THE INFLUENCE OF BASE FLUID AND GRAPHENE NANOPARTICLES CONCENTRATION ON SURFACE INTEGRITY OF SAE 52100 STEEL AFTER GRINDING

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Abstract: *Grinding is known as a high specific energy process, in which most of it is transformed into heat and conducted to the workpiece, especially when using conventional abrasives like aluminum oxide and silicon carbide. Thus, the use of cutting fluid is indispensable to attenuate or avoid the occurrence of thermal damage. However, concerning human health and the environment, as well as economic aspects and the search for more sustainable processes, strategies that reduce cutting fluid usage such as the minimum quantity lubrication (MQL) technique have gained prominence. This technique uses a much lower quantity of cutting fluid than flood (conventional coolant delivery technique), which is directed to the cutting zone with compressed air. Nevertheless, although the MQL technique has shown promising results in comparison to dry grinding and flood technique for different materials, the use of nanofluids has been showing great potential to improve the MQL technique, since the presence of nanoparticles tends to improve lubrication and cooling capacities of the base fluid. In this sense, this work aims to evaluate the influence of the type of base fluid and nanoparticles concentration on the surface integrity of SAE 52100 hardened steel after grinding with graphene-based nanofluids applied with the MQL technique. Two different base fluids were tested: a semi-synthetic vegetable base and a synthetic one. The graphene was added to the base fluids at two different concentrations: 0.025 wt.% and 0.075 wt.%. Grinding trials using the base fluids only (without nanoparticles) were also performed for comparison purposes. The surface integrity of the workpiece after grinding was analyzed in terms of surface finish (Rq parameter) and microhardness below the machined surface. The results showed that the nanofluid's efficiency in reducing the surface roughness of the ground surface was strongly influenced by the base fluid and graphene concentration: best results (8.6% reduction in Rq roughness compared to the traditional MQL technique) were found after grinding with combination between semi-synthetic fluid and the lowest graphene concentration (0.025 wt.%). Additionally, the presence of graphene in the cutting fluid attenuated the occurrence of thermal damage in terms of microhardness reduction; for the highest nanoparticles concentration (0.075 wt.%), such reductions were only 1% and 3% after grinding with semi-synthetic and synthetic fluid, respectively.*

Keywords*: Grinding; Nanofluids; Semi-synthetic fluid; Graphene; MQL technique; Surface integrity; Thermal damage.*

1. INTRODUCTION

Due to some inherent characteristics of grinding (e.g., high cutting speeds, low radial depth of cut values that means low material removal rate, intense friction, plastic deformation in cutting mechanism, and high specific energy compared to machining processes with multipoint cutting tools with defined geometry, such as milling), the use of cutting fluid becomes indispensable to prevent the surface integrity of the workpiece from surface finishing deterioration and thermal damages as well as cutting efficiency of the grinding wheel. This is particularly important when grinding high-carbon hardened steels such as SAE 52100 due to the high prone for microstructure alteration under the elevated temperatures developed during the cutting process, especially considering conventional abrasives such as aluminum oxide (Al_2O_3) (Malkin and Guo, 2008; De Paiva et al., 2021).

However, the use of cutting fluid goes against the recent politics regarding sustainable and more environmentally friendly processes, as most of the cutting fluids, especially the mineral ones, are harmful to both human health and the environment, not to mention the costs for purchase, maintenance, and disposal (Hadad, 2015; Sanchez et al., 2010). In this context, there is a need for cooling-lubrication strategies that can reduce and amount of cutting fluids especially in grinding where flow rates are generally higher than 10 L/min (600,000 mL/h). So, the minimum quantity lubrication (MQL) technique is the most common and widely used one. It consists of delivering an extremely low quantity of fluid to the cutting zone (flow rates usually lower than 500 mL/h) with the aid of compressed air (Walker, 2013).

Despite some promising results in grinding hardened steels with the MQL technique, its poor cooling capacity when grinding some hardened materials is a concern and usually limits its widespread application in the metalworking industry, among others. In this sense, the addition of nanoparticles to the cutting fluid has been extensively tested for MQL applications, since the presence of nanoparticles usually enhances the base fluid lubrication and cooling capacities, thereby improving MQL technique performance (Devendiran and Amirtham, 2016; Sharma et al., 2015).

