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Effect of minimum quantity lubrication on surface integrity in high-speed grinding of sintered alumina using single layer diamond grinding wheel

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A R T I C L E I N F O

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A B S T R A C T

Exceptional properties of advanced ceramics attract various heavy engineering industries. But surface and sub-surface defects generated during final stage abrasive machining processes make them vulnerable and limit their widespread use. This study aims to provide an understanding of the effectiveness of Minimum Quantity Lubrication (MQL) in reducing surface and sub-surface damages in high-speed grinding of brittle materials. In the present work, high-speed grinding of alumina was performed under MQL-neat oil, MQL-soluble oil (5% concentration in water) and conventional wet grinding environment with the single layer electroplated diamond grinding wheel. In-depth analysis of surface topology, surface morphology, residual stress and sub-surface damage was carried out using 3D surface profilometer, scanning electron microscope, X-ray diffractometer, and X-ray micro-CT, respectively. Grinding under MQL-neat oil provided leptokurtic (peaky) surface profile due to increased plastic deformation, whereas conventional wet grinding generated platykurtic (plateaued) surface profile because of brittle fracture. A simple model has been proposed to understand the underlying mechanism of generation of peaky and plateaued type of surface in grinding due to ductile deformation and brittle fracture, respectively. Morphological observation of the sample ground under MQL-neat oil showed distinct microcutting and ploughing marks. MQL-neat oil condition also provided more compressive residual stress and less sub-surface damage than other grinding environments. This is attributed to increased plastic deformation due to efficient lubrication under the MQL-neat oil grinding regime. The mechanism of increased plastic deformation and reduced sub-surface damage due to improved lubrication under MQL in high-speed grinding of brittle materials has been discussed.

1. Introduction

Ceramics have made possible various applications which were virtually inconceivable few years back. Present day status of aviation and aerospace industries is one of the examples. A wide spectrum of unique properties such as low density, heat resistance, high hardness, high strength to weight ratio, high wear and corrosion resistance, and biocompatibility make ceramics very popular and demanding. Apart from aviation and aerospace industries, ceramics are very much sought after in biomedical, chemical, automotive and sports industries [1]. The same properties, which make ceramics a favored choice over the other contemporary materials, also bring in processing difficulties. For instance, high hardness, which provides high wear resistance to ceramics, also incites brittle fracture and leads to the generation of surface defects during their processing [2]. Surface and sub-surface defects generated during processing of ceramic components, deteriorate their strength and spoil their functionality [3]. Production of defect free ceramic component incurs high manufacturing cost which is by far the most severe limitation in widespread use of ceramics [4].

In one of the fundamental studies, Lawn and Swain [5] showed the presence of median and lateral cracks under quasi-static indentation in brittle solids. The median and lateral cracks, similar to quasi-static indentation, were also observed by Swain [6] during scratching of different brittle materials including polycrystalline alumina. The lateral cracks, generated due to scratching, move towards the free surface and lead to brittle microfracture or chipping. While the lateral cracks help in material removal, the median cracks remain in ground components as flaws and degrade their strength. In grinding of advanced ceramics, which can be looked as a congregation of multiple single scratches, the brittle microfracture was identified as the primary mode of material removal at low grinding speed [7]. Zhang et al. [8] characterized the grinding induced damage using destructive inspection techniques in various advanced ceramics. Microcracking and pulverization were identified as two types of damage in the tested ceramics including alumina.

Bifano et al. [2] proposed the hypothesis of ductile regime grinding

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for brittle materials, which highlighted the possibility of plastic deformation in grinding of brittle materials. According to the hypothesis, when the scale of machining is reduced below a certain critical level, plastic deformation becomes energetically more favorable than fracture which consequently reduces the possibility of defect generation. The scale of machining below which the probability of occurrence of plastic deformation in grinding of brittle material increases, is called critical depth of cut (d_c) and is a function of material properties and is given in Eq. (1).

$$d_c \propto \left(\frac{E}{H}\right)\left(\frac{K_c}{H}\right)^2 \tag{1}$$

where, E is the elastic modulus of the material, H is the hardness of the material and K_c is the fracture toughness of the material.

The scale of machining in grinding is represented by uncut chip thickness (h_m), which has been expressed by Malkin and Guo [9] as given in Eq. (2).

$$h_m = \left(\frac{3}{C\ \tan\alpha}\frac{v_w}{v_s}\sqrt{\frac{a}{d_s}}\right)^{\frac{1}{2}} \tag{2}$$

where C is the cutting point density, α is the semi-included grit angle, v_w is the work speed, v_s is the wheel speed, a is the wheel downfeed, and d_s is the wheel diameter.

For plastic deformation to occur during grinding of brittle materials like ceramics, the uncut chip thickness (h_m) should be less than the critical depth of cut (d_c). In conventional low speed grinding, this can be achieved by employing low work speed (v_w) and/or depth of cut (a), but with compromised productivity. An efficient approach to reduce uncut chip thickness in grinding is by increasing the grinding speed (v_s), which has been utilized by many researchers to reduce the amount of brittle fracture in grinding of various advanced ceramics. For example, Hwang et al. [10] reported a reduction in grinding forces due to smaller uncut chip thickness at higher grinding speed during grinding of silicon nitride with electroplated diamond grinding wheels. Though the reduction in forces was observed, surface roughness and strength of ground specimens remained unaffected. Earlier, Klocke et al. [11] also reported no detrimental effect of high speed grinding on the fracture strength of silicon infiltrated silicon carbide and aluminum oxide samples. Huang and Liu [12] experimentally investigated the material removal mechanisms of alumina, alumina-titania and yittria partially stabilized zirconia (Y-TZP) in high-speed grinding using the resin bonded diamond grinding wheel. They identified lateral cracking as the prevalent mode of material removal for alumina and alumina-titania, whereas ductile cutting was found to be more prominent for Y-TZP. They also observed microcracks under the ground surface using bonded interface sectioning technique for all the three tested ceramics. Yin and Huang [13] systematically studied the response of different advanced ceramics in high-speed grinding using resin bonded diamond grinding wheels. Reduction in grinding forces at high wheel speed was observed here as well. Morphological studies revealed brittle fracture for relatively hard and brittle ceramics like silicon carbide and alumina; and ductile cutting for tougher ceramics like zirconia and silicon nitride. This was attributed to the smaller critical depth of cut (d_c) for hard and brittle ceramics. They also noticed surface finish improvement for silicon carbide and alumina at higher wheel speeds, whereas surface finish of zirconia and silicon nitride remained more or less the same. Chen et al. [14] employed brazed diamond wheels in high speed grinding of alumina, silicon nitride and zirconia; and studied grinding forces, surface roughness and surface morphology. The results showed a reduction in grinding forces and surface roughness with increased grinding speed. Here also, the brittle fracture was seen on ground alumina samples.

