	MQL
Soybean-based (8 wt.%)	MQL
Lubricants containing MoS_2 microparticles	
Paraffin-based (8 wt.%)	MQL
Soybean-based (8 wt.%)	MQL
Pure base fluids	
Pure paraffin oil	MQL
Pure soybean oil	MQL
Water-based coolant	
Water-based synthetic grinding fluid	Flood

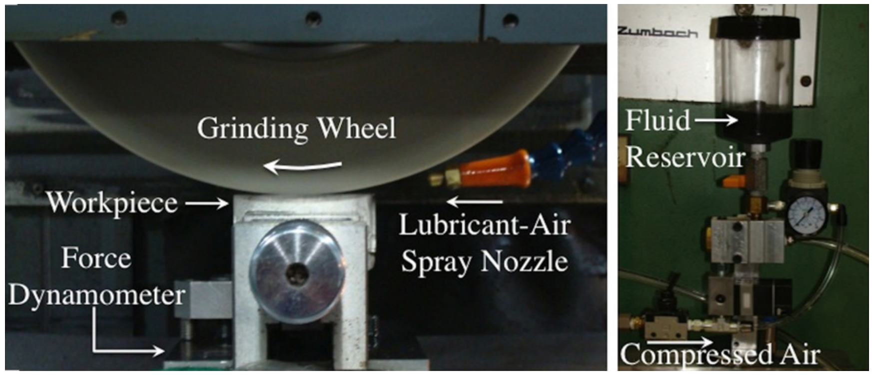

Fig. 2. (a) Surface grinding setup and (b) MQL-fluid delivery system.

Table 3
Surface grinding process parameters.

Parameters	Cast iron	EN 24 steel
Wheel speed (m/s)	30	30
Workpiece speed (m/s)	0.06	0.1
Depth of cut (μm)	20	20
Grinding passes (n)	100	100
Grinding width, b_w (mm)	7.2	7.5
MQL flow rate (ml/min)	2.5	2.5
Flood flow rate (ml/min)	8450	8450

2.3. Grinding wheel and workpiece

A vitreous bonded aluminum oxide (Al_2O_3) grinding wheel (specification: 32A46-HVBEP, Saint-Gobain/Norton abrasives) with an average abrasive grain size of 508 μm was used in the tests. The workpiece materials employed in this research were ductile cast iron (100-70-03, Durabar) and EN 24 alloy steel. The workpiece specifications are listed in Table 4.

2.4. Analytical techniques and measurements

For each grinding operation, in-process measurements of tangential and normal forces were carried out using a piezoelectric dynamometer (Kistler 9257A) mounted under the workpiece holder. Grinding force data was collected at 1 kHz sampling rate. The forces were used to calculate the coefficient of grinding and specific energy. Grinding wheel wear and grinding-ratio was measured using the same method as described in [4,5].

Table 4
Workpiece material specifications.

Workpiece material Composition		Ductile cast iron 100-70-03, 50 HRC [Durabar, Inc.]	
Element	Mass [%]	Element	Mass [%]
C	3.5	Si	2.25
Mn	0.15	S	0.025
P	0.05		
Workpiece material		EN 24 alloy steel, 50 HRC	
Composition			
Element	Mass [%]	Element	Mass [%]
C	0.44	Si	0.35
Mn	0.70	S	0.04
Cr	1.40	Mo	0.35
P	0.035	Ni	1.70

2.4.1. Friction coefficient in grinding (μ)

Friction coefficient in grinding is the ratio of tangential grinding force (F_t) and normal grinding force (F_n). Typical values of μ in grinding lie between 0.2 and 0.7 [8]. A low value of μ corresponds to well-lubricated blunt abrasive grains in contact with the workpiece surface.

$$\text{Coefficient of friction, } \mu = \frac{F_t}{F_n}$$

2.4.2. Specific energy (U)

Specific grinding energy is defined as the energy required per unit volume of material removal. Specific energy is widely used as an inverse measure of process efficiency. A low consumption of energy is representative of an energy–efficient process.

$$\text{Specific energy, } U = \frac{P}{Q_w} = \frac{F_t \cdot v_s}{b_w \cdot a_e \cdot v_w}$$

where, P: total machining power, Q_w: volumetric material removal rate, F_t: tangential grinding force, v_s: wheel peripheral speed, v_w: workpiece traverse speed, b_w: grinding width, a_e: depth of cut.