Zhang, D. et al. (2015) compared the grinding of hardened AISI 1045 steel with MoS_2-based nanofluid applied via MQL technique with the traditional MQL technique (oil without nanoparticles). The oil tested by the authors was a vegetable one (colza oil). The results showed that the MQL nanofluid at 1% concentration led to a reduction in tangential grinding force, coefficient of friction, specific energy, and surface roughness (Ra parameter) by 27%, 21%, 28%, and 6%, respectively. According to the authors, the presence of nanoparticles in the cutting fluid improved the lubrication property and consequently the efficiency of the traditional MQL technique, which is attributed to the nanoparticle's anti-wear and anti-friction capability. The authors also tested different nanoparticle concentrations and observed a decrease in grinding performance (e.g., higher coefficient of friction, specific energy, and surface roughness) for volume concentrations over 2%. According to them, nanoparticles tend to cluster at high concentrations, which reduces lubrication performance.

De Paiva et al. (2020) during the grinding of SAE 52100 hardened steel also evaluated the influence of graphene concentration dispersed in a semi-synthetic fluid applied with the MQL technique and found that, in terms of surface finish, graphene-based nanofluid was able to reduce surface roughness (Ra parameter) of ground surface up to 12% in comparison to the traditional MQL technique. Furthermore, they reported that the surface roughness of the ground surface increased with graphene concentration. According to the authors, high nanoparticle concentration diminishes the lubrication capacity of the cutting fluid due to particle agglomeration. Additionally, the agglomerated nanoparticles can act as abrasives at the contact zone, which tends to deteriorate the surface roughness of the ground surface.

Considering the importance of the type of fluid, type of nanoparticles, and their concentration to grinding performance, this work sought to evaluate the influence of base fluid and nanoparticles concentration on surface integrity of SAE 52100 hardened steel after grinding with graphene-based nanofluids applied with MQL technique. Two different and commercially available cutting fluids were used as the base fluid for graphene dispersion at different concentrations. The surface integrity of the workpiece after grinding was analyzed in terms of surface finish (Rq parameter) and microhardness below the machined surface.

2. METHODOLOGY

Grinding tests were performed on a MELLO P-36 peripheral surface grinding machine with a motor nominal power of 2.25 kW and a nominal speed of 2400 rpm. The resolution of the main spindle, the vertical axis in which the grinding wheel rotates, is 5 µm. A conventional white aluminum oxide (Al_2O_3) grinding wheel, from Norton-Saint Gobain Abrasives, has a 250 mm external diameter. Its designation is 38A60K6V. The workpiece material was the SAE 52100 hardened steel (60 ± 2 HRC) having a cylindrical geometry: 16 mm diameter and 17.4 mm height. Two parallel directly opposite surfaces of the workpiece were those used for the grinding tests. Worth mentioning that this particular material is widely employed for bearing applications and, therefore, is commonly submitted to the grinding process after heat treatment (Balart et al., 2004).

The cutting parameters employed for all grinding trials are grinding wheel speed (vs) of 31 m/s, workspeed (vw) of 7 m/min, and radial depth of cut (ae) of 30 µm. Two different cutting fluids were tested in this work: a semi-synthetic vegetable-based oil (Vasco 7000) and a synthetic oil (Grindex 10), both from Blaser Swisslube. The fluids were used as base fluid to add multilayer graphene at two different concentrations: 0.025 wt.% and 0.075 wt.%. The multilayer graphene nanoparticles were produced by natural graphite exfoliation according to the methodology employed by Machuno et al. (2015). They consist of nanosheets with 1-30 nm thickness and 1-20 µm length. The graphene dispersion in the base fluids was performed using a commercially ultrasonic bath for two hours and a frequency of 40 kHz.

Six (6) different cutting fluids were tested in this work, all of them delivered via the MQL technique at a flow rate of 150 mL/h and 0.3 MPa of compressed air pressure. A conventional geometry nozzle was used, positioned to deliver the cutting fluid tangentially to the workpiece ground surface. The main characteristics of each base fluid as provided by the manufacturer shown in Table 1. For characterization, the thermal conductivity and kinematic viscosity of each cutting fluid tested were measured by using a Linseis THB-1 and an Anton Paar SVM 3000 viscosimeter, respectively. The results are shown in Table 2.

Table 1. Main characteristics as provided by Blaser Swisslube for each base fluid.

