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INFLUENCE OF CUTTING FLUID TYPE ON CUTTING REGION TEMPERATURE DURING GRINDING OF BEARING STEEL

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Abstract. *Bearing components require tight dimensional tolerances and superior finishing which are commonly achieved through grinding process. However, grinding is known as a high specific energy process, that means, a great amount of energy is consumed to remove a small volume of material. Furthermore, most of this energy is transformed into heat at the contact zone, thereby increasing the local temperature, especially when employing conventional abrasive grits, such as white alumina for instance. Also, the development of high temperatures at the cutting zone adversely affects workpiece's surface integrity. In this sense, the selection of grinding conditions, including the type of cutting fluid, plays an important role to maintenance of component's integrity. Thus, this work sought to evaluate the influence of two different vegetable-base cutting fluids (semisynthetic and synthetic) delivered by conventional technique (flood) on cutting region temperature during grinding of the hardened SAE 52100 steel under two radial depth of cut values (*a_e *= 10 µm and 30 µm). Surface roughness and hardness below ground surface were the output variable evaluated. The results showed that, although no significant differences were observed when grinding at the soft cutting condition (*a_e *= 10 µm), when grinding with the semisynthetic fluid contributed to reduce cutting region temperature by about 30% in comparison to the use of synthetic fluid at the highest radial depth of cut (*a_e *= 30 µm). Also, under this severest condition, grinding with the semisynthetic fluid contributed to reduce surface roughness and hardness variation.*

Keywords: *Grinding, Cutting fluid type, Bearing steel, Radial depth of cut, Temperature, Surface finish.*

1. INTRODUCTION

Grinding is an important machining process for bearing industry, since it can provide to a given component a good combination of tight dimensional tolerances and superior finishing, which is fundamental to improve tribological conditions in bearing application (Hutchings; Shipway, 2017; Stephenson; Agapiou, 2016). However, it is known that grinding process consumes a great amount of energy to remove a small volume of material, that is, it is a high specific energy process in comparison to turning and milling, for instance (Stephenson; Agapiou, 2016). Additionally, most of this energy is transformed in heat at the contact zone (Klocke, 2009), which in turn is conducted to the workpiece during the process, particularly when grinding with conventional abrasive grits such as alumina and silicon carbide. This is due to the relatively low thermal conductivity of these ceramic materials, especially at high temperatures (Ashby; Jones, 2005; John, 1992). In addition, the small size of chips generated during grinding also contributes to increase the heat partition which is mostly conducted to the workpiece.

As a consequence of this great amount of heat conducted to the workpiece, high temperatures are usually developed near the contact zone, which can adversely affect surface integrity of workpiece thereby resulting in thermal damages such as grinding burns, great hardness variation, undesirable residual stresses and microcracks (Malkin; Guo, 2008; Seidel *et al*., 2018). In this context, the use of cutting fluid in grinding operations play an important role in controlling the temperature at the contact zone, thereby avoiding or attenuating the negative effects of high temperatures.

The use of cutting fluid in grinding can control the temperature at the contact zone by direct cooling the specially the workpiece surface and by reducing the friction and then heat generation (lubrication effect), which consist in the two major functions of cutting fluids (Marinescu *et al*., 2016). In this sense, different cutting fluids will perform dissimilar according to their cooling and lubrication capacities. Considering the cutting fluids classification in ASTM E2523-13 (2007) and ASTM D2881-19 (2009), two types of water-based cutting fluids stand out: the semisynthetic and synthetic types. Synthetic fluids present excellent cooling capacity, but poor lubricity; semisynthetic types, on the other hand, present a good lubrication capacity, but lower cooling ability in comparison to the synthetic ones, as well as lower mixture stability (Debnath *et al*., 2014).

Even though the cutting fluids characteristics in terms of cooling and lubrication capacity are crucial factors to temperature control in grinding, especially when using conventional abrasive grinding wheels, literature regarding temperature measurements for different cutting fluids, especially considering the conventional technique application (flood) is still scarce. Hadad *et al*. (2012), for instance, evaluated the temperature during grinding of bearing steel with different cutting fluids delivered minimum quantity lubrication technique (MQL) and reported a significant difference in grinding temperature. They observed that the higher lubrication effect (e.g., higher viscosity) presented the lower temperature in comparison to the others.

