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Reduction of oil and gas consumption in grinding technology using high pour-point lubricants

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ABSTRACT

Important research effort is currently being spent on reduction (if not complete removal) of lubricant consumption in machining operations. While scientific and industrial advances can be found in turning, milling and drilling technologies; advances in fluid reduction in grinding are still very limited. The main reason being abrasive processes generate large amounts of heat due to friction thus, the cooling/lubricant action of the fluid becomes critical. The Minimum Quantity of Lubricant-low temperature gas grinding technology (MCG, Minimum Coolant Grinding) can be considered a recent advance in this field. However, the economic and ecological application of the process requires minimization of both gas and oil consumption. The hypothesis put forward in this paper, is that the amount of lubricant required for the efficient industrial application of the MCG process can be largely reduced by using higher pour point lubricants. Since the explanation of the phenomena involved in the MCG process is that only a thin film of oil is responsible for effective tribo-action, then the amount of oil can be greatly reduced if effective freezing is achieved. The performance of two specifically-designed fluids for this purpose was studied. Experimental results show that even with very low quantities of oil and gas (3 mL/min and 0.2 kg/min) the MCG process produces better results than conventional cooling in terms of specific grinding energy and wheel wear. As far as residual stresses are concerned, results show that under industrial conditions these are similar in nature and magnitude to those generated using conventional cooling.

1. Introduction

Traditionally coolant fluids have been used in grinding processes to reduce workpiece temperature and decrease the risk of thermal damage. In addition, thanks to their lubricant properties fluids serve to enhance process performances (Irani et al., 2005). However, despite their advantages, coolants have important drawbacks which recommend limiting or even eliminating their use. These drawbacks are due mainly to economical costs, environmental effects and health hazard limitations. Likewise, the growing concern of sustainable production development (Pusavec et al., 2010a,b) means that not only the economic cost but also the environmental impact must be considered (Jovane et al., 2008). In addition, it is now well known that cooling fluid does not fulfil its role properly, since most of the fluid directed to the workpiece cannot enter the contact zone. In fact, according to (Morgan et al., 2008) the useful flow rate, i.e., the amount of fluid passing through the contact zone, varies from 5 to 20% of the total jet.

Considerable research effort is being devoted to the reduction of fluids in machining processes. A number of successful applications of fluid reduction techniques in processes such as turning, milling or drilling can be found in both scientific literature and industry. The effects of dry machining were studied in detail in (Klocke and Esenblatter, 1997). In (Fratila, 2009) a study on the requirements for successful application of Minimum Quantity of Lubricant (MQL) in gear milling is presented. More recently, Zhang et al. (2012) used a combination of MQL with cryogenic air (Minimum Quantity Cooling Lubricant, *MQCL*) to improve the machinability of Inconel 718,

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Nomenclature

b	grinding wheel width mm
Q'	specific removal rate mm^3/mm s
V'_w	specific volume of part material removed mm^3/mm
V'_s	specific volume of wheel worn mm^3/mm
v_w	workpiece speed m/min
e_c	specific grinding energy J/mm^3
v_s	grinding wheel speed m/s
P	CO_2 Pressure bar
G	grinding ratio -
q_s	relation between wheel speed and workpiece speed (v_w/v_s) -
T	temperature K
σ_1, σ_2	main stresses MPa
Φ	main stress angle °
f_o	MQL oil flow rate mL/min
f_{CO_2}	CO_2 flow rate kg/min
C_{sin}	manufacturing cost per single piece (€) €
t_s	manufacturing time €/part
C_{mth}	machine tool hourly rate €/h
C_{wag}	wages including overhead €/h
C_{coo}	cost for cooling fluids, including disposal of used fluids €/h
C_{tow}	cost for tool wear €/h

finding that tool wear and cutting forces decreased in comparison to dry machining. Fratila and Caizar (2011) have also reported successful use of MQL in face milling of $AlMg_3$. Many other works of fluid reduction in conventional machining can be found in literature.

Application of fluid reduction techniques is much more limited in grinding. Grinding is used for the manufacture of high-precision high added-value components. Large amounts of fluid are delivered, thus making necessary the use of pumps, fluid recovery and filtration systems, etc. During grinding, friction between abrasive grits and workpiece surface generates important heat quantities which in turn, raise ground surface temperature. In the worst case, grinding burns may ruin components that have previously already undergone costly manufacturing operations (forging, heat treatments, etc.). Therefore, the role of grinding fluids is critical both for friction reduction and workpiece cooling. This explains the limited success of fluid reduction techniques in this case.

