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Investigation on minimum quantity lubricant-MQL grinding of 100Cr6 hardened steel using different abrasive and coolant–lubricant types

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ABSTRACT

Large quantities of coolant–lubricants are still widely used in the metal working industry, generating high consumption and discard costs and impacting the environment. Alternatives to current practices are getting more serious consideration in response to environmental and operational cost pressures. In the grinding process, promising alternatives to conventional dry and fluid coolant applications are minimum quantity lubrication (MQL) or near dry grinding process. Despite several researches, there have been a few investigations about the influence of different types of coolant–lubricants and grinding wheels on the process results. The current study aims to show the effects of the above parameters on grinding performance such as grinding forces and surface quality. The tests have been performed in presence of fluid, air jet and eleven types of coolant–lubricants, as well as, in dry condition. The grinding wheels employed in this study were vitrified bond corundum, resin bond corundum and vitrified bond SG wheels. The results indicate that SG wheels and MQL oils have potential for the development of the MQL process in comparison to vitrified and resin bond corundums and water miscible oils. Also, the lowest thermal damages, material side flow on the ground surface and wheel loading were generated by using the SG grinding wheel in MQL grinding process.

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1. Introduction

Grinding is mostly a final process on the workpiece that the dimensional and form accuracy as well as surface quality is very important. Therefore the negative effect of high temperature on these parameters should be prevented. In spite of many advantages of the use of cutting fluids in the machining processes, they have serious disadvantages, such as ecological and economical problems, which have guided research works in the last decades to reduce or even eliminate the use of metal cutting fluids [1–7]. One attractive alternative for dry and fluid grinding processes is MQL grinding. This process uses a minimum quantity of lubrication and is referred to as near dry grinding. In this process aerosols are oil droplets dispersed in a jet of air, oil droplets carried by the air fly directly to the tool working zone, providing the needed cooling and lubricating actions [8,9]. Tawakoli et al. [10] investigated the effects of the workpiece material hardness and grinding parameters on the MQL grinding process. Based on the results of their investigations, significant improvement can be achieved by MQL grinding of hardened steel in comparison to dry grinding process. Brunner [11] showed that the MQL grinding of 16MnCr5 (SAE-5115) with 4 ml/min ester oil, as compared to 11 ml/min mineral oil, reduces process normal and tangential forces to one third, but increases surface roughness by up to 50%. Investigations by Brinksmeier et al. [12] confirmed these results and showed additionally that the type of coolant–lubricant can also considerably influence the MQL process.

In order to achieve a finer surface quality and avoid thermal damage to the workpiece, the chip formation mechanism has to be improved so that both the friction forces and thermal partition to the workpiece reduces. Hence, the influences of the wheel and coolant–lubricant characteristics on the MQL grinding process have to be studied from the grinding forces, chip formation and temperature generation stand points.

Literature review shows the lack of study on the effects of grinding wheel and MQL oil type in minimum quantity lubrication grinding process. In this paper experiments conducted under different Al_2O_3 grinding wheels and coolant–lubricant types, showed the performance of the MQL grinding operation based on an evaluation of grinding forces and surface quality.

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2. Experimental procedure

The experimental setup is summarized in Table 1. In order to compare the effects of abrasive and coolant–lubricant types on MQL performances, three AL_2O_3 grinding wheels with the same grain size and porosity were used (Table 1). The grinding wheels employed in this study were vitrified bond corundum, resin bond corundum and vitrified bond SG wheels. The vitrified bond corundum and SG wheels had hardness (I), while the resin bond corundum had the hardness degree (E). To investigate the effects of MQL fluid type, eleven types of oil and water miscible grinding fluids with different viscosities (Table 2) as well as conventional dry, fluid and air jet grinding conditions were used. The grinding wheels were dressed before each experiment with the conditions shown in Table 1. Surface grinding tests were done through the 8 mm width for 100Cr6 hardened steel using ELB micro-cut AC8 CNC universal surface grinding machine. The total depth of material removal in each grinding test was 9.0 mm (300 grinding passes).The equipment utilized to control the minimum quantity of lubricant (MQL) was Accu-Lube system in which an oil supply pump system is used. In this system, the compressed air and lubricant flow can be adjusted separately and mixed in the special nozzle (with nominal diameter 3 mm) to make microdroplets of cutting oil flying to the cutting zone by compressed air. The workpiece roughness was measured by Hommel Tester T-1000 (mobile roughness measurement) with a cut-off length of 0.8 mm (according to DIN EN ISO 3274:1998). At the end of each test (after the 300th pass), R_z and R_a across the grinding direction were measured at five different points of ground surface. The grinding force components were recorded using a piezo-electric transducer based dynamometer (type Kistler 9255B) positioned under the workpiece clamping device. Chips, surface morphology and grinding wheel surfaces were observed using a digital microscope (Keyence: VHX) which possesses a maximum magnification of 1000 times.