In a more recent work, Talon *et al*. (2020) carried out a study about the application of different cutting fluids that were delivered by the conventional coolant application technique (flood) on cylindrical grinding of the hardened AISI 4340 steel with alumina wheel, in which four different fluids tested three of them were semisynthetic type with corrosion inhibitors and one was a standard synthetic fluid. According to their findings, the different cutting fluids presented different performances in terms of surface roughness (Ra parameter) and the standard synthetic fluid resulted on the highest values of Ra, especially for more severe cutting conditions (higher values of feed rate). Comparing the semisynthetic ones, the surface roughness values decreased as viscosity increased. The authors also evaluated the micrographic and hardness of workpiece after grinding. The cutting fluid type tested resulted in no significant variations regarding these output parameters.

In this context, this work aims to contribute to the analysis on the performance of different cutting fluids applied via conventional technique during grinding, especially concerning temperature at the contact zone during the process. Grinding experiments of bearing steel with alumina wheel were carried out using two different cutting fluids (semisynthetic and synthetic). Two cutting conditions were evaluated in terms of radial depth of cut. Besides the cutting region temperature, hardness beneath machined surface and surface roughness (Ra parameter) were also evaluated.

2. METHODOLOGY

The grinding experiments were conducted in a surface grinding machine MELLO P-36, with nominal power of 2.24 kW and constant rotational speed of 2400 rpm. A conventional white alumina grinding wheel was employed in all grinding tests, with external diameter of 250 mm, width of 25.4 mm and designation of 38A60K6V, from Norton – Saint Gobain Abrasives. The workpiece material was the hardened bearing steel SAE 52100, with 60 ± 2 HRC and cylindrical dimensions of 16 mm x 17.4 mm (diameter x height). Two different types of cutting fluid were tested: the vegetable-based semisynthetic VASCO 700 and the synthetic GRINDEX 10, both from Blaser Swisslube. Each fluid was dispersed in water at 5% concentration. Both fluids were delivered by the conventional coolant technique (flood) at a flow rate of 9 L/min, with the nozzle positioned tangential to the grinding wheel as shown in Figure 1.

The kinematic viscosity and thermal conductivity of the cutting fluids were measured with an Anton Paar viscosimeter SVM 3000 and a Linseis thermal conductivity analyzer THB-1. The measurements were used to auxiliary the results discussion and they are shown in Table 1.

Besides the cutting fluid type, the radial depth of cut was also varied in two levels: 10 µm and 30 µm. The grinding wheel speed was ≈ 31 m/s and the workpiece speed was 3 m/min, both kept constant for all grinding experiments. The grinding wheel was dressed prior to each test by using a single point diamond dresser. The dressing parameters were dressing width (b_d) of 0.31 mm and dressing speed (v_d) of 150 mm/min, resulting in a grinding wheel overlap ratio (U_d) of 5.

The output parameters analyzed were the cutting region temperature, surface finish and hardness by microindentation beneath machined surface. The cutting region temperature was measured by employing the methodology used by Ruzzi *et al*. (2021). The workpiece was split into two parts by using a metallographic abrasive cutter. They were cut perpendicular to the surface to be ground. The two sections were positioned together with K type thermocouple wires in between the two parts, separated by three mica sheets of 0.3 mm thickness as shown in Figure 2. During the engagement of the grinding wheel with the surface, the hot junction of the thermocouple is formed, measuring then the cutting region temperature. The cold junction of the thermocouple was connected to a KEYSIGHT acquisition data system AGILENT 34970A (Figure 2). The grinding experiments with temperature measurement were replicated twice for each grinding condition. The mean value and standard deviation of temperature acquired in each experiment was considered for analysis.