In grinding, effective penetration of coolant-lubricant in grinding zone has always been an issue [15], particularly for high speed grinding which is susceptible to high grinding temperature [11]. Problems related to high grinding temperature in high-speed grinding can be addressed either by removing excess heat from the grinding zone or by reducing the amount of heat generation with improved lubrication in the grinding zone. A simple way of removing excess heat from the grinding zone is by using high coolant flow rates. However, increasing flow rates beyond certain limit in high-speed grinding introduces turbulence in grinding zone which results in process instability [11]. On the other hand, Small Quantity Lubrication (SQL), more commonly recognized as Minimum Quantity Lubrication (MQL), provides better lubrication in grinding zone and helps in reducing heat generation [16]. In a recent article, Boswell et al. [17] comprehensively reviewed the current state of the art in MQL in conventional machining of metallic alloys. The performance improvements in various aspects of machining such as tool wear, surface roughness, cutting temperature and forces were reported from the use of MQL. The mechanism of enhanced lubrication under MQL was demonstrated by Tawakoli et al. [18] in the low-speed grinding of hardened steel using vitrified and resin bonded alumina grinding wheels. Over and above efficient lubrication, MQL is also environment friendly and provides less machining cost as compared to the conventional fluid delivery system. Despite several advantages, literature available on the application of MQL in ceramic grinding is very scant. In one such article, Emami et al. [19] demonstrated the efficient application of MQL jet by correlating the theoretical analysis with experimental results in the low-speed grinding of alumina using resin bonded diamond grinding wheel. The results showed less grinding forces and surface roughness for MQL grinding as compared to conventional flood cooling. In another study, Emami et al. [20] compared the performance of different commercial lubricants in MQL grinding of alumina using metal bonded diamond grinding wheel at grinding speed of 30 m/s. The use of synthetic oil provided less grinding forces, whereas hydrocracked oil rendered low surface roughness.

Survey of the previous work highlights that even after having a good understanding of material removal mechanisms in grinding of advanced ceramics, both the low and high-speed grinding approaches have resulted in surface defects. Particularly, brittle and hard ceramics are more prone to fracture and sub-surface defects during grinding because of the small critical depth of cut (d_c). Most of the studies on evaluation of sub-surface defects and damages in the grinding of advanced ceramics have used a destructive approach which is not an economically feasible option keeping in view the high manufacturing cost of ceramic components. MQL as a fluid delivery system, on the other hand, has not been given adequate attention in machining of advanced ceramics. In grinding, MQL has not been attempted at high wheel speeds for any material where the added advantage of reduced uncut chip thickness (h_m) can be utilized along with improved lubrication condition under MQL. Also, the mechanism of MQL in ceramic grinding is not explained in the literature available in the public domain. To assess surface integrity aspects, most of the articles on grinding of advanced ceramics have focused only on surface roughness and ground surface morphology, which do not portray the completeness in surface integrity assessment as residual stresses and sub-surface defects can also severely deteriorate the quality of the ground component.

Therefore, this article aims to study the effect of MQL with neat and soluble oil on ground surface topology, ground surface morphology, residual stress and sub-surface damage in the high-speed grinding of alumina using single layer electroplated diamond grinding wheel. To the best of authors' knowledge, this is the first time when MQL is being attempted in high-speed grinding of any material. The conventional wet grinding environment is used as the benchmark. Ground surface topology is analyzed taking into account three surface finish parameters, viz. Root-Mean-Square (RMS) roughness (Rq), ten-point height (Rz) and kurtosis (Rku). Ground surface morphology and residual stresses were assessed using Scanning Electron Microscope (SEM) and X-ray diffractometer, respectively. Morphological observations are also supported by scratch testing under neat oil and soluble oil environment. A non-destructive technique, X-ray micro-CT (Computed Tomography) is

Table 1
Important nominal properties of alumina [14].

Density	Hardness (Vickers)	Elastic modulus	Fracture toughness
3850 kg/m^3	18 GPa	390 GPa	4 MPa/m$^{0.5}$

used to characterize sub-surface damages generated during grinding.

2. Material and methods

High-speed plunge grinding experiments were carried out on Log-O-Matic LFS 2 CNC 6540 high-speed surface grinder using a single layer electroplated diamond wheel in up grinding mode. A blocky grade of synthetic diamond (PDA878 of Element six) with an average grit size of 151 µm was used for the single layer grinding wheel. High purity (99.8%) and densely sintered α–alumina blocks of dimensions 25 mm × 8 mm × 6 mm were used in the present work. Some of the important nominal properties of alumina are given in Table 1.

Literature indicated that at high grinding speed (160 m/s), brittle to ductile transition takes place for alumina; and alumina can be ground effectively with reduced amount of brittle fracture at high grinding speed [12–14]. However, at moderately high grinding speed of 80 m/s, the brittle fracture has been widely observed and reported. So, to investigate the effect of different lubrication modes upon the brittle fracture during grinding of alumina, a moderately high grinding speed of 80 m/s was selected. The highest possible combination of table speed and downfeed was selected to avoid wheel loading. The experimental set-up is shown in Fig. 1 and the complete experimental details are given in Table 2.