Nevertheless, from the study viewpoint of process fundamentals at lab scale dry grinding offers some advantages (chiefly more accessibility to temperature measurement), the temperatures generated produce problems of: geometrical distortion, poor surface finish and heat affected zone. This is why alternatives in the application of dry grinding have been explored. For instance, Aurich et al. (2008) developed an electroplated wheel with controlled grain pattern specifically designed for this purpose.

Cryogenic grinding, which uses liquid nitrogen to cool the contact zone, has been proposed as an alternative to dry grinding. Using this technique, in (Ben Fredj et al., 2006) the authors reported improvements in surface quality with respect to dry conditions in the grinding of AISI304 austenitic stainless steel. However, from an economic point of view the use of liquid nitrogen does not seem to be a feasible industrial alternative (Pusavec et al., 2010a,b). Cool air has been proposed as a low-cost candidate to substitute liquid nitrogen. In a recent paper (Lee and Lee, 2011) the use of compressed cold air on surface micro-grinding has been studied. The authors concluded this technology can effectively reduce grinding forces, tool wear, and surface roughness especially for conditions involving shallow-cut and low feed speed.

Since neither cold air nor cryogenic nitrogen can provide sufficient lubrication action, the possibility of combining these technologies with oil mist has been proposed. Thus, in (Nguyen and Zhang, 2003) four different cooling-lubricant systems for surface grinding were tested: dry grinding, compressed cold air, Compressed Cold Air and Oil Mist (CAOM) and conventional coolant. Results show the presence of oil improves the performance of cold air when grinding larger depths of cut, thus confirming the need for lubricant action in grinding.

A further step in research is the application of MQL technology on grinding. As already mentioned, application to other conventional machining processes is widely accepted. This has not been grinding so far, due to the already explained need for extremely efficient cooling and lubrication action. Even though, active research is currently centred on adapting MQL to grinding process needs. Although the first research works date from the 90's (Brinksmeier et al., 1997), the technology has received a boost in recent years. Good results have been obtained in the grinding of both hardened (Tawakoli et al., 2009) and softer steels (Barczak et al., 2010). In all cases the authors claim a better performance compared to conventional cooling, and a drastic reduction in oil consumption and related costs. The performance of different oils and water-based emulsions in MQL grinding has been presented in (Tawakoli et al., 2011). Results show the increased performance of oil, thus confirming the critical role of lubrication action in the grinding process. Only a few research papers (Da Silva et al., 2007) show the application of MQL on cylindrical grinding. No doubt, access to the contact zone is considerably more difficult than in the case of surface grinding.

The advantage provided by the MQL approach has moved researchers to introduce modifications in the technique to improve lubricant and coolant properties. In (Mao et al., 2011) an oil and water mix is applied to the MQL device, the temperatures being lower and the heat affected zone smaller than in the case of conventional MQL. A novel grinding wheel in which micro-graphite particles are impregnated into an aluminium oxide matrix to form an auto-lubricant grinding wheel has been presented in (Tsai and Jian, 2012). This revolutionary grinding wheel has been tested with MQL oil application. MoS_2 nanoparticles can also be added to MQL oil to reduce friction (Kalita et al., 2012).

The use of MCG system (Minimum Coolant Grinding) combining MQL and application of a low-temperature gas was first reported in (Sanchez et al., 2010). The basics of the technology for surface grinding were presented in that paper and further developed in (Alberdi et al., 2011). The system combines the application of lubricant in the form of micro-drops using the Minimum Quantity of Lubricant technology with the application of a CO_2 flow at low temperature. The temperature of the gas is low enough to freeze the lubricant drops on the abrasive grits. Previous results show that the surface of the grinding wheel is thus protected by the generation of a durable tribofilm around the grits that improves sliding and lubrication under conditions of extreme pressure.

With regard to previously published results it has been found that economic ecological application of the process requires minimizing both CO_2 and oil consumption. The hypothesis put forward in this paper is that the amount of lubricant required for efficient industrial application of the MCG process can be largely reduced by using lubricants with higher pour point. Since the explanation of the phenomena involved in the MCG process is that only a thin film of oil is responsible for effective tribo-action, then the amount of oil can be greatly reduced if effective freezing is achieved. To do so this