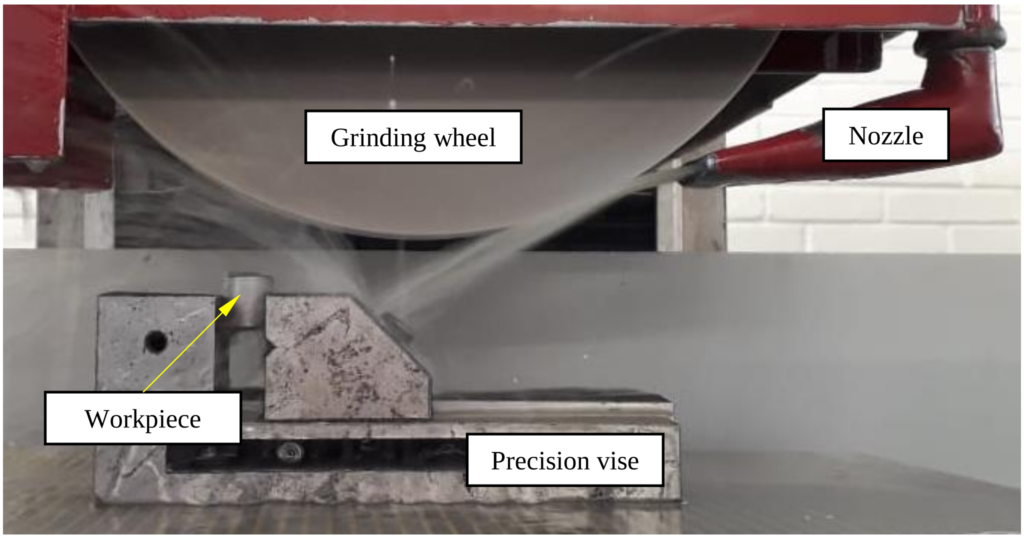

Figure 1: Setup for grinding experiments.

Table 1: Thermal conductivity at 25 °C and kinematic viscosity at different temperatures for both cutting fluid tested.

Cutting fluid type	**Thermal conductivity at 25 °C [W/(mk)]**	**Kinematic viscosity [mm²/s]**			
		25 °C	**40 °C**	**55 °C**	**70 °C**
Semisynthetic (SS)	0.6020	1.0835	0.8233	0.6463	0.5233
Synthetic (S)	0.6001	1.0829	0.7934	0.6196	0.4952

The hardness by microindentation beneath the ground surface was measured after metallographic preparation. For each grinding condition, eight hardness measurement were taken according to profile shown in Figure 3. The distance between the center of the indentations and the sample's edge was at least 2.5 times the mean diagonal length of the indentation. This minimum distance was also considered for two adjacent indentations, in accordance with ISO 6507-1 (2005). These measurements were replicated twice, and mean value and standard deviation were considered as results. The measurement at 3000 µm beneath machined surface was used as reference for bulk material hardness. A microhardness tester (SHIMADZU HMV-2) with Vickers indenter was used, with a load of 980.7 mN (HV 0.1) and 10 seconds of application time. The surface finish was measured with a Taylor Hobson portable surface roughness tester Surtronic S128. A cut-off of 0.8 mm, 5 sample lengths, and Gaussian filter were used in accordance with ISO 4288:1996 (1996). Five measurements of Ra parameter were taken on ground surface after each test, perpendicular to grinding wheel direction. The mean value and standard deviation were considered for analysis.