According to Malkin and Guo [9], under fixed machine settings, the normal and tangential grinding forces increase with wearflat area, A_a (flattened edges of abrasive crystals sliding against the workpiece with negligible material removal), and are expressed as,

$$F_t = F_{t,c} + F_{t,sl} = F_{t,c} + \mu \cdot p \cdot A_a \tag{1}$$

$$F_n = F_{n,c} + F_{n,sl} = F_{n,c} + p \cdot A_a \tag{2}$$

where, $F_{t,c}$ and $F_{n,c}$ the tangential and normal components of cutting force, respectively. $F_{t,sl}$ and $F_{n,sl}$ the tangential and normal components of sliding force, respectively. p the contact stress.

For any given set of grinding conditions, the cutting force components in Eqs. (1) and (2) remain constant. Thus, a drop in sliding frictional losses (low values of μ) will be translated to a proportional reduction in tangential forces and specific energy.

2.4.3. Grinding (G)-ratio

G-ratio is defined as volume of material removal (V_w) per unit volume of grinding wheel wear (V_s). High G-ratio is a representative of low wheel wear and hence, prolonged wheel life. Low interfacial friction extends wheel life by reducing attritious wear and fracture of abrasive crystals.

3. Results and discussions

3.1. Coefficient of friction

3.1.1. Workpiece—EN 24 steel

The results of the friction coefficient as a function of lubrication condition, obtained during grinding of EN 24 steel, are shown in Figs. 3 and 4. Each plotted data point was acquired by averaging the values of 100 grinding passes. Comparative observations are based on the mean values of 100 grinding passes and are not based on any statistical analysis.

Under the investigated process conditions, flood cooling showed the highest value of $\mu = 0.76$. In comparison to flood cooling, MQL with pure paraffin and soybean oil showed a reduction in friction ($\mu_{\text{para}} = 0.63$, $\mu_{\text{soy}} = 0.60$). This is primarily due to the enhanced penetration of lubricant into the grinding zone with MQL fluid delivery, thereby offering certain degree of interfacial lubrication during grinding. Addition of MoS_2 microparticles to the base oils showed a slight improvement in their lubricity ($\mu_{\text{micropara}} = 0.57$, $\mu_{\text{microsoy}} = 0.58$). Further significant reduction in the values of μ was observed during application of nanolubricants. With paraffin-based nanolubricant (8 wt.%) and soybean-based nanolubricant (8 wt.%), friction coefficient values reduced to 0.43 and 0.41, respectively. Nanolubricants containing 8 wt.% of nanoadditive showed 14% average reduction in the values of grinding coefficient, compared to the case of 2 wt.% of nanoadditive. This is an indicative of improved lubrication with an increase in the concentration of MoS_2 nanoparticles. Overall, soybean-based nanolubricants showed a better performance than paraffin-based nanolubricants.

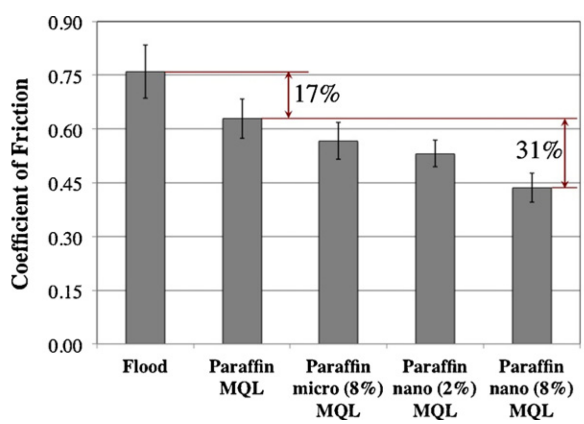

Fig. 3. Coefficient of friction obtained for flood cooling and paraffin-based lubricants during grinding of EN 24 steel (average values of 100 measurements, error bars represent standard deviation).

