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Assessment of cooling-lubrication and wettability characteristics of nano-engineered sunflower oil as cutting fluid and its impact on SQCL grinding performance

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ABSTRACT

In small quantity cooling lubrication (SQCL) grinding, small quantity of cutting fluid is air-atomized to serve the purpose of cooling and lubrication during the process. As the flow rate of cutting fluid is intended to be set as low as possible, it is essential to develop high performance cutting fluids. In the present work, it has been attempted to enhance cooling-lubrication and wetting characteristics of a bio-degradable flower seed extracted oil, namely sunflower oil, with suspension of multi-walled carbon nano tubes (MWCNT). The suspension was realized by ultrasonic agitation provided through a 700 W probe sonicator. This new generation fluid was used as a cutting fluid in small quantity cooling-lubrication (SQCL) mode; for grinding hardened AISI52100 steel by a vitrified bonded alumina wheel. Thermal conductivity, anti-frictional properties and therefore the cooling-lubrication characteristics of sunflower oil could be enhanced significantly by the dispersion of nanoparticles. Similarly, wettability of the ordinary sunflower oil was substantially improved with nano-suspension. Augmentation of its overall quality by such nano particle suspension subsequently led to remarkable reduction in requirement of specific energy in the grinding process, as compared with the values obtained by using ordinary sunflower oil (SQCL mode) and soluble oil (delivered in conventional flood and SQCL mode). The wear rate of wheel was also significantly minimized and F_t/F_n ratio could be kept at steady and lower level, which depict the better sharpness retention of grits under nano-SQCL environment. Surface quality was superior under the nano-SQCL environment. Compressive residual stress could be achieved on the ground surface along with acceptable surface roughness.

1. Introduction

With stricter environmental laws, search for suitable "green" cutting fluid for machining applications becomes inevitable. Cutting fluid composition has a significant influence on process outputs, energy consumption and nevertheless on environmental pollution. Thus, a proper balance between environmental, technological and economic requirements must be ensured (Winter et al., 2015) while selecting a suitable metal working fluid for any machining operation. It is recognized that many vegetable oils are non-toxic, highly bio-degradable and renewable in nature. The cost of these oils are also low. Vegetable oil molecules contain long triglyceride structured fatty acid chains, which make them excellently lubricious. The polar chains enhance interaction of oils with the object surfaces and helps in achieving effective boundary lubrication. In many applications vegetable oils, even without any additives, are reported to outperform mineral based oils in reducing friction, improving anti-wear properties (Asadauskas et al., 1996) and enhancing fatigue resistance (Odi-Owei, 1989). Krahenbuhl (2002) observed that higher flash point of lubricious vegetable oil makes it a potential alternative for petroleum based cutting fluids. These oils have been reportedly used at high cutting velocity and feed rate during machining of titanium and stainless steel effectively, which led to achieve an increased productivity at a reduced tool cost. Winter et al. (2012) identified Jatropha oil as an ecologically benign metal working fluid, which has the advantage of renewability, bio-compatibility and excellent lubricity. This oil has been recommended for use to address the scarcity problems of non-renewable resources.

Application methods of coolant-lubricants are also very important. Minimum quantity lubrication (MQL) are being preferred to

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conventional flood cooling method, as it reduces the consumption rate substantially. Use of vegetable oils in MQL mode conforms to sustainability criteria. In MQL method, cutting fluid is atomized at a very low flow rate (5–100 ml/h) by a highly pressurized stream of air/gas. In this process, aerosol is produced and it is further utilized for machining. However, the quality requirements of the coolant-lubricants in grinding are very stringent. De Chiffre and Belluco (2002) reported a comparative analysis on the performance of water based cutting fluids and straight oils during MQL assisted turning, drilling and reaming of austenitic stainless steel. Application of vegetable oils in MQL machining has been found to be effective in many turning and drilling case studies. Use of vegetable oil resulted in lowering of cutting force and enhancement of tool life. Khan et al. (2009), during the turning of AISI9310 steel using food grade vegetable oil under MQL mode, observed a 31% improvement in surface finish than flood cooling. Lowered flank wear and improved chip formation mechanism could be achieved. In another study, Xavior and Adithan (2009) identified coconut oil as an effective choice for reducing tool wear and improving surface finish during the turning of AISI3040 steel. Palm oil appeared as another effective choice for producing cooling and lubrication during high speed drilling of Ti-6Al-4V. An approximate reduction of 33% and 22% in thrust force and workpiece temperature was observed respectively, when palm oil was used replacing synthetic ester oil (Rahim and Sasahara, 2011). Effectiveness of other oils like soybean, rapeseed, sunflower etc., are also reported. However, scope of vegetable oils were less explored in high speed process like grinding, where the requirements are more challenging. Alves and de Oliveira (2006) developed a new, highly bio-degradable cutting fluid made of castor oil, which could improve the wheel life and surface finish during grinding of SAE8640 material using cBN wheel. Similarly, MQL application of another bio-oil was found to be successful in minimizing thermal softening on the ground surface of Ti-6Al-4V super alloy (Sadeghi et al., 2009).

