Grinding of ceramics – sintered ceramics versus ceramic coatings

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Abstract

In this paper, the study of grinding characteristics of sintered alumina ceramic and plasma sprayed alumina coatings with respect to grinding forces, specific grinding energy, force ratio and surface integrity was undertaken. High-speed grinding experiment was conducted at moderate downfeed and the effect of high wheel speed was studied. The ground surface of sintered ceramic showed some signatures of plastic deformation along with micro-brittle fracture whereas, in plasma sprayed ceramic coatings, micro-brittle fracture was the predominant mode of material removal under the same grinding condition. This is attributed to the comparable value of critical depth \(d_c\) in ceramics and very low value of \(d_c\) in ceramic coatings as compared to maximum uncut chip thickness. In sintered alumina, the specific tangential and normal forces are 0.10 N/mm and 0.30 N/mm respectively. On the other hand, the forces observed in plasma sprayed alumina coatings were low, and the maximum forces recorded were 0.05 N/mm and 0.23 N/mm respectively. Ratio of normal to tangential grinding forces in sintered ceramics was as high as 7.5 in sintered alumina as compared to a lower value of 6 in plasma coatings. The chips were studied under SEM to validate the grinding mechanism. In both cases, fragmented chips were observed, and this is attributed to micro-brittle fracture as the predominant mode of material removal. Average surface roughness was measured along and across the grinding direction for all the samples. In all the cases, variation in surface roughness did not follow a specific trend with respect to wheel speed. Average surface roughness was found to be low in sintered alumina as compared to that in plasma sprayed coatings. Sintered ceramic was free from residual stress whereas in ceramic coatings, tensile residual stresses were observed.

Keywords: thermal spray, high-speed grinding, critical depth, sintered alumina, alumina coating, residual stress
1. Introduction

Advanced ceramics are increasingly used due to their superior properties like high thermal strength, hardness, wear resistance, fracture toughness, high-temperature stability and chemical inertness [1–3]. These properties enable them to be used in many areas including turbine engines, ball bearings, armor plates and medical applications [4–7]. Plasma sprayed ceramic coatings are composed of layers of ceramic material as splats. They are used in applications such as printing rolls, automobile, turbine components etc [8–10]. Such applications require high accuracy, surface finish and dimensional tolerance that can be achieved by finishing operations like grinding. High grinding speeds yield smaller values of maximum undeformed chip thickness \( h_{\text{m}} \) which results in low wheel wear, smaller forces, better surface integrity and reduced surface damage [11–15]. Finishing studies on ceramic coatings like alumina, alumina-titania, tungsten carbide and chromia coatings have been conducted [16–19]. Kar et al, have conducted research on high-speed grinding of plasma sprayed ceramic coatings using monolayer electroplated diamond grinding wheels [19]. They have reported that at low grinding speed, micro-brittle fracture is the predominant mechanism of material removal. They have observed lower grinding forces, less grinding damage and less tensile residual stress on the ground surface at high wheel speeds.

The above literature presents research on grinding of sintered ceramics and ceramic coatings, but no research has been conducted on the comparison of the two. Thus, the objective of the present study is to experimentally investigate and compare the effect of high-speed grinding on sintered alumina and plasma sprayed alumina coatings using single layered electroplated diamond wheel.

2. Experimental procedure

Sintered alumina ceramic bars of dimensions 25 × 8 × 6 mm were procured. Alumina powders with two particle sizes, namely Al\(_2\)O\(_3\) NS (45 ± 15 µm) and Al\(_2\)O\(_3\) SFP (31 ± 3.9 µm) were used for plasma sprayed coatings. Table 1 shows the material properties. Plasma spraying was done in-house with an air plasma spray system (SULZER METCO 9MC series spray unit with 9MB Gun (80 kW); spray current – 500 A). Low carbon steel plates of dimensions 100 × 10 × 10 mm were used as the substrate. The thickness of the coating was 300 – 700 µm. High-speed grinding tests were conducted using a CNC high-speed surface grinder (model: LFS 2 CNC 6540, Log–O–Matic, Germany (HEDG)). A monolayer electroplated diamond grinding wheel of grit size 151 µm (make: Wendt(India)) was used for the experiments. Table 2 shows the grinding parameters and figure 1 shows the grinding setup.

| Table 1: Material properties of sintered alumina and plasma sprayed alumina coatings [19,20] |
|---|---|---|
| Parameter | Sintered | NS 500 | SFP 500 |