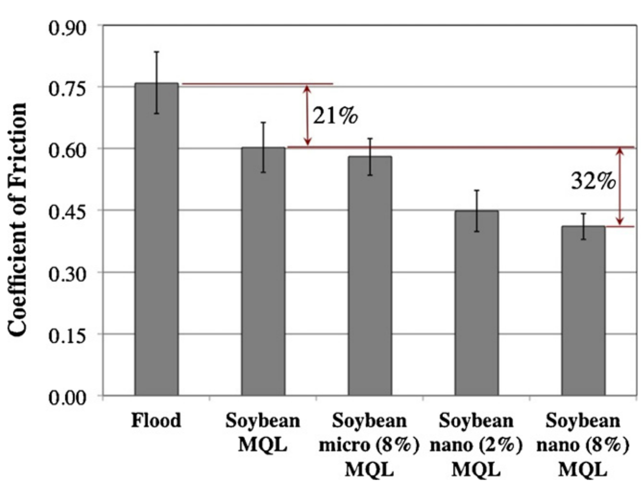

Fig. 4. Coefficient of friction obtained for flood cooling and soybean-based lubricants obtained during grinding of EN 24 steel (average values of 100 measurements, error bars represent standard deviation).

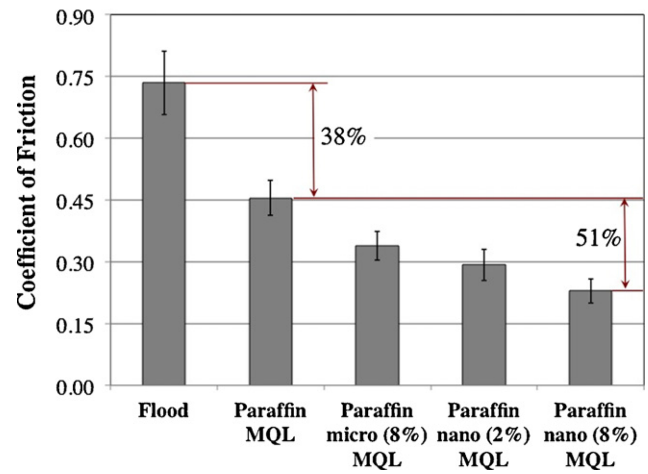

Fig. 5. Coefficient of friction obtained for flood cooling and paraffin-based lubricants during grinding of cast iron (average values of 100 measurements, error bars represent standard deviation).

3.1.2. Workpiece—ductile cast iron

The results of the friction coefficient as a function of lubrication condition, obtained during grinding of cast iron, are shown in Figs. 5 and 6. Each plotted data point was obtained by averaging the values of 100 grinding passes.

Under the investigated process conditions, flood cooling showed the highest value of μ (0.73). Compared to flood cooling, MQL with pure base oils showed a better performance in reducing friction ($\mu_{\text{soy}} = 0.46$, $\mu_{\text{para}} = 0.46$). In case of soybean-based lubricant, addition of microparticles showed a slight reduction in friction ($\mu_{\text{microsoy}} = 0.44$), whereas in paraffin-based lubricant, microparticles showed a distinctive improvement in lubricity ($\mu_{\text{micropara}} = 0.34$) over pure base oil. Nanolubricants showed further reduction in friction coefficient values as a function of increase in the concentration of nanoparticles. Friction coefficient values of 0.22 and 0.32 were recorded for paraffin-based and soybean-based nanolubricant (8 wt.%), respectively. Nanolubricants with 41% average reduction in friction coefficient over pure base oils

