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An investigation on application of nano-fluids in high speed grinding of sintered alumina

Amit Choudhary*, Anirban Naskar, S. Paul

Machine Tool & Machining Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal, 721 302, India

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ABSTRACT

Ceramics are the most sought-after materials in various advanced engineering applications. Diamond abrasive machining is used to achieve dimensional tolerances for hard ceramic materials. Micro-brittle fracture and grain dislodgement are the primary material removal mechanisms which generate surface and sub-surface defects. High processing cost and manufacturing defects limit their widespread use. This paper investigates the effectiveness of different grinding environments in reducing the brittle fracture in high speed grinding of highly pure and dense alumina work samples using single layer electroplated diamond grinding wheel. Grinding environments included straight cutting oil, water soluble oil at 5% concentration (soluble oil), and two water based nanofluids of alumina and hBN, all in Minimum Quantity Lubrication (MQL) mode. Conventional flood cooling with 5% concentration of soluble oil in water was used as the benchmark. Grinding forces were measured to estimate the specific grinding energy and apparent coefficient of friction. Surface integrity aspects of ground samples such as surface morphology, surface roughness and residual stresses were studied using Scanning Electron Microscope (SEM), 3D surface profilometer and x-ray diffractometer, respectively. Morphology of the grinding wheel was studied using stereo zoom microscope. Based on the experimental observations, a new model is proposed to demonstrate the interaction of nanoparticles in the grinding zone for grinding of brittle materials including alumina. Results showed that the nanofluid MQL yielded highly fractured surface because of high contact stress fields, whereas straight cutting oil MQL provided better lubrication in the grinding zone which promoted ductile deformation. Compressive residual stresses of the order of 105 MPa were observed in the samples ground with straight cutting oil MQL which can improve the fatigue life. Single scratch experiments done using diamond indenter also showed better lubrication efficiency of the straight cutting oil in comparison with soluble oil.

1. Introduction

Ceramics are highly demanded in advanced engineering applications in aerospace, biomedical and chemical industries because of their inherent properties such as high thermal strength, chemical inertness, and wear and corrosion resistance. Ceramics are very hard and final dimensional tolerances are achieved by abrasive machining using diamond grits. The same properties which make ceramics preferable choice in various applications also bring in manufacturing difficulties. The poor machining characteristics of ceramics render low productivity, and surface and sub-surface defects. The defects due to machining impair the functionality of ceramic components. The manufacturing cost alone comprises 80% of the total cost for ceramic components which is by far the most severe limitation in their widespread use [1].

The literature on low speed grinding of some representative advanced ceramics using resin bonded and metal bonded diamond grinding wheels have identified micro-brittle fracture due to lateral cracks as the prevalent material removal mechanism [2,3]. There are reports which highlight grain dislodgement and intergranular fracture over lateral chipping in ceramic wear [4]. The brittle fracture during grinding generates surface and sub-surface defects which impairs the functionality and pose the main challenge in ceramic grinding [5].

As an alternate to reduce fracture during machining of hard and brittle material, ductile regime machining was proposed [6]. According to the theory, if the scale of machining is reduced below a certain critical level then the energy required for fracture initiation and propagation become higher than the energy required for shear deformation and therefore ductile deformation becomes more favorable instead of brittle fracture. With the increase in grinding wheel speed, the scale of

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* Corresponding author.
E-mail addresses: achoudhary@iitkgp.ac.in (A. Choudhary), aniprit.09@iitkgp.ac.in (A. Naskar), spaul@mech.iitkgp.ernet.in (S. Paul).

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grinding i.e., maximum undeformed chip thickness (h_m) or maximum depth of cut taken by an individual grit, get reduced as given in Eq. (1) [7]. The Eq. (1) provides an average value of maximum undeformed chip thickness (h_m) assuming uniform grit spacing and zero wheel deflection.

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

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.

The reduced grinding scale increases the probability of shear deformation in grinding of hard and brittle materials which is a typical benefit of high speed grinding. Many researchers have utilized this benefit of high speed in grinding of several advanced ceramics and have reported a reduction in the fracture, grinding forces and surface roughness at higher wheel speeds [8–10]. It was observed that high speed grinding increased ductile removal for the ceramics having high fracture toughness such as ZrO_2 and Si_3N_4 [11], but micro-brittle fracture and grain dislodgement prevailed as material removal mechanism for comparatively brittle and hard ceramics such as alumina and alumina-titania even at higher grinding speeds [11,12]. Ground alumina showed deeper sub-surface damages as compared to zirconia at similar grinding parameters with resin bonded diamond grinding wheels [9].