The grinding experiments were performed under three different cooling-lubrication conditions, viz. MQL-neat oil, MQL-soluble oil and conventional wet grinding. At least 10 grinding passes were given under each grinding environment to prepare the samples for further examination. The grinding performance of MQL delivery system was compared with that of the conventional wet grinding environment by using the same fluid composition (5% concentration of soluble oil by volume in water) in MQL mode and conventional wet grinding, whereas neat oil was used in MQL mode to explore the effect of high lubricity in grinding of hard and brittle alumina ceramic. Specification and compositional details of the grinding environments used for the present work are given in Table 2.

Most of the commercially available MQL systems were not capable of delivering aerosol continuously, hence an indigenously developed MQL system was used which was capable of delivering the aerosol continuously. The indigenously developed MQL system, shown in Fig. 1, consists of an air compressor (make: Kirloskar), a pressure regulator (make: Festo), a rotameter (make: Roth BS), a medical grade syringe pump (make: Life Plus) and an external mixing type air atomizing MQL nozzle (make: Spraying Systems Co.). The syringe pump was capable of delivering continuous flow in the range of 10–1200 mL/h with an accuracy of 3%. As the performance of MQL delivery system is significantly influenced by nozzle position and flow parameters, systematic experiments were carried out for optimization of nozzle position and MQL flow parameters before undertaking actual grinding experiments. Grinding parameters were kept constant throughout the optimization and actual grinding experiments (Table 2). Actual grinding experiments were then conducted under obtained optimum MQL nozzle position and optimum MQL flow parameters.

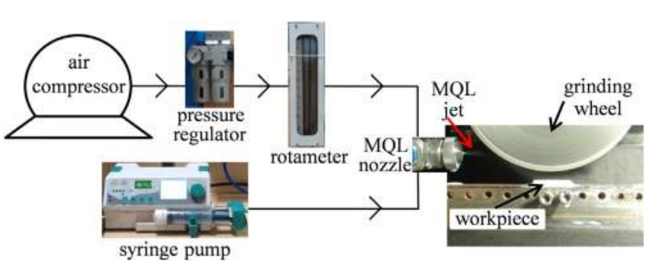

Fig. 1. Experimental set-up.

Table 2
Experimental details.

Machine tool	"Log-O-Matic LFS 2 CNC 6540" high-speed surface grinding machine
Grinding wheel	single layer electroplated diamond wheel wheel diameter (d_s) 125 mm wheel width (b_w) 10 mm grit diameter (d_g) 151 µm
Work material	Alumina (purity 99.8%)
Grinding parameters	grinding speed (v_s) 80 m/s downfeed (a) 50 µm table speed (v_w) 1 m/min
MQL parameters	fluid flow rate 400 mL/h air flow rate 50 Lpm
Environment	1. MQL-neat oil ➢ straight cutting oil (HP – Trimofin 23) 2. MQL-soluble oil (water soluble oil) ➢ 5% concentration by volume in water (Veedol – Solucut super) 3. Conventional wet (water soluble oil) ➢ 5% concentration by volume in water (Veedol – Solucut super)

To investigate the topographic details of ground alumina specimens, a Taylor Hobson make 3D tactile profilometer "Form Talysurf 50 Intra 2" was used. 4 mm × 4 mm ground surface area was mapped three-dimensionally by taking 80 consecutive linear tracks of 4.mm length with a resolution of 50 µm perpendicular to the grinding direction. The Abbott-Firestone curves were then plotted from the three-dimensional profiles with the help of Taylor Hobson Ultra software coupled with the profilometer. Five linear profiles, each 0.5 mm away, were extracted to measure three surface finish parameters, viz. Root-Mean-Square (RMS) roughness (Rq), ten-point height (Rz) and kurtosis (Rku). As the roughness provided by single layered electroplated wheels is higher than resin bonded or vitrified wheels, a cut-off length of 0.8 mm was used for the measurement of the three surface finish parameters. The average value of those five linear profiles is then reported.

The ground surface morphology was observed under Zeiss Evo 18 Scanning Electron Microscope (SEM) to examine the mode of material removal and the extent of the surface damage. Scratch tests were performed on polished alumina samples under neat oil and soluble oil (5% concentration in water) conditions to explore the effect of lubrication on the mechanism of material removal using DUCOM TR-101M5 scratch tester. During the scratch test, neat oil and soluble oil were delivered at the tip of the indenter with the help of a syringe. A standard Rockwell C diamond indenter with a nose radius of 200 µm was traversed at the constant linear speed of 12 mm/min. The normal load was varied linearly from 5 N to 30 N during the scratch test. The scratches were then observed under the SEM.

Residual stresses generated due to grinding were measured employing multiple exposure method ($\sin^2\psi$) of X-ray diffraction. Nickel filtered Cu-kα radiation from copper source operated at 45 kV and 40 mA was used to determine the elastic strain in {4.0.10} lattice planes having diffraction peak 2θ close to 145°. Incident beam optics consists of an X-ray lens, whereas a parallel plate collimator was used at diffracted beam side along with the detector in open mode. Total 14 scans were done including two scans at $\psi = 0°$ and other scans at $\psi = \pm 18.43, \pm 26.57, \pm 33.21, \pm 39.23, \pm 45.00, \pm 50.77,$ with 80 points per scan. The X-ray elastic constants S1 (1/TPa) and 1/2S2 (1/TPa) used for the stress calculations are –0.57 and 3.08, respectively [21]. Since stresses in the grinding direction are maximum [22], only the stress component parallel to the grinding direction was measured.