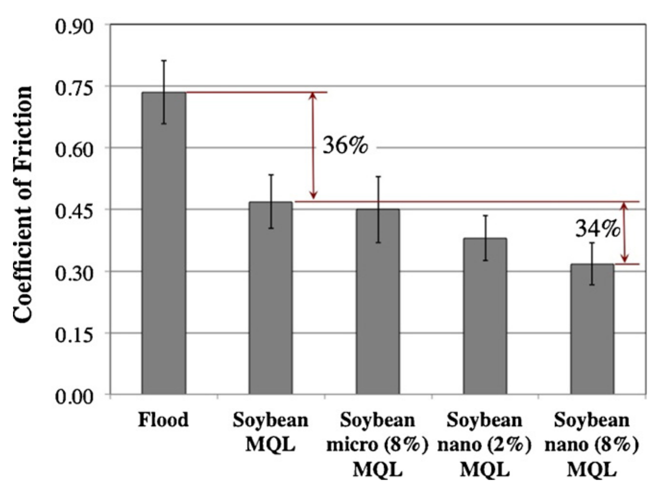

Fig. 6. Coefficient of friction obtained for flood cooling and soybean-based lubricants during grinding of cast iron (average values of 100 measurements, error bars represent standard deviation).

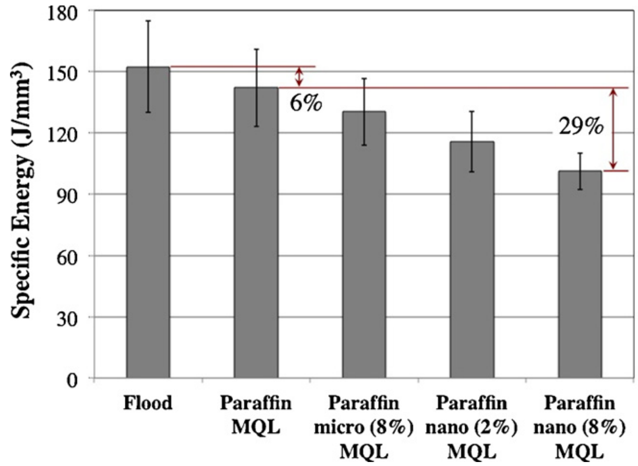

Fig. 7. Specific grinding energy obtained during grinding of EN 24 steel using flood cooling and paraffin-based lubricants (average values of 100 measurements, error bars represent standard deviation).

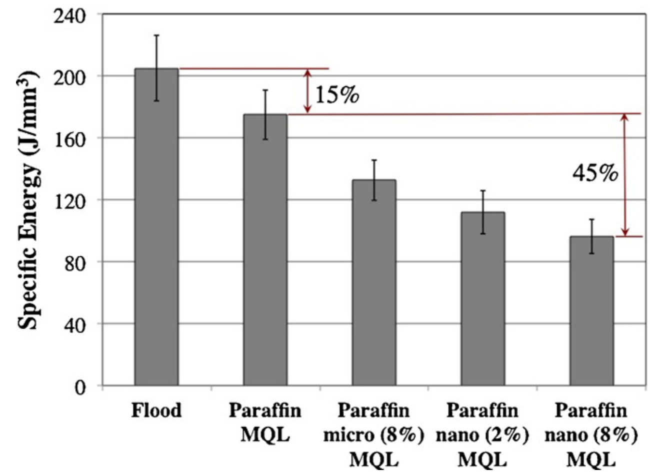

Fig. 9. Specific grinding energy obtained during grinding of cast iron using flood cooling and paraffin-based lubricants (average values of 100 measurements, error bars represent standard deviation).

have confirmed the excellent lubrication capability of multicomponent nanoadditive in MQL grinding.

3.2. Specific grinding energy

3.2.1. Workpiece—EN 24 steel

The results of specific energy consumption (average of all energy measurements of 100 grinding passes), obtained during grinding of EN 24 steel, are shown in Figs. 7 and 8, for paraffin and soybean-based formulations, respectively.

