Minimum Quantity Lubrication in Grinding Process of Zirconia (ZrO_2) Engineering Ceramic

Mohsen Emami, Mohammad Hossein Sadeghi, Ahmed Sarhan

***Abstract*--**Engineering ceramics due to their high hardness, wear resistance, brittleness, low thermal conductivity have poor machinability. Grinding is the most widely used material removal process for engineering ceramics. The grinding process of engineering ceramics is associated with high cutting force, high wheel wear as well as surface and sub-surface damage. Efficient lubrication of wheel-workpiece interface can decrease wheel-workpiece friction and improve the grindability of engineering ceramics. Minimum quantity lubrication (MQL) is a new technique for lubricant delivery in machining applications. Moreover, MQL is a low cost and ecologically friendly method of fluid application in machining processes. In the present study the effects of MQL on grinding process of zirconia ($ZrO_{2)}$ engineering ceramic is investigated. Experimental tests were performed to compare MQL with conventional wet grinding. The results depict that MQL compared with conventional wet grinding decreases the grinding force and surface roughness and results in lower surface damages and better surface quality in zirconia ceramic grinding.

***Keywords*—**Grinding process, Minimum quantity lubrication, Zirconia (ZrO_2) Engineering Ceramic.

I. Introduction

ENGINEERING ceramics are increasingly being used in modern industrial applications due to their special properties such as low density, high hardness, wear resistance, temperature mechanical strength, creep resistance, corrosion resistance, and chemical inertness. Alumina (Al_2O_3), Silicon nitride (Si3N4), silicon carbide (SiC), and zirconia (ZrO_2) are the most widely utilized engineering ceramics. For instance, zirconia (ZrO_2) and some of its inert composites have being used as bioceramics in the human body [1]. On the other hand, machining (material removal) processes are mostly necessary in ceramics manufacturing to ensure geometry requirements and dimensional tolerances of the final product [2]. Abrasive processes are the most successful methods of ceramics machining. Grinding process using diamond wheel is one of the conventional material removal processes that has been widely used for machining of engineering ceramics. However, grinding process of engineering ceramics is associated with low efficiency; low material removal rate, high cutting forces low surface quality and rapid tool wear [3]. The friction between wheel and workpice generate heat in the grinding contact zone and therefore accelerates diamond grains wear. High wheel wear increases normal and tangential (friction) grinding forces, surface damages as well as machining costs. Therefore, various researches have being performed in order to improve the efficiency of engineering ceramics [4-7].

Cooling and Lubrication in grinding process can aid reducing the friction between wheel and workpiece. Besides, lubricants reduce grinding force and heat generation at contact zone, wash away grinding chips and clean the wheel surface. Fluid delivery in grinding process is an important issue regarding the fully penetration of fluid to the wheel-workpiece contact zone and its lubrication efficiency [2]. Research performed on fluid delivery in grinding process shows that in conventional fluid delivery, cutting fluid doesn't fully penetrate the grinding contact zone [8-9]. Moreover, many health hazards associated with cutting fluids such as respiratory diseases, skin and eye irritation and therefore their consumption must be restricted. Minimum quantity lubrication (MQL) is a new technique of fluid delivery in machining processes that has shown to be more environmentally friendly, cost effective than conventional flood cooling [10-12]. In this technique a small amount (10-200 ml/hr) of oil is sprayed with compressed air jet assistance at a nozzle tip and delivered to the machining zone. MQL not only reduces the amount of lubricant is used, but also has a better lubricant penetration to the grinding contact zone. However, more experiments need to be performed for evaluating the performance of MQL in different machining processes. In this study the effects of MQL in grinding process of zirconia (ZrO_2) engineering ceramics is investigated through evaluation of grinding forces, surface roughness and ground surface texture.

II. Experimental setup

The work material used in this study is zirconia (ZrO2) engineering ceramic. Table 1 shows the physical and mechanical properties of the workpiece material. All the

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zirconia specimens were prepared to rectangular bars of 24×10×3.5 mm. Fig. 1 shows the experimental setup used in this study and in Table 2 the grinding parameter settings are summerized. The grinding machine used for the experiments is Naga Ichi model model NI 450AV2. A resin bonded diamond grinding wheel with grain size 181µm was applied for material removal process. Wheel truing was done using brake-controlled truing device with a vitrified aluminum oxide wheel 38A60-MVBE at a speed 1250s.f.p.m, depth 20µm and transverse feed rate 200mm/min. An alumina stick Norton 38A150-I8VBE was used for wheel dressing. In order to maintain the consistency of the grinding wheel conditions, prior to each test, the grinding wheel was trued and dressed. The grinding experiment was done in up-cut plunge mode on the 24×3.5 specimen surface. An MQL system equipped to separately control the oil and air flow rates as well as an atomizing nozzle were used for MQL spray generation. The MQL nozzle tip was aimed at an angle a=15°, distance L=30 mm toward a point on the wheel surface and at a height H=15mm. Synthetic oil with 80% biodegradability was used as the MQL lubricant. The applied MQL oil and air flow rates were 150 ml/hr and 30 l/min respectively. Additionally, conventional flood cooling test was performed by using Mobilcut 100 (at a 5% concentration and 5 l/min flow). Grinding forces were measured by using dynamometer Kistler Type 9257A together with charge amplifier Kistler Type 5019. Additionally, for recording the force signals, data acquisition system Type NI cDAQ-9174 and Labview software were used. The ground surface roughness was measured by a portable Mitutoyo SJ-201 roughness tester with a 1.75mm cutoff length along the grinding direction. Arithmetical Mean Roughness (Ra) and Ten-point mean roughness(Rz) were recorded. Each experiment was repeated five times with the same settings, and the mean value was calculated as the result.