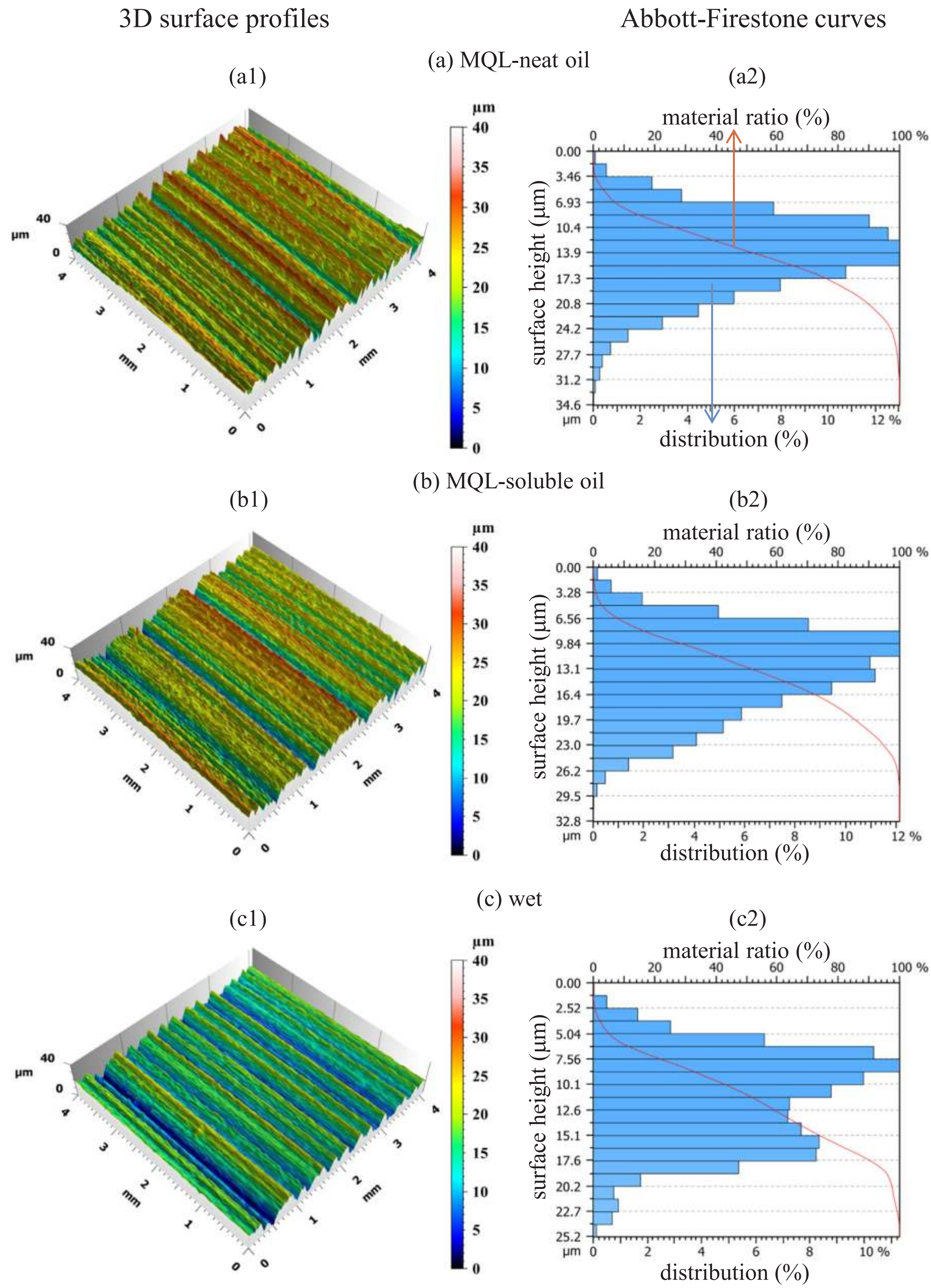

Fig. 2. Three-dimensional surface profiles and Abbott-Firestone curves for alumina grinding under different grinding environments; (a). MQL-neat, (b). MQL-soluble, (c) conventional wet.

Sub-surface cracks and damages in the as-received and ground samples were identified and quantified through X-ray micro-CT (Computed Tomography) imaging. The ground samples were scanned by X-ray radiation for 3D imaging using GE phoenix v|tome|x micro-CT system with a source voltage of 100 kV and beam current of 50 µA. The scanning resolution of 5.5 µm was achieved. High-end X-ray imaging software VGStudio MAX (Volume Graphics, Germany) was used for the analysis and visualization of CT data.

3. Results and discussion

Fig. 2(a), (b) and (c) show three-dimensional surface profiles and Abbott-Firestone curves for alumina samples ground under MQL-neat oil, MQL-soluble oil and conventional wet grinding environment, respectively. Use of MQL-neat oil generated the deepest grooves on the ground surface which can be distinctly observed from the three-dimensional surface profile in Fig. 2(a1). The conventional wet grinding environment, on the other hand, produced the shallowest grooves among the three tested cooling-lubrication conditions as shown in Fig. 2(c1). The depths of the grooves generated under MQL-soluble oil were in-between the depths of the grooves generated by MQL-neat oil and conventional wet grinding environment (Fig. 2(b1)). The Abbott-Firestone curve, which shows statistical distribution of surface heights, revealed a Gaussian type profile of surface height distribution for the alumina sample ground using MQL-neat oil (Fig. 2(a2)) and a flat-top profile of surface height distribution for grinding under the conventional wet environment (Fig. 2(c2)). The surface height distribution for grinding under MQL-soluble oil was a combination of both, the Gaussian and flat-top profiles (refer Fig. 2(b2)). The Gaussian type of profile indicates a peaky surface which results in grinding when the ground surface deforms plastically and retains the form of rotating grinding wheel. A flat-top profile, on the other hand, represents a plateaued type of surface which is typically generated in hard and brittle ceramics due to lateral chipping. The plausible mechanism of generation of peaky and plateaued type of surface because of different material removal modes in grinding is discussed in the subsequent section with the help of a simple model.