Flood cooling using water-based grinding fluid showed the highest energy consumption (152 J/mm^3). With MQL, a slight reduction in specific energy was observed for both paraffin and soybean oil (6% and 8%, respectively).

Nanolubricants showed further reduction in specific energy values due to multicomponent nanoadditive and as a function of increase in their concentration. Specific energy decrements of 34%, 29% and 22% were recorded for paraffin-based nanolubricant (8 wt.%) compared to flood cooling, MQL with pure paraffin and MQL with paraffin-microlube, respectively. Soy-based nanolubricant (8 wt.%) reduced energy consumption by 38%, 33% and 26%, compared to flood, pure soybean and soybean microlube, respectively. This demonstrates that the use of nanolubricants in MQL grinding caused a significant drop in sliding frictional losses, which fostered a proportional reduction in tangential forces and specific energy. This is consistent with the previous findings of authors' [4], where the use of oil-based nanolubricants in MQL grinding resulted in significantly low tangential forces.

3.2.2. Workpiece—ductile cast iron

The results of specific energy consumption (average of 100 energy measurements) while grinding cast iron are shown in Figs. 9 and 10 for paraffin and soybean-based formulations, respectively.

Specific energy results of cast iron showed a similar pattern as seen in the case of EN 24 steel, with flood cooling exhibiting the highest consumption of energy and nanolubricants (8 wt.%) the least. MQL grinding using paraffin-based nanolubricant (8 wt.%) reduced specific energy by 53%, 45% and 28%, compared to flood, pure paraffin and paraffin-microlube, respectively. Soy-based nanolubricant (8 wt.%) reduced energy consumption by 35%, 32% and 27%, compared to flood, pure soybean and soybean-microlubricant, respectively.

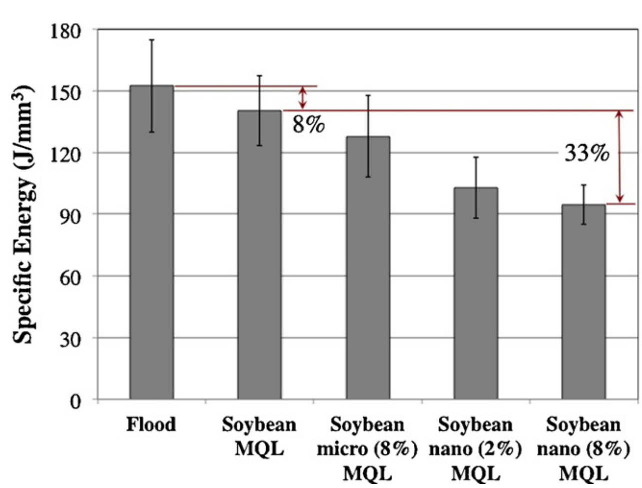

Fig. 8. Specific grinding energy obtained during grinding of EN 24 steel using flood cooling and soybean-based lubricants (average values of 100 measurements, error bars represent standard deviation).

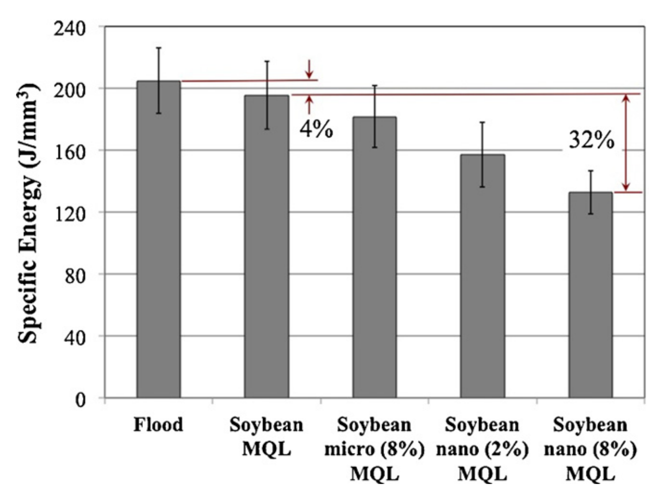

Fig. 10. Specific grinding energy obtained during grinding of cast iron using flood cooling and soybean-based lubricants (average values of 100 measurements, error bars represent standard deviation).