	Semi-synthetic (Vasco 7000)	**Synthetic (Grindex 10)**
Color	Light brown	Yellow
Water content	-	40%
Esther content	25%	-
Density at 20 °C (g/cm³)	0.98	1.12

Table 2. Thermal conductivity and kinematic viscosity at 40 °C for each cutting fluid tested in this work.

Cutting fluid	Graphene concentration (wt.%)	Thermal conductivity ($Wm^{-1}K^{-1}$)	Kinematic viscosity (mm^2s^{-1})
Semi-synthetic	0 (without nanoparticles)	0.3137	71.8045
	0.025	0.2942	82.4005
	0.075	0.2939	81.1800
Synthetic	0 (without nanoparticles)	0.3548	10.6905
	0.025	0.3559	13.0490
	0.075	0.3615	13.9235

The grinding wheel was dressed before each grinding test by using a single-point diamond dresser, with 0.31 mm dressing width (b_d) and a dressing speed (v_d) of 150 mm/min, which guarantee a grinding wheel overlap ratio (U_d) equal to 5. Each grinding test consisted in removing the total radial depth of cut of the plane surface of the workpiece through one passage of the grinding wheel, with one spark-out passage (with no depth of cut increment). Each grinding experiment was replicated once to increase the reliability of the results.

The surface integrity of the workpiece after grinding was evaluated in terms of surface finish (roughness Rq) and microhardness below the machined surface. A Taylor Hobson Surtronic S128 portable surface tester was employed for roughness measurements. Based on ISO 4288:1996 (1996), a 5.0 mm evaluation length, 0.8 sampling length, and Gaussian filter were used. Five surface roughness measurements were done for each grinding test and the mean and standard deviation values for the Rq parameter were selected for analysis. For microhardness measurements, a SHIMADZU HMV-2 microhardness tester was employed with Vickers indenter and parameters of 980.7 mN of load ($HV_{0.1}$) for 10 seconds. The microhardness measurements were performed at 20 µm below the machined surface after standard metallographic preparation of samples (sanding using sandpapers with granulometry mesh #120, #200, #400, #600, and #1200, followed by polishing with 1.0 µm alumina paste). For each grinding trial, three measurements were taken, and the mean and standard deviation values were used for analysis.

3. RESULTS AND DISCUSSIONS

The mean values of surface roughness (Rq parameter) for each cooling-lubrication condition tested in this work are shown in Figure 1, where the error bars represent the standard deviation of the measurements. One notes that both base fluids (semi-synthetic and synthetic) presented the same results in terms of surface finish after grinding without nanoparticles. Considering the nanofluids, it can be noticed that for the lower concentration of nanoparticles (0.025 wt.%), the addition of graphene in the semi-synthetic fluid improved grinding performance by reducing Rq values by 8.6%. For the synthetic fluid, in contrast, a 60% increase in roughness Rq was observed. When machining at a higher concentration of nanoparticles (0.075 wt.%) dispersed in semi-synthetic and synthetic fluids, the presence of graphene led to an increase in Rq values of 7% and 91%, respectively.