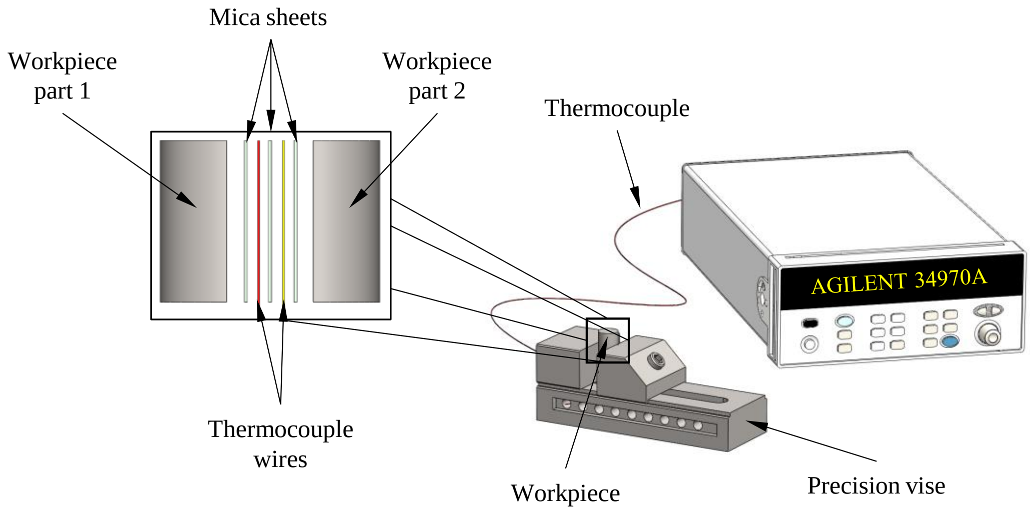

Figure 2: Schematic illustration of the methodology used for cutting region temperature measurement.

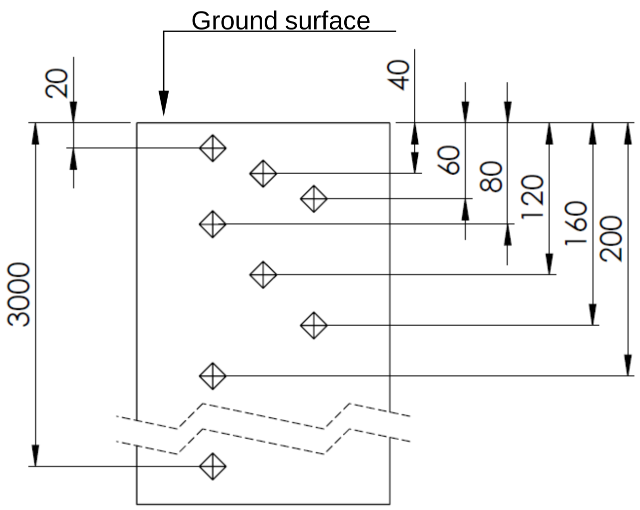

Figure 3: Detail of hardness profile adopted. Dimension in µm.

3. RESULTS AND DISCUSSION

The measurements of cutting region temperature are shown in Figure *4*. One notes that, for the mild cutting condition (a_e = 10 µm), the temperature during grinding of hardened SAE 52100 was very similar when using both cutting fluids, presenting values near 300 °C. When machining with the a_e = 30 µm, however, it can be observed from Figure *4* that the cutting fluid type significantly affected the cutting region temperature. The use of the semisynthetic fluid presented a mean temperature of 406 °C, while the use of the synthetic fluid presented a mean temperature of 588 °C. This indicates that the use of semisynthetic fluid, in comparison to the synthetic one, contributed to reduce in 36% the mean temperature during grinding with the highest depth of cut (a_e = 30 µm). This is associated to the better lubrication capacity of the semisynthetic fluid, a consequence of its higher viscosity as shown in Table *1*. The better lubrication at the contact zone can reduce the friction between the abrasive grains and the workpiece, which in turn reduces heat generation (Brinksmeier *et al.*, 1999). Consequently, there is a reduction in cutting region temperature as observed in the results of Figure *4*. Regarding the effect of radial depth of cut in cutting region temperature, one notes from Figure *4* that the temperature at the contact zone increased with depth of cut (a_e). According to Malkin and Guo (2008) and Klocke (2009), the heat generation due to grinding increases with depth of cut. Thus, an increase in temperature at the contact zone with this input parameter was expected. Ruzzi *et al.* (2021) also observed an increase in cutting region temperature with a_e. According to the authors, the increase in radial depth of cut increases grinding power and then heat generation at the contact zone, thereby increasing the cutting region temperature.