To get a deeper insight into the topography of the ground alumina surfaces, three distinct and important surface finish parameters were measured (following the ISO 4278 standard) and analyzed. Basic description of the three surface finish parameters is given below.

(i) Root-Mean-Square (RMS) roughness (Rq): RMS roughness is the standard deviation of the distribution of surface heights. It is sensitive to frequent large deviations of the surface roughness profile from the mean line and thus is a more genuine surface finish parameter as compared to widely reported roughness parameter, arithmetic average height (Ra).
(ii) Ten-point height (Rz): The ten-point height (Rz) represents the maximum height of the surface and is more sensitive to sporadic high crests and deep troughs.
(iii) Kurtosis (Rku): Kurtosis (Rku) is the fourth order moment of the profile amplitude density function and delineates the sharpness (peakedness) of the surface.

The alumina samples ground under MQL-neat oil provided the highest Rq and Rz values (refer Fig. 3(a) and Fig. 3(b)), indicating deeper grooves which were also seen in the three-dimensional surface profile in Fig. 2(a1). On the other hand, conventional wet grinding yielded the lowest Rq and Rz values (refer Fig. 3(a) and Fig. 3(b)), indicating shallow grooves on the ground surface as shown in Fig. 2(c1). The high roughness values obtained for alumina sample ground using MQL-neat oil may be attributed to the low friction under MQL-neat oil, which increased the plastic deformation and helped in retaining the peaks and valleys intact on the ground surface; whereas high friction under conventional wet grinding environment could have increased the brittle fracture which removed peaks from the ground surface and resulted in low values of Rq and Rz. High degree of plastic deformation for MQL-neat oil was confirmed from SEM images and is discussed later. Interestingly, the values of Rq and Rz for MQL-soluble oil condition lied in between the values obtained for MQL-neat oil and conventional wet grinding because of an intermediate frictional condition which provided the intermediate amount of plastic deformation (refer Fig. 3(a), Fig. 3(b) and Fig. 2(b1)). The high roughness values under MQL-neat oil condition should not be misinterpreted since roughness in grinding depends primarily upon the wheel condition (grit size and shape) and grinding parameters, which can be selected based on required surface finish. In the present work, the main purpose of studying surface roughness parameters is to understand the mechanics of the grinding process. For grinding of hard and brittle materials (such as alumina), the main concern is to arrest the brittle fracture, which introduces surface and sub-surface damage and impairs the functionality of the ground component. High RMS roughness (Rq) and height (Rz) under MQL-neat oil simply indicate retained wheel profile on the sample because of reduced fracture and increased plastic deformation.

Coming to kurtosis (Rku), a value greater than 3 indicates a peaky surface having many high peaks and the distribution curve is said to be leptokurtic [23], which looks similar to the Gaussian profile obtained in Fig. 2(a2); and a value less than 3 indicates a plateaued surface and the distribution curve is said to be platykurtic [23] that is similar to a flat-top profile obtained in Fig. 2(c2). The higher kurtosis value of 3 for alumina sample ground under MQL-neat oil (Fig. 3(c)), further manifests the peaky nature of the surface observed in the three-dimensional surface profile and Abbott-Firestone curve (Fig. 2(a)); whereas the shallowest and plateaued surface obtained under conventional wet grinding exhibited the lowest kurtosis value of 1.95 (refer Fig. 3(c) and Fig. 2(c)). Expectedly, the combined peaky and plateaued surface generated under MQL-soluble oil exhibited medium kurtosis value of 2.54 (refer Fig. 3(c) and Fig. 2(b)).

The generation of peaky or plateaued surface based on the mode of material removal is explained with the help of the schematic shown in Fig. 4. Two cases are considered here; (i) Fig. 4(a) – where material removal in grinding is due to ductile deformation (ductile materials such as metallic alloys); and (ii) Fig. 4(b) – where material removal in grinding is due to brittle fracture (hard and brittle materials including ceramics and glass). In case (i) of grinding ductile material (refer Fig. 4(a)), the material fails in shear and deforms plastically along the grit edges forming a counter profile of the grits on the workpiece yielding a peaky surface having high kurtosis (refer Fig. 4(a2)). In case (ii) of grinding brittle materials, median and lateral cracks are developed in the work material underneath the grinding grits in the grinding zone (refer Fig. 4(b1)). The lateral cracks propagate towards the free surface of the work material and participate in material removal. Two different lateral cracks emanating under adjacent grits, eventually, can meet and modify the wheel's counter profile generated on the work material resulting in a flat or plateaued type of surface having low kurtosis (refer Fig. 4(b2)).

The better lubrication under MQL-neat oil is believed to promote ductile deformation in the grinding zone and generated a peaky surface similar to the one shown in Fig. 4(a2), which is in very good agreement with the three-dimensional surface profile observed in Fig. 2(a1). On the contrary, high friction under conventional wet grinding environment increased the brittle fracture in the grinding zone and resulted in a flat or plateaued surface similar to Fig. 4(b2), which is also in good agreement with the three-dimensional surface profile obtained for the conventional wet grinding environment in Fig. 2(c1). Following the above explanation, a mix of peaky and plateaued surface obtained under MQL-soluble oil (Fig. 2(b1)), proves that lubrication efficiency of MQL is better than conventional wet grinding, which provided better plastic deformation for MQL-soluble oil than the conventional wet environment. The correlation between low friction and enhanced plastic deformation during grit-work material interaction has been explained with the help of a simple model in Fig. 7.