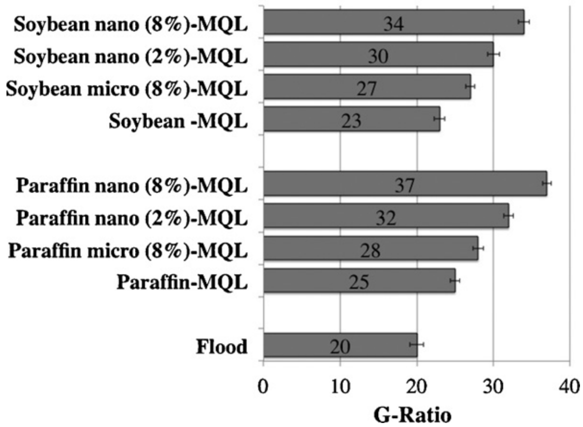

Fig. 11. G-ratio obtained during grinding of cast iron (average value of 2 measurements).

3.3. *Grinding (G)-ratio*

G-ratio values as a function of lubrication condition, obtained after 100 passes of grinding of cast iron and EN 24 steel, are shown in Figs. 11 and 12, respectively.

For both workpieces, least G-ratio values were observed in flood cooling. In MQL, improvement in G-ratio values was apparent with addition of solid lubricant particles to the base fluids. For cast iron, high G-ratio values of 37 and 34 were obtained for paraffin and soybean-based nanolubricant (8 wt.%), respectively, compared to the values of 25 and 23 with the respective pure base fluids. For EN 24 steel, paraffin and soybean-based nanolubricant (8 wt.%) showed G-ratio increments of 44% and 50%, respectively, as compared to the respective base fluids. Nanoparticles showed better anti-wear characteristic than the micro-sized particles, corroborating with its previous results of anti-friction. As compared to the microlubricants, nanolubricants (8 wt.%) showed average G-ratio increments of 29% and 27% for cast iron and EN 24 steel, respectively. High G-ratio values with nanolubricants are a confirmation of reduction of attritious wear during grinding. This anti-wear property of nanolubricants ensured the retention of tip geometry of abrasive grits for prolonged machining cycle times.

The low values of friction coefficient and specific energy and high values of G-ratio have proved the high process efficiency of nanolubricants in MQL grinding. Reduction of frictional losses

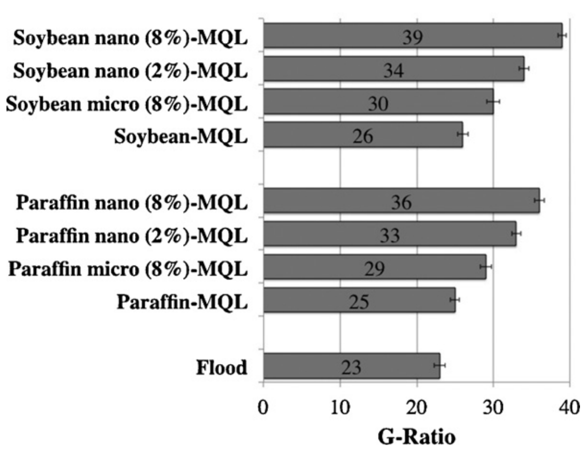

Fig. 12. G-ratio obtained during grinding of EN 24 steel (average value of 2 measurements).