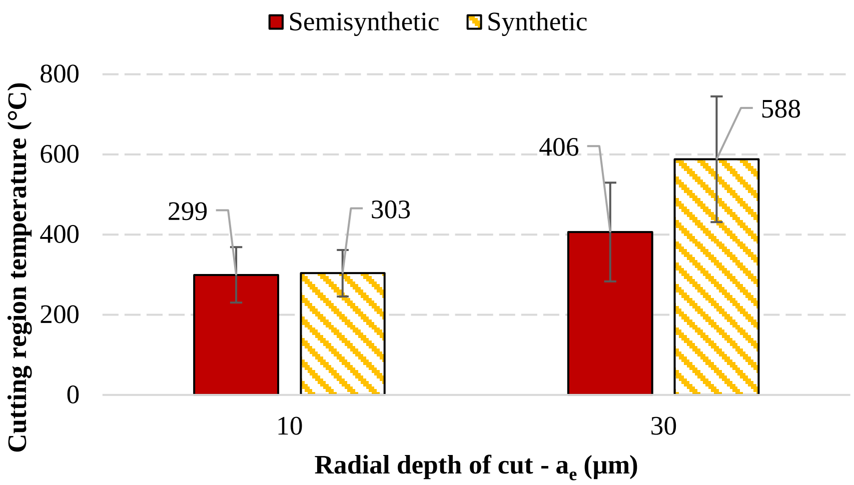

Figure 4: Cutting region temperature as a function of radial depth of cut, for both cutting fluids.

The hardness of workpiece after grinding is shown in Figure 5 as a function of depth beneath machined surface. The dotted line represents the bulk hardness of the material (801 HV 0.1). It can be noticed that the workpieces ground using the semisynthetic fluid did not present any hardness variation, irrespective to cutting condition (a_e value) tested. When grinding with synthetic fluid, on the other hand, a significant reduction on hardness was observed from ground surface until 60 µm beneath machined surface [Figure *5*(b)]. As previously mentioned, hardness reduction after grinding process is a phenomenon associated to the development of high temperatures at the contact zone, that, depending on its time of action, can induce thermal damages that can be understood as a non-intentional heat treatment near machined surface (Malkin; Guo, 2008; Seidel *et al.*, 2018). Thus, the results of hardness indicate that the grinding with synthetic fluid and the highest radial depth of cut (a_e = 30 µm) contributed to the development of temperatures sufficiently high to cause excessive tempering on the workpiece, therefore reducing its hardness at regions near the ground surface (until 60 µm beneath machined surface). This corroborates the results of cutting region temperature (Figure *4*), since this grinding condition in fact presented the higher temperature measured during grinding.

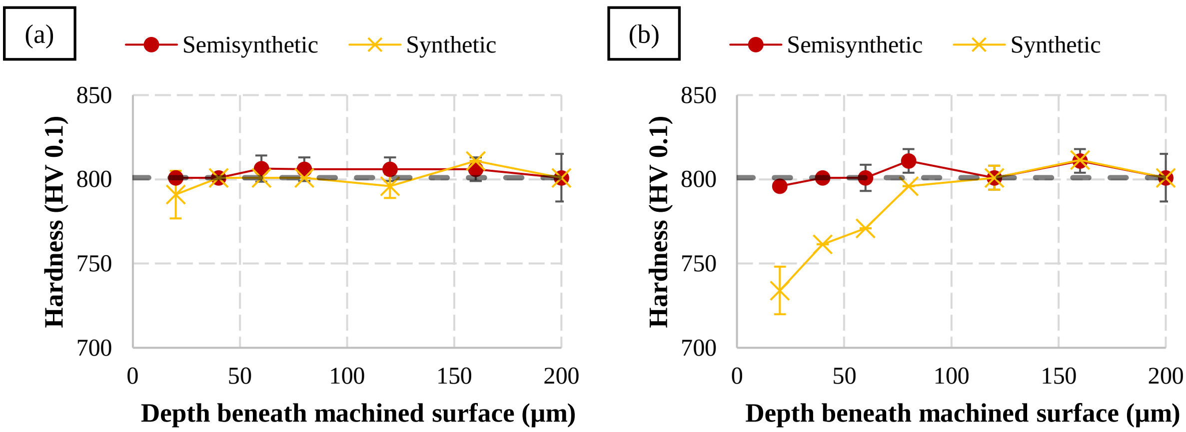

Figure 5: Hardness as a function of depth beneath machined surface for both cutting fluids.
(a) a_e = 10 µm. (b) a_e = 30 µm.