3. Lubrication mechanism in MQL grinding process

The physical and chemical properties of the coolant–lubricants determine their effectiveness in the grinding process. By reaction of the coolant–lubricant with the workpiece material in the contact zone, intermediate layers can emerge to separate the surfaces and reduce friction [13]. A successful coolant–lubricant might be thought to form a low shear strength layer between the grain wear flat face and the workpiece surface to eliminate the region of strong adhesion. In other words, if the lubricant is unable to access to the whole of the interface between the grain and the workpiece surface, then at least it is necessary to limit the region of adhesion and so to reduce the friction forces exhibited at the grain-workpiece boundary.

It is possible to consider that the oil droplets access the contact zone through lubricant sources, namely the fractured grooves on the grain wear flat area and wheel pores (spaces between grains on the wheel or porosity). The rate of transportation of the oil droplets within these lubricant sources can help the lubrication of the grinding zone. Also, the pores on the surface of the wheel entrain and pump the oil mist through the grinding contact to cool the cutting zone [1]. Grain fractured grooves and the wheel pores in the contact zone as lubricant sources are shown in Fig. 1. Because the grain fractures are developed by dressing process and soon after the beginning of the grinding process, the existence of the lubricant sources between the grain wear flat area and the workpiece surface could be always taken into account. Lubricating action of the MQL oil mist requires penetration of the oil droplets into the lubricant sources. Therefore, the penetration time of the oil droplets into the lubricant source must be less than the passing time of the lubricant source. The passing time of the lubricant source is the time that lubricant source passes from the leading edge in front of the nozzle to the contact zone. Therefore, the penetration time can be defined as $t_{pen}=l_s/V_{oilmist}$, and the lubricant source passing time can be calculated from $t_{pass}=l_s/V_c$.

l_s is the length of the lubricant source, $V_{oilmist}$ indicates the average velocity of the oil droplet penetration into the lubricant

Table 2
MQL coolant–lubricants used in this study.

MQL coolant–lubricant	viscosity (mm^2/s) at 40 °C
MQL oil 1 (based on mineral oil)	46
MQL oil 2 (based on fat alcohol)	18
MQL oil 3 (based on mineral oil)	10
MQL oil 4 (based on hydrocracked oil)	9.1
MQL oil 5 (based on ester)	9
MQL oil 6 (based on white oil)	7.5
MQL oil 7 (based on carbon hydride)	30
MQL water-miscible 1 (based on high polymer proportion)	5% concentration
MQL water soluble 2 (based on synthetic oil)	5% concentration
MQL water miscible 3 (based on mineral oil)	5% concentration
Pure water	——

Table 1
Grinding conditions.

Grinding mode	Plunge surface grinding, down cut
Grinding wheel	89A60I6V217 (vitrified bond corundum) 454A60I6V3 (vitrified bond SG) 89A60E6B22 (resin bond corundum)
Grinding machine	ELB micro-cut AC8 CNC
Wheel speed (V_c)	V_c=30 m/s
Work speed (V_{ft})	V_{ft}=3000 mm/min
Depth of cut (a_e)	a_e=30 μm
Environments	dry, fluid, air jet, MQL
Conventional fluid grinding	Syntilo XPS Castrol in a 5% concentration
MQL oil flow rate	Q=100 ml/hr
Air pressure (also for air jet grinding)	P=4 bar
MQL nozzle distance from contact zone (d) and horizontal angle to the workpiece (α)	d=80 mm, α=15°
Workpiece material	Hardened (100Cr6) with 50 ± 2 HRC (60 mm × 8 mm × 13.8 mm)
Dresser	Two point diamond dresser
Total depth of dressing (a_d)	a_d=40 μm
Dressing speed (V_d) and overlap (U_d)	V_d=350 mm/min, U_d=2

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