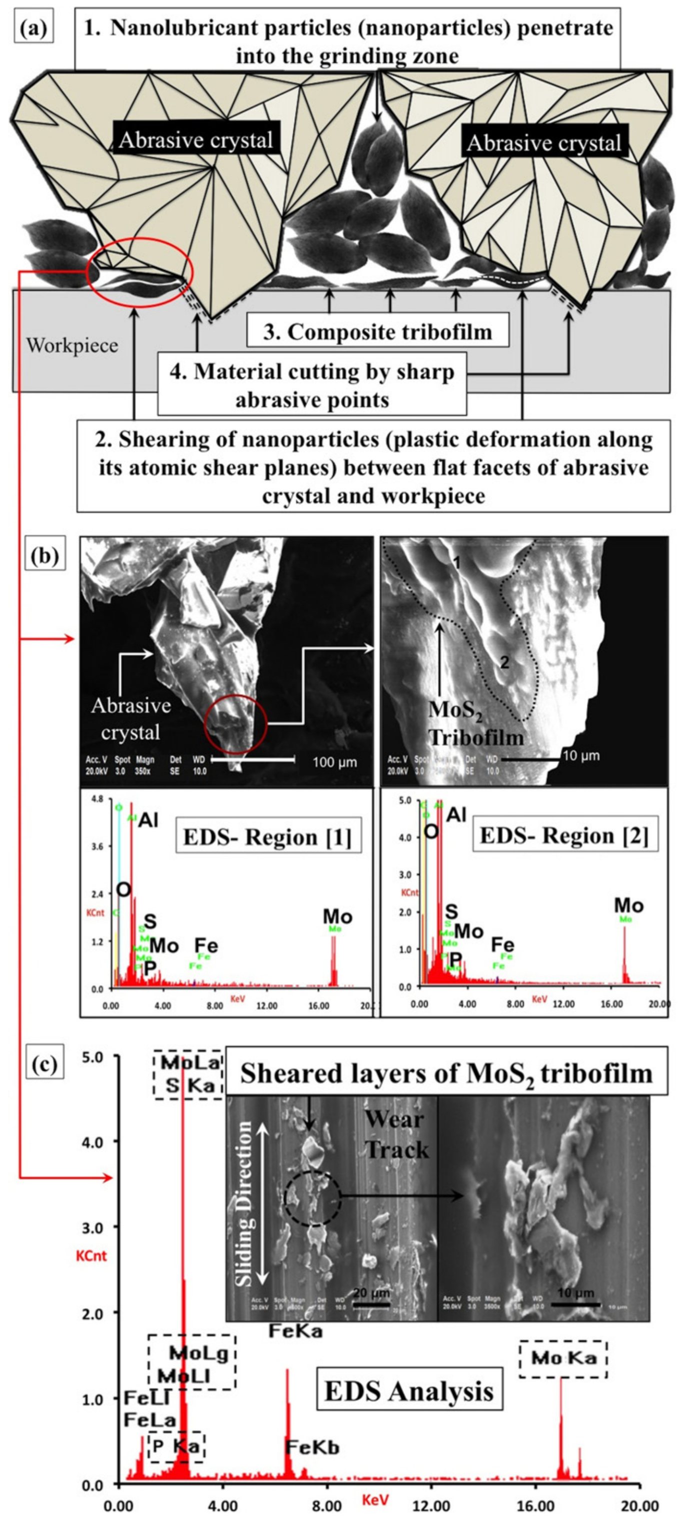

Fig. 13. (a) Processes involved in the formation of nanolubricant tribofilm during grinding, (b) SEM micrographs and EDS spectra of the surface of an abrasive grain, (c) SEM micrographs and EDS spectrum of the surface of workpiece. SEM micrographs and EDS spectra clearly shows the formation of MoS_2 lubricant film.