High specific energy processes like grinding require high performance cutting fluids. Excessive heat generation at grinding zone can adversely affect the performance of vegetable oil. Nanolubricants, which are colloidal dispersion of nanoparticles in a base fluid, can potentially play a beneficial role. The thermal conductivity as well as lubrication properties of the base fluid is found to be augmented by the dispersion of nanoparticles, which in turn, effectively controls temperature rise at the grinding zone. Shen et al. (2008) observed the outperformance of nanolubricants over pure base oil and synthetic soluble oil during grinding of cast iron. When delivered under MQL mode, nanolubricants were able produce a lower level of force. The ability of nanolubricants to reduce friction and to withstand high pressure at the grinding zone in MQL applications, also depends on its penetration capacity through the contact interface and formation of an effective tribo-chemical film by the decomposition of lubricants (Kalita et al., 2012). The formation of a sacrificial layer was observed during grinding of ASTM A536 grade ductile cast iron using MoS_2 dispersed nanolubricants. The deformation of organic molecules and nanoparticles caused by the high shear and extreme pressure present at the grinding interface was argued to be the reason behind the formation of such a film, which in turn, was found to adhere to the workpiece surface, reducing frictional force. At the same time, oil based graphite and hexagonal boron nitride lubricants were also found to be effective in reducing friction during a ball on disc tribo-test with the latter producing better result (Nguyen et al., 2012). Similarly, the effect of different types of base fluids in pure form as well as with dispersed MoS_2 nanoparticles on grinding of AISI4500 steel, was analyzed by Zhang et al. (2015). Out of the different types of fluids, MoS_2 dispersed palm oil was found to produce excellent lubrication property when supplied under MQL environment. It was concluded that the presence of carboxyl group in the palm oil was the major contributing factor. Increase in mass fraction of nanoparticles was also found to escalate the lubrication properties, however, a concentration of 6 wt.% was reported to be optimal for grinding performance.

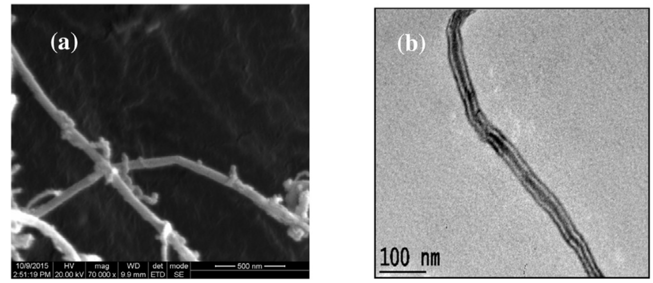

Fig. 1. (a) SEM image of clustered MWCNT particles and (b) TEM image of a single strand of MWCNT.

In the reported literatures, mostly force and surface roughness aspects have been highlighted in nano-SQCL grinding. Important attributes like G-ratio, specific energy, residual stress and chip morphologies have not been given adequate attention. Moreover, multi-walled carbon nano tubes (MWCNT), which have good potential in enhancing both heat dissipation ability and lubrication of the SQCL medium, has not been explored, in particular with base fluids like vegetable oils. The studies on their wettability and high temperature tribological characteristics are grossly missed out in the available literatures. In the present study, aforesaid grindability aspects have been studied with the MWCNT suspended sunflower oil in SQCL grinding of hardened AISI52100 steel. The nanoparticles dispersed oil was thoroughly characterized and the impact of salient characteristics on grinding performance was critically analyzed. The terminology SQCL is introduced as a more generic substitute of MQL, encompassing a wider domain of cutting fluid consumption rate.

2. Preparation of nano-engineered sunflower oil

Earlier works of the present research group has found that the sunflower is more promising as SQCL medium than other vegetable oils like palm oil (ManojKumar et al., 2014) in terms of achieving good G-ratio and reduced force level. Therefore, sunflower oil has been selected in the present work as the base fluid for producing the nanofluid. The nanopowder of interest was multi-walled carbon nanotubes (MWCNT's), considering its capability to enhance thermal conductivity and anti-friction characteristics of the cutting fluid. After some trials, 1 wt.% suspension of MWCNT powder (make: M.K. Impex Corp, Canada) was successfully achieved by adopting a two-step method, in which the nano powder (≈40 nm external diameter and ≈2 μm length; 99.9% purity) was added to sunflower oil, followed by ultrasonic agitation of the mixture for a period of 5 min. A 700 W probe sonicator (Make: QSONICA, U.S.A.) was used for this purpose, in which the high frequency (20 kHz) vibration (with 30 μm amplitude) exhibited by the tip of a probe helped in disintegrating the agglomerated particles to obtain a steady, well dispersed nanofluid. The morphology of MWCNT particles in agglomerated form in the procured sample powder is shown Fig. 1(a). When a single strand was imaged under TEM, its multiwalled morphology could be resolved to an appreciable extent, as visualized in Fig. 1(b).

3. Characterization of the nanofluid

3.1. Pertinent physical characteristics and thermal conductivity

Some salient characteristics of the nanofluid were closely studied and compared with those of the base fluid and soluble oil.