The morphology of the ground alumina specimens under different grinding environments is shown in Fig. 5. Distinct microcutting marks can be observed for alumina sample ground under MQL-neat oil condition (Fig. 5(a)), which can be attributed to enhanced plastic deformation induced under low friction condition. The conventional wet grinding, on the other hand, yielded a severely fractured surface (Fig. 5(c)) due to high friction in the grinding zone because of poor penetration of coolant-lubricant in the grinding zone under

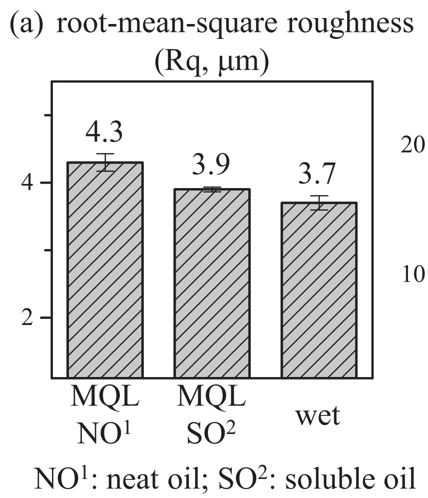

Fig. 3. Variation of different surface finish parameters for alumina grinding under different grinding environments; (a) root-mean-square roughness, (b) ten-point height, (c) kurtosis.

conventional wet grinding environment. The issue of poor penetration of grinding fluid under conventional wet grinding environment is very well reported by Ebbrell et al. [15]. The surface generated under MQL-soluble oil showed the presence of both microcutting and fracture (refer Fig. 5(b)) owing to the intermediate frictional conditions. To understand the role of friction in grinding upon the mode of material removal for hard and brittle materials like alumina, simple scratch tests were performed under different lubrication conditions and the morphological features of the scratches are presented in Fig. 6. The scratch made under neat oil showed plastic deformation along with characteristic microcutting marks (refer Fig. 6(a1) & (a2)) similar to those observed under MQL-neat oil grinding (refer Fig. 5(a)); whereas the scratch made with soluble oil generated both brittle fracture and ductile flow marks (refer Fig. 6(b1) & (b2)), similar to those obtained under MQL-soluble oil grinding as shown in Fig. 5(b). Similar type of plastic deformation has also been observed by Desa and Bahadur [24] while scratching alumina under mineral oil and light cutting oil.

For the scratch test, the interaction mechanism of the indenter with the work material under low and high friction condition has been proposed in Fig. 7(a) and (b), respectively. Enhanced lubrication on indenter surface lifts up the cut-off point and allows more work material to go underneath the indenter as shown in Fig. 7(a), which is very well supported by Klocke [25]. Because of this, two simultaneous phenomena take place. First, with the lifting up of the cut-off point, the effective chip thickness (h_{eff}) reduces (see Fig. 7(a)). A reduction in effective chip thickness promotes chances of ductile deformation in hard and brittle materials as described earlier with the help of Eq. (1) and Eq. (2). Second, as more material is allowed to pass under the indenter, this induces more plastic deformation in the material. Increased plastic deformation helps in healing the cracks generated below the cut-off point as the scratch progresses. On the other hand, high friction on the indenter surface holds the material more firmly during scratch and allows less material to pass beneath the indenter as shown in Fig. 7(b), thus reducing the amount of plastic deformation. With reduced plastic deformation under high friction condition, crack healing also reduces and cracks easily propagate to generate a substantial amount of fracture. Moreover, higher effective chip thickness (h_{eff}) under high friction condition (Fig. 7(b)) further increases the brittle fracture of hard and brittle materials. Generation of the sharp and peaky surface under MQL-neat oil (refer Fig. 2(a1)), and fractured and plateaued surface under

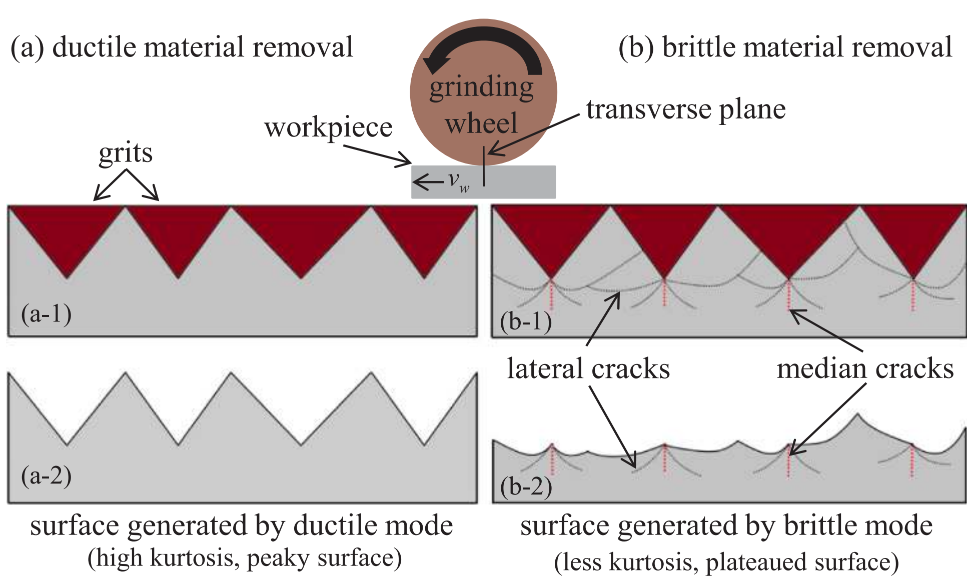

Fig. 4. Schematic showing the generation of peaky and plateaued ground surface because of different material removal modes; (a) material removal due to ductile deformation, (b) material removal due to brittle fracture.