Effective application of the coolant/lubricant in the grinding has always been a topic of research be it reachability or penetration issue of coolant/lubricant into the grinding zone [13] or be it of environmental interest [14,15]. Small Quantity Lubrication (SQL), more commonly recognized as Minimum Quantity Lubrication (MQL), is one such technique which addresses both the issues. Silva et al. [16] reported that effective lubrication and cooling of the abrasive grains in MQL reduced the surface roughness and provided more compressive residual stress in cylindrical plunge grinding of ABNT 4340 steel using alumina wheels. In a study conducted by Tawakoli et al. [17] employing conventional alumina grinding wheel, it was observed that MQL provided better surface finish and quality for hard steel as compared to soft steel. They also indicated that MQL offered better lubrication in the grinding zone which facilitated a reduction in grinding forces for both the steels. While there is abundant literature on MQL in machining of metallic alloys, the studies pertaining to MQL machining of ceramics are very few. One such article is authored by Emami et al. [18] in which theoretical working range of MQL spray parameters was worked upon first and then the theoretical range was validated experimentally in grinding of alumina using resin bonded diamond grinding wheel. An optimum nozzle position and MQL flow parameters were obtained by minimizing grinding forces and surface roughness. The optimum conditions were then utilized to compare the performance of MQL grinding of alumina with conventional flood cooling and the comparison revealed a reduction in forces and better surface quality for MQL. In yet another study on MQL grinding of alumina, Emami et al. [19]. investigated the performance of four different commercial lubricants including mineral oil, hydrocrack oil, vegetable oil and synthetic oil in MQL grinding of alumina using metal bonded diamond grinding wheels at grinding speed of 30 m/s. The hydrocracked oil provided better surface quality whereas synthetic oil rendered low grinding forces among all. However, the study was based on statistics which considered only grinding forces and surface roughness as the output parameter and lacked physical explanations.

Grinding fluid facilitates the removal of excessive heat from the grinding zone and prevents thermal defects in the work sample. The small quantity of fluid and extremely low thermal conductivity of carrier gas in MQL limit its heat removal capacity from machining zone. The nanofluids, a colloidal suspension of nanometer sized metallic or non-metallic solid particles in a base fluid, have shown 20–30% increase in thermal conductivity of suspension as compared to the base fluids [20]. Besides increasing thermal capacity, nanoparticles also enhance the lubrication properties of the base fluid by a variety of mechanisms such as ball bearing effect, by forming a protective film, mending effect and polishing effect [21]. For instance, Lee et al. [22] showed that addition of alumina and diamond nanoparticles in paraffin oil promoted the formation of extreme pressure tribo-film and nano-ball bearing effect in the grinding zone which reduced grinding forces and surface roughness as compared to pure MQL in micro-scale grinding of tool steel using cBN grinding wheel. In a detailed review article, Sharma et al. [23] have compiled the beneficial effects of using different nanofluids in different metal machining processes. Nanofluids have been used successfully in metal machining operation but information on machining of ceramics using nanofluids is very scant. In a very recent and rare report, Kumar et al. [24] experimentally compared the performance of different water based nanofluids with dry grinding in low speed grinding of silicon nitride using resin bonded diamond grinding wheel. They speculated that formation of tungsten oxide and molybdenum oxide layers while using WS_2 and MoS_2 nanofluids, respectively, provided a reduction in grinding forces and surface roughness.

From the literature presented above, it is evident that functional deteriorations caused by surface defects in the ground ceramic components remain to be the main challenge even after having a general understanding of the material removal mechanism in low and high speed grinding of ceramics. While there is limited literature available on the use of MQL in ceramic grinding, the reports those are available have only considered surface roughness and grinding forces to conclude the overall grinding of ceramics which can be delusive as other surface integrity aspects such as residual stresses and surface cracks can severely impact the service life of the ground components. The mechanism of interaction of nanofluid in metal machining is very well discussed in the literature; however, the same has not been discussed in machining of hard and brittle materials including ceramic. Also, no report could be located which dealt with MQL in high speed grinding where chip load is less and the better lubrication characteristics of MQL can be utilized more efficiently.

Therefore, this article aims to study the effect of different MQL environments and conventional flood cooling on ground surface characteristics of alumina in high speed grinding using single layer electroplated diamond grinding wheels. Different MQL environments included straight cutting oil, water soluble oil at 5% concentration (soluble oil) and two water based nanofluids of alumina and hBN. In addition to grinding forces and surface roughness, ground surface morphology and residual stresses have also been investigated. A model is proposed which gives insight into the interaction of nanofluid MQL with diamond grit and work material inside the grinding zone. The performance comparison of straight cutting oil with soluble oil has also been investigated with the help of scratch test.

2. Experimental methods

Highly pure (99.8%) sintered α–alumina blocks of dimension 25 mm × 8 mm × 6 mm were used as the work material for present study. Important nominal properties of alumina are given in Table 1.

A single layer electroplated diamond wheel of width 10 mm with an average grit size of 151 μm was used to grind 25 mm long and 8 mm

Table 1
Nominal properties of alumina [2,11].

Density	3850 kg/m^3
Hardness (Vickers)	18 GPa
Young's modulus	390 GPa
Poisson's ratio	0.25
Fracture toughness	4 MPa/m$^{0.5}$
Thermal conductivity	15 W/m-K