The surface roughness (Ra parameter) of ground surfaces is shown in Figure *6* as a function of radial depth of cut, for both cutting fluids tested in this work. As it can be noticed from Figure 6, no significant difference was observed on surface roughness when grinding with the lowest radial depth of cut (a_e = 10 µm) and semisynthetic and synthetic fluid. For more severe cutting conditions (a_e = 30 µm), it is clear that the grinding using the semisynthetic fluid outperformed the grinding with synthetic fluid in terms of reducing Ra parameter. This result is in good agreement with the findings reported by Hadad *et al.* (2012) and Talon *et al.* (2020), and the reduction in surface roughness when grinding with semisynthetic fluid can be attributed to its better lubrication capacity in comparison to synthetic fluid, which contributes to improve tribological conditions in the grinding wheel-workpiece interface and leading to lower cutting forces and consequently lower surface roughness values are generated. In this work, this was more effective when grinding for the highest value of radial depth of cut.

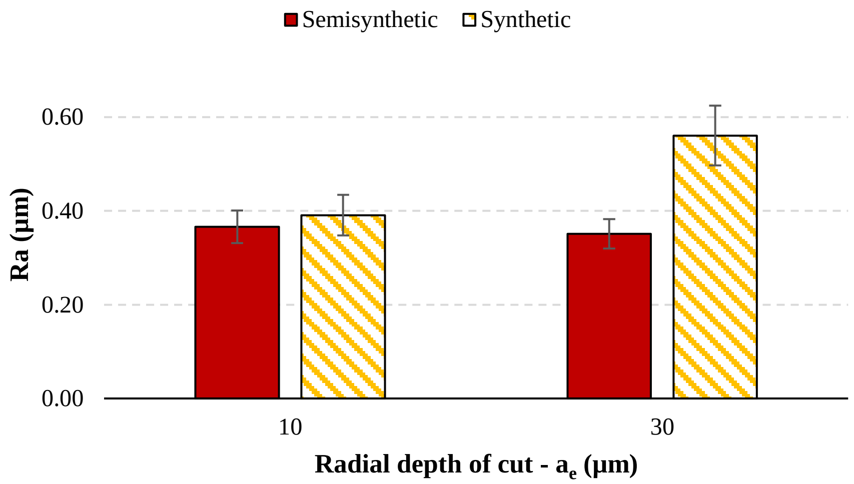

Figure 6: Surface finish (Ra parameter) as a function of radial depth of cut for both cutting fluids tested.

4. CONCLUSIONS

Considering the results found in this work, the following conclusion can be drawn:

i. The grinding using the semisynthetic cutting fluid contributed to reduce in 36% the cutting region temperature in comparison to the grinding using the synthetic one for the highest depth of cut (a_e = 30 µm). For the mildest cutting condition (a_e = 10 µm), no significant differences in cutting temperature were observed by varying the cutting fluid type.
ii. Negligible hardness variation beneath machined surface was observed after grinding using the semisynthetic cutting fluid, irrespective to radial depth of cut tested. However, when grinding with the synthetic fluid and the highest depth of cut (a_e = 30 µm), a significant hardness reduction was found until 60 µm beneath machined surface.
iii. The grinding using the semisynthetic fluid contributed to improve finishing of ground surface (lower values of Ra) in comparison to the grinding using the synthetic one, especially for a_e = 30 µm.
iv. Considering the conditions tested in this work, the lubrication capacity of the cutting fluid was crucial to improve grindability of bearing steel in terms of cutting region temperature, hardness variation and surface finish, especially for more severe cutting conditions (higher value of a_e). Thus, the semisynthetic fluid exhibited better performance in general when compared to the synthetic one.

5. ACKNOWLEDGEMENTS

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