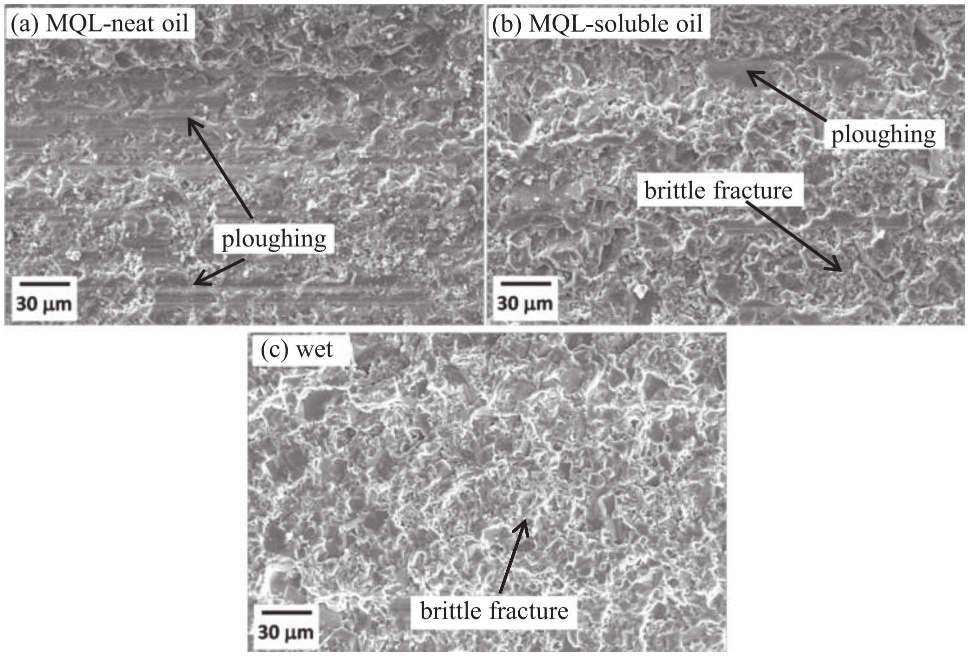

Fig. 5. SEM images of the ground alumina surface under different grinding environments; (a) MQL-neat oil, (b) MQL-soluble oil, (c) conventional wet.

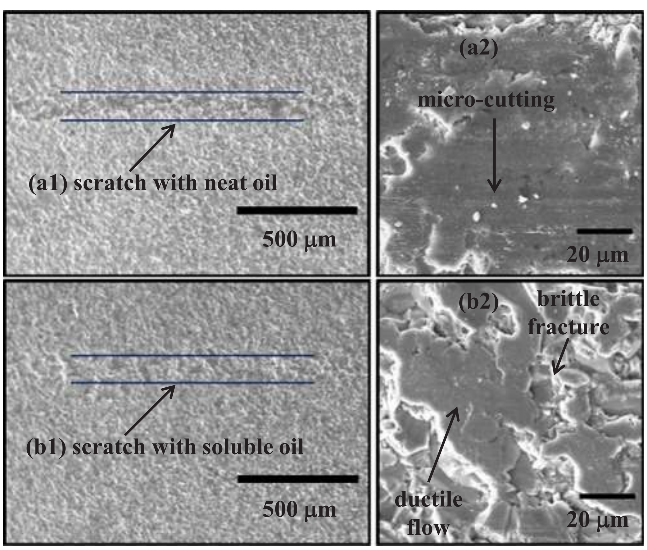

Fig. 6. SEM images of the scratch made on polished alumina surface under different lubrication conditions; (a1 and a2) scratch made using neat oil, (b1 and b2) scratch made using soluble oil.

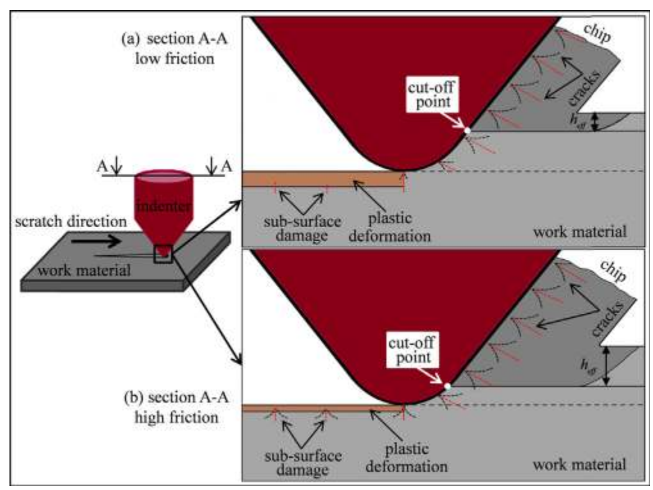

Fig. 7. Schematic diagram of the proposed mechanism for sub-surface crack healing and compressive residual stress generation under different friction conditions.

the conventional wet grinding environment (refer Fig. 2(c1)) can now easily be understood by extending the above-explained concept of single scratch to the multi-point grinding process. Less friction under MQL-neat oil in the grinding zone reduced the effective chip thickness (h_{eff}) and promoted the ductile deformation, along with increased plastic deformation which helped in crack healing and maintaining the peaks intact (refer Fig. 2(a1) and Fig. 4(a2)). Whereas, less amount of material passing under the grits under conventional wet grinding produced less amount of plastic deformation, which could not heal the cracks and cracks then easily propagated through least resistance path between adjacent grits to break sharp peaks resulting in fractured and plateaued surface (refer Fig. 2(c1) and Fig. 4(b2)).

The nature and magnitude of surface residual stresses generated in grinding are vital and governs the fatigue life of the component. Compressive residual stresses have been found to increase the strength of ceramic components [26]. The primary reasons for generation of residual stresses in grinding are mechanical deformation, thermally-induced plastic deformation and phase change upon grinding [22]. Stresses generated due to mechanical deformation are of compressive nature, thermally-induced plastic deformation generates tensile stresses and the nature of stresses generated due to phase change during grinding depends upon the volume of the new phase. Residual stress generation on the ground surface may be attributed either to the action of all the three factors acting simultaneously, or to the action of any two factors combined, or to the action of any single factor acting solely depending upon the grinding conditions such as wheel material, work material, cooling-lubrication conditions, etc. Kitajima et al. [27] observed a maximum grinding temperature of 575 °C in low speed grinding of alumina using metal bonded diamond grinding wheel, whereas a maximum grinding temperature of 200 °C was observed by Chen et al. [28] during high speed grinding of alumina using brazed diamond grinding wheel. The maximum grinding temperatures observed above by Kitajima et al. [27] and Chen et al. [28] are very much less to induce a phase change and associated residual stresses in