by delivering interfacial tribofilm is the attributive factor of high performance of multicomponent nanolubricants. The various processes involved in the formation of tribofilm during grinding are summarized in Fig. 13(a). Fig. 13(b) and (c) demonstrates the SEM micrographs and EDS spectra of an abrasive grain and workpiece surface, respectively, showing the formation of MoS_2 tribofilm. The process starts with the effective penetration of nanolubricant particles into the grinding zone. Continuous sliding of wearflats (blunt abrasive grains) over the workpiece surface results in the shearing of MoS_2 nanoparticles and delivery of organic molecules. The shearing of nanoparticles between wearflat-workpiece surfaces can be explained based on blunt asperity contact (adhesion friction) and sharp asperity contact (abrasive cone friction) theory [8]. At small penetration depths, the actual area of contact between the asperity of abrasive grain and the workpiece is large in the case of wearflat than sharp abrasive points (considering geometry of contact). The low shear stress associated with the former case result in rubbing of contacting surfaces (with negligible grain penetration) and shearing of softer material, which is undoubtedly HCP-layered MoS_2 nanoparticles (assuming that they are sandwiched between abrasive grain and workpiece surface). Thus, a protective tribofilm is formed which allow low-friction sliding/rubbing of wearflats over the workpiece surface. However, high stresses at sharp asperity contact result in the penetration of abrasive grains into the workpiece. It causes material removal without any effect from lubricant transfer film. These mechanisms of sliding/rubbing and abrasive cutting in the presence of nanolubricant film will be investigated in future research.

3.4. Effect of nanolubricant composition on process efficiency

Based on the results of coefficient of grinding and specific energy, on an average, soy-based and paraffin-based nanolubricants showed better process efficiency in near-dry grinding of EN 24 steel and cast iron, respectively. A similar trend was also observed in MQL grinding using soybean-based microlube.

The observed variation in the performance of lubricants in near-dry grinding of cast iron can be explained based on

1. The sludge formation during cast iron machining.
2. Polarity of sulfurized-triglyceride molecules of soybean-based nanolubricant.

It has been reported that machining of cast iron creates fine particles (range of 25 pm), in addition to metal chips. Due to their size, the particles become suspended in the lubricant to create sludge. The polarity of sulfurized-triglyceride molecules of soybean-based nanolubricant creates a strong affinity between the lubricant and the metal surface. This strong polar attraction may have resulted in the deposition of sludge particles (trapped in the lubricant films) over the workpiece surface, thereby causing an increase in friction due to over-clogging of grinding zone. Mineral-based paraffin oil has no polarity and therefore, no affinity to metal and less clogging of the grinding zone. Plausible mechanisms for these effects will be studied in depth in future research. While grinding EN 24 steel, the observed variations were a direct implication of the chemistry of base oils. The polarity of soybean-based lubricants provides strong metal affinity and more effective lubricant transfer film protection at the abrasive grains/workpiece interface. This was evident in the tribological findings of authors' [7]. Simulated abrasive tribotesting showed the formation of a continuous transfer film (tribofilm) on the workpiece surface by soybean-based nanolubricant.

4. Conclusions

The process efficiency of oil-based nanolubricants using minimum quantity lubrication (MQL) was investigated in the grinding of ductile cast iron and EN 24 steel. Surface grinding tests were carried out under different lubrication conditions—*MQL* grinding using nanolubricants (varying compositional chemistry and concentration of nanoparticles), pure base oils (without nanoparticles) and base oils containing MoS_2 microparticles (3–5 μm), and *flood* grinding using water-based coolant. Based on the experimental findings, it can be concluded that MQL grinding using nanolubricants increases the process efficiency by reducing frictional losses and energy consumption. Both soybean-based and paraffin-based nanolubricants showed better performance with an increase in the concentration of nanoparticles. A lowest friction coefficient of 0.22 and a maximum reduction of 53% in energy consumption were observed with nanolubricants. Enhancement of wheel life (G-ratio increment of 50%) was another attribution of nanolubricants to the overall process improvement.

An effect of compositional chemistry of nanolubricants was observed in their performances, while grinding different workpiece material. On an average, soybean-based and paraffin-based nanolubricants showed better process efficiency in MQL grinding of EN 24 steel and cast iron, respectively.

The suitability of oil based-nanolubricants in near-dry (MQL) grinding was proven under the investigated process conditions, concerning both frictional losses and energy consumption. Further investigations related to the mechanisms of material removal are required to optimize the lubrication performance of oil-based nanolubricants in near-dry grinding.

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