TABLE 1
WORKPIECE MATERIAL PROPERTIES

Ceramics Material	Relative Density [Mgm^{-3}]	Elastic modulus [GPa]	Vickers Hardness [GPa]	Fracture toughness [$MPam^{1/2}$]
ZrO_2 (3 mol% Y-TZP)	99	205	13.2	5.1

TABLE 2
GRINDING CODITIONS

Workpiece material	ZrO_2 engineering ceramic (24 mm × 10 mm × 3.5 mm)
Grinding machine	Horizontal surface grinding machine Naga Ichi (NI-450AV^2)
Grinding wheel	1A1 200×10×32 D181C75B
Grinding mode	Plunge surface grinding, up cut
Wheel speed (V_c)	30 m/s
Work speed (V_w)	15 m/min
Depth of cut (a_e)	10, 15 µm
Environments	MQL, Wet
MQL oil	Synthetic oil
Conventional flood cooling fluid	Mobilcut 100 (5% concentration)
MQL Liquid (oil) flow rate	150 ml/hr
MQL gas (air) flow rate	30 l/min
Truing	Brake controlled truing device-Norton Type 4597 Truing wheel:38A60-MVBE
Dresser	Aluminum oxide stick Norton 38A150-I8VBE

Fig. 1 Experimental setup

III. RESULTS AND DISCUSSION

Grinding force

During grinding process due to the contact of wheel with workpiece surface and material removal action of abrasive grains, two grinding forces called tangential and normal force are generated. The tangential force is generated along the reciprocating movement of work table whereas, the normal force is exerted to the work surface. With increase in friction, the tangential force increases while normal forces are mostly affected by the workpiece hardness. Ceramics compared with metals, due to their high hardness have greater grinding normal force. The specific tangential $F'(t)$ and normal $F'(n)$ grinding forces are calculated using the following equations.

$$F'(t) = F(t)/b \quad (1)$$

$$F'(n) = F(n)/b \quad (2)$$

Where, F(t) and F(n) are the measured tangential and normal grinding forces respectively and b is the grinding width. The specific tangential and normal grinding force results are shown in Figs. 2 and 3 respectively. As can be seen in Figs. 2 and 3, the forces in MQL grinding are lower than grinding forces in conventional flood cooling. The lower force in MQL grinding compared with conventional flood cooling is attributed to the lubrication performance of the method is used. Results depict that although in MQL grinding the amount of lubricant delivered to the contact zone is much lower than coolant flow rate in flood cooling, the efficiency of fluid penetration in MQL is more than wet grinding. Moreover, in MQL grinding the applied lubricant is neat oil (Immiscible oil) whereas in wet grinding water mixable fluid is used. Neat oils compared to water mixable fluids have higher lubricating properties. Moreover, MQL oil forms a boundary lubrication film on the surface of grinding wheel and reduces the friction significantly. However, in conventional wet grinding, the volumetric percentage of water is much more than oil. In other words, the cooling properties of water-mixable fluid outperform its lubricating properties. Hence, in MQL grinding by using neat oil grinding force decrease (Figs. 2 and 3).