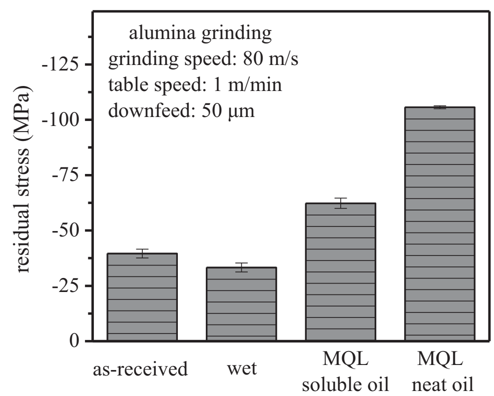

Fig. 8. Surface residual stress generation in high speed grinding of alumina under different grinding environment.

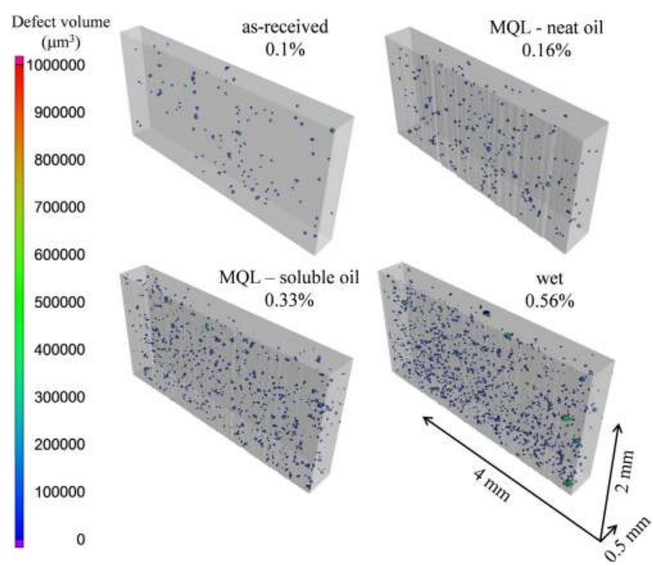

Fig. 9. X-ray micro-CT images showing degree of sub-surface defects on alumina samples ground under different grinding environments vis-à-vis as-received alumina sample; (a) as-received, (b) MQL-neat oil, (c) MQL-soluble oil, (d) conventional wet.

alumina. Less grinding temperature and low linear expansion coefficient (7.2 µm/m-°C) for alumina further rule out the possibility of thermally-induced plastic deformation and coupled residual stresses. Hence, mechanical deformation remains to be the only factor for residual stress generation for the present case.

Residual stresses generated on ground alumina samples under different cooling-lubrication conditions are shown in Fig. 8. It can be observed that the highest compressive residual stress of the order of 105 MPa was generated on the alumina sample ground under MQL-neat oil environment, which is attributed to increased plastic deformation under low friction condition as explained earlier with the help of Fig. 7(a). At the same time, the residual stresses generated on the sample ground under conventional wet environment were similar to that obtained on the as-received alumina sample indicating no stress generation under conventional wet grinding. This happened because of the severe brittle fracture due to high friction in the conventional wet grinding environment that can also be seen in SEM image in Fig. 5(c). Intriguingly, MQL-soluble oil rendered slightly more compressive residual stresses as compared to conventional wet grinding owing to its ability to reach the grinding zone and better lubrication efficiency.

As pointed out earlier, the main challenging issue in the grinding of hard and brittle materials is the induction of sub-surface defects which deteriorate the fatigue life of the component. Sub-surface defects generated under different grinding environment are shown in Fig. 9. It can be observed that under improved lubrication condition (MQL-neat oil grinding) only 0.16% defects were present which was very minimal and close to the defects in the as-received material (0.1%). More defects were originated as the lubrication condition deteriorated; use of MQL-soluble oil provided 0.33% defects and the use of conventional wet grinding environment yielded even higher defects close to 0.56%. The mechanism of generation of sub-surface defects is explained earlier with the help of Fig. 7. Accordingly, increased plastic deformation due to reduced friction under MQL-neat oil condition helped in crack healing and curtailing the amount of defects generated, whereas high friction reduced the amount of plastic deformation and crack healing in case of conventional wet grinding which resulted in higher number of defects in the sub-surface.

4. Conclusions

High-speed grinding of alumina was carried out under different grinding environments, viz. MQL-neat oil, MQL-soluble oil and conventional wet. Important surface and sub-surface characteristics were examined in detail. The following conclusions are drawn:

- Low friction under MQL-neat oil condition increased the amount of plastic deformation in the grinding zone which generated a sharp and peaky surface, whereas inefficient lubrication in conventional wet grinding increased the amount of brittle fracture yielding a flat and plateaued kind of surface.
- Increased plastic deformation because of reduced friction in MQL-neat oil generated higher compressive residual stress as compared to the other grinding environments, while there was no residual stress generation in the conventional wet grinding environment due to severe brittle fracture.
- Higher plastic deformation under MQL-neat oil condition provided better crack healing and consequently fewer defects in the ground surface. On the other hand, defects generated on the sample ground under conventional wet grinding were quite high because of substantial brittle fracture.
- The grinding performance of MQL-soluble oil lied in between the performance of MQL-neat oil and the conventional wet grinding environment because of an intermediate frictional condition which proves better lubrication efficiency of MQL delivery system as compared to conventional wet grinding environment.

The proposed mechanism of stress and defect generation under varying friction conditions for grinding of hard and a brittle material such as alumina not only improve the understanding of the behavior of hard and brittle materials but also highlights the effect of lubrication in changing the state of plastic deformation in the processing of hard and brittle materials.

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