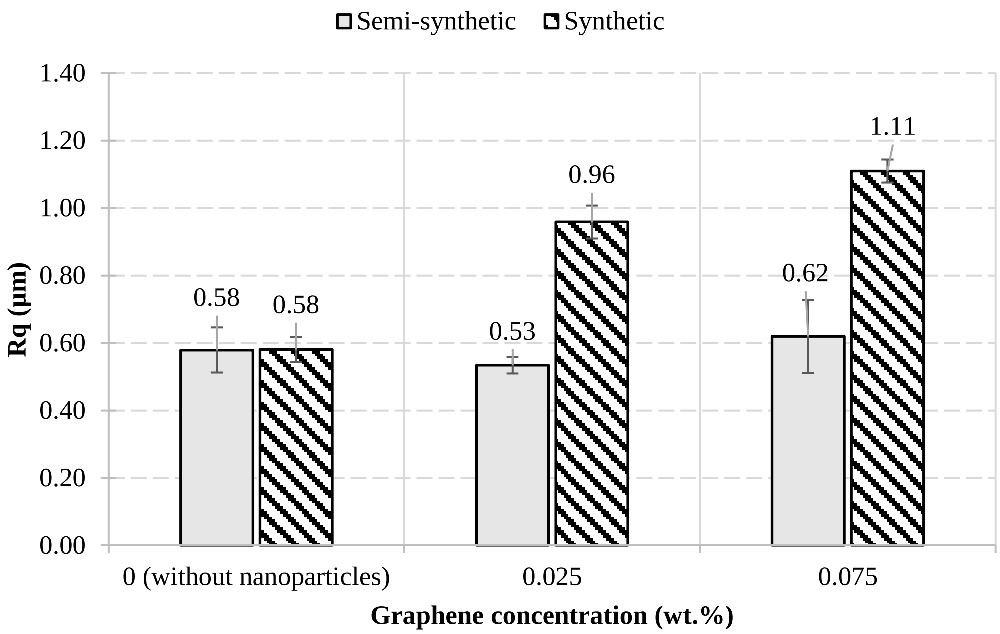

Figure 1. Rq roughness of SAE 52100 hardened steel for the different cooling-lubrication conditions tested.

The benefits in terms of reducing surface roughness in grinding with nanofluids applied with the MQL technique are associated with the action mechanisms of nanoparticles at the contact zone, especially those which contributed to tribofilms formation. These protective films enhance tribological conditions between abrasive grains and the workpiece by reducing friction, which resulted in surface finishing improvement of components (Singh et al., 2019).

The action mechanisms of nanoparticles at the contact zone, however, are adversely affected in case of cluster formation in the nanofluid when a higher nanoparticles concentration is employed, which is associated with nanoparticle agglomeration that tends to occur due to high particle concentration, for instance. Zhang, Y. et al. (2015) evaluated different nanoparticle concentrations in MoS_2 nanofluids during the grinding of stainless steel with an Al_2O_3 wheel. The authors observed an increase in the coefficient of friction and the specific energy for nanoparticle concentrations over 6%. According to them, the dynamic stability of nanoparticles diminishes once their concentration in the base fluid increases, thereby reducing the lubrication capacity of the nanofluid. Thus, the increase in Rq values with graphene concentration, irrespective of base fluid, may be attributed to a possible nanoparticle's agglomeration, which is in good agreement with the findings from Zhang, D. et al. (2015), De Oliveira et al. (2019) and De Paiva et al. (2020).

Regarding the influence of the base fluid, it is worth mentioning that the synthetic fluid tested in this work presents water in its chemical composition as shown in Table 1. In this sense, the hyper hydrophobic characteristic of graphene (Alberts et al. (2009 e Nguyen et al. (2012)) may have favored agglomeration in comparison to the semi-synthetic fluid, which explains the worst results in terms of surface finish even for the lower nanoparticles concentration. Additionally, the abrasive-like behavior of nanoparticles is maximized with agglomeration (Azman et al., 2016; Lee et al., 2009), which can lead to deeper and wider grooves in the ground surface, thereby increasing the surface profile amplitude and Rq values as consequence. Thus, considering the cutting fluids evaluated in this work and the surface finish of the ground surface, the semi-synthetic outperformed the synthetic one as the base fluid for graphene dispersion.

The mean values of microhardness below the ground surface are shown in Figure 2, where the dotted line represents the workpiece hardness prior to the grinding operation (801 HV), and the error bars stand for the standard deviation of the measurements. As can be noticed, the grinding with cutting fluids without nanoparticles resulted in a reduction in microhardness by 5% and 11% for the semi-synthetic and synthetic fluids, respectively. This microhardness reduction was attenuated when grinding with nanofluids, irrespective of the base fluid and nanoparticles concentration. For the semi-synthetic fluid, the microhardness reduction below the machined surface was 2% and 1% for 0.025 wt.% and 0.075 wt.% graphene concentration, respectively. For the synthetic fluid, the reductions were slightly higher: 5% and 3% as shown in Figure 2.

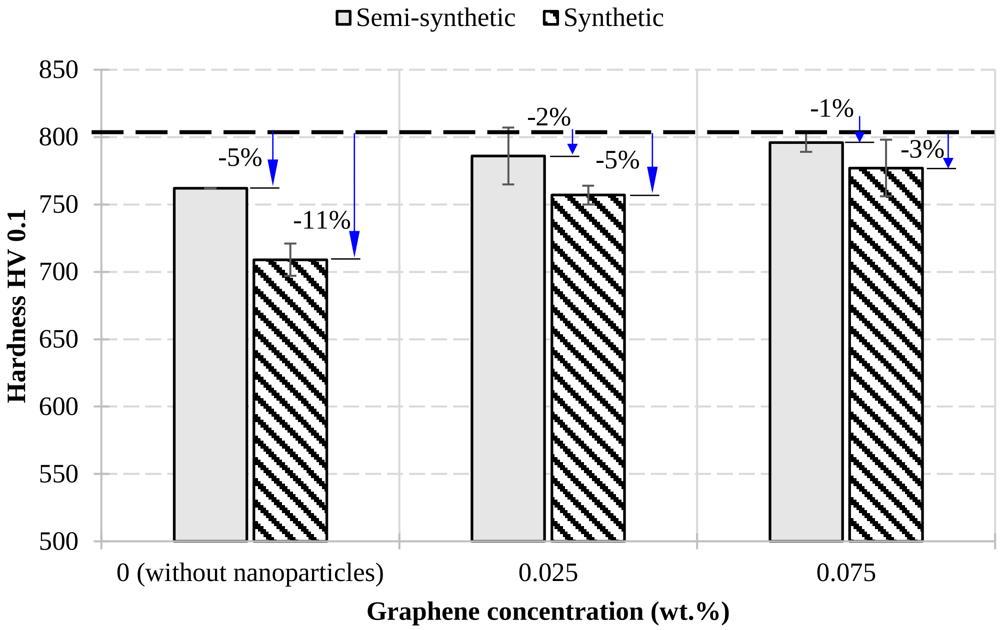

Figure 2. Microhardness at 20 µm below the machined surface for the different cooling-lubrication conditions tested.

The hardness reduction in ground parts is a common phenomenon in grinding, especially considering high-carbon hardened steels such as SAE 52100. This reduction is associated with an excessive tempering near the contact zone as a consequence of the development of high temperatures during the cutting process (Malkin and Guo, 2008; Seidel et al., 2018) that causes heat to be more concentrated in the grinding zone and is mostly directed to the workpiece when a conventional abrasive grinding wheel is used, like that one employed in this work. An increase in hardness (rehardening) beneath the ground surface can also occur, which is a consequence of reaustenitization followed by the formation of untempered martensite (Malkin and Guo, 2008). Worth mentioning that the thermal damage extension beneath the ground surface, including the presence or not of untempered martensite, depends on the contact zone temperature level and its time of action. In terms of microhardness reduction (excessive tempering) for instance, an affected layer up to 180 µm below the machined surface was reported by De Paiva et al. (2021) after grinding SAE 52100 hardened steel, with a 22% hardness reduction at 20 µm below the ground surface.

In this context, the microhardness results found in this work indicate that the presence of graphene in the cutting fluid contributed to better temperature control at the contact zone, thereby attenuating possible thermal damage to the workpiece in terms of hardness reduction beneath the machined surface. Worth mentioning that this better temperature control may be either associated with a reduction in temperature during grinding or a reduction in the heat partition that is conducted to the workpiece, which can be accomplished by friction reduction and/or heat dissipation enhancement. Although further analysis (e.g., cutting power and temperature measurements) must be carried out to better understand the graphene role in thermal damage reduction during grinding with nanofluids, the lamellar structure and outstanding thermal conductivity of graphene (Liu et al., 2014; Zhang, G. et al., 2015) can provide better lubrication and cooling, respectively, which may explain the better temperature control at the contact zone.

4. CONCLUSIONS

After grinding the SAE 52100 hardened steel with graphene nanofluids applied with the MQL technique using different base fluids and nanoparticles concentrations, the following conclusions can be drawn:

i. Both base fluid and nanoparticle concentration affected the surface integrity of the workpiece in terms of surface finish (Rq parameter) and microhardness below the machined surface.
ii. In terms of surface finish, the addition of graphene improved grinding performance by reducing Rq roughness (8.6% reduction) only for the semi-synthetic fluid at low graphene concentration (0.025 wt.%).
iii. Considering the cutting fluids evaluated in this work and the results of the surface finish of the ground surface, the semi-synthetic outperformed the synthetic one as the base fluid for graphene dispersion.
iv. Surface roughness of the ground surface increased with nanoparticle concentration irrespective of the base fluid.
v. For the conditions tested in this work, the presence of graphene in the cutting fluid contributed to attenuating thermal damage in terms of microhardness reduction below the machined surface. The best results were found after grinding with the higher nanoparticles concentration (0.075 wt.%), which promoted microhardness reductions of only 1% and 3% for semi-synthetic and synthetic fluids, respectively.

5. ACKNOWLEDGEMENTS

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