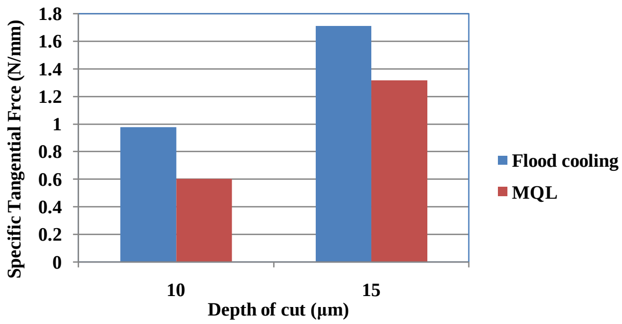


Fig. 2 Specific tangential grinding force

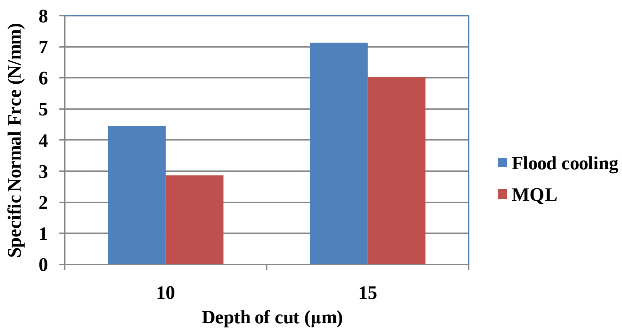


Fig. 3 Specific normal grinding force

Surface roughness

Surface roughness value is one of the important quantitative parameter that depicts the surface quality. In Figs. 4 and 5 the results of surface roughness measurements Ra and Rz are shown respectively. As can be seen in Figs. 4 and 5, MQL grinding results in lower surface roughness compared to conventional wet grinding. This result is attributed to the formation mechanism of surface damages in grinding process. Brittle materials like ceramics are very sensitive to surface and sub-surface damage due to mechanical stresses exerted to the work surface during grinding. With decrease in fracture toughness of the work material and increase in applied normal load, the surface damages such as cracks and voids increase. In other words, with decrease in normal grinding force, surface damages and therefore the surface roughness decrease. MQL grinding compared to wet grinding results in lower normal grinding force and hence lower surface damages. Consequently, in MQL grinding surface roughness decreases due to the lower normal grinding force.

Surface Texture

Fig. 6 (a) and (b) shows the surface texture images taken by (FESEM) from the ground surface of zirconia samples. Fig. 6 (a) illustrates the ground surface image after wet grinding. As can be seen in this figure brittle fractures and cracks are observed on the surface. Whereas, in MQL grinding, a better surface texture containing lower amount of surface defects is obtained (Fig. 6 (b)).

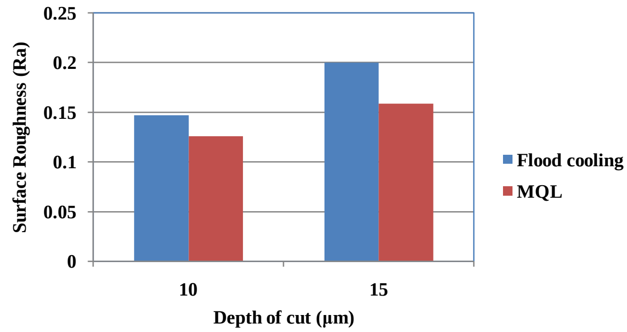


Fig. 4 Surface roughness (Ra)

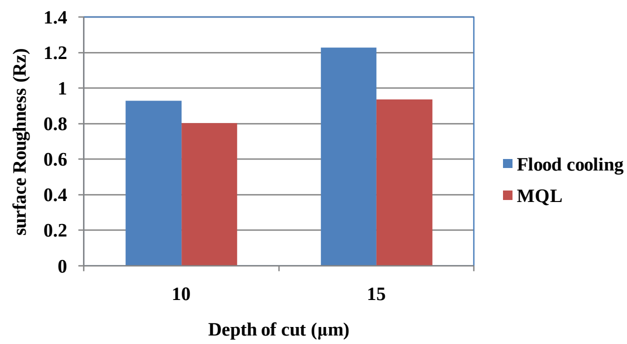
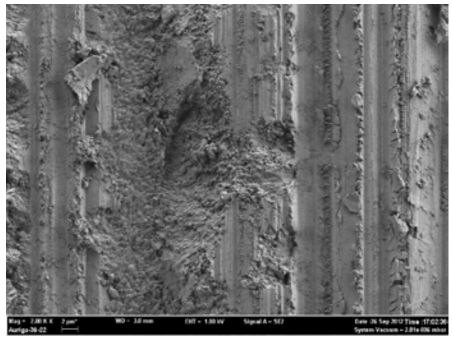
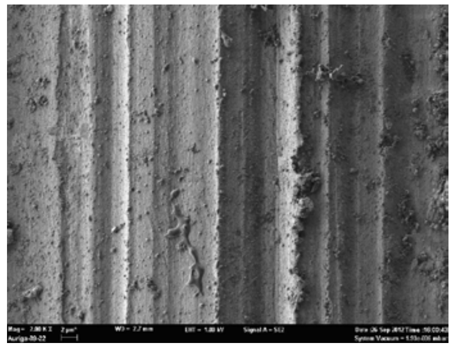


Fig. 5 Surface roughness (Rz)



(a)



(b)

Fig. 6 Surface texture images taken by (FESEM)
(a) wet grinding, (b) MQL grinding

IV. Conclusion

In the present investigation, the effects of MQL technique in grinding process of zirconia engineering ceramic, was evaluated. The following conclusions can be drawn:

1- Minimum quantity lubrication is an ecologically friendly and cost effective method of fluid delivery that can be used as an efficient alternative in grinding process of zirconia ceramic.
2- MQL compared to conventional flood cooling reduces the tangential and normal forces in grinding process of zirconia ceramic.
3- Although the amount of lubricant used in MQL is much lower than flood cooling, lubricating performance of MQL outperforms conventional flood cooling.
4- MQL improves the ground surface finish and decreases the surface roughness values in grinding process of zirconia ceramic.
5- In MQL grinding, a better surface texture containing lower amount of surface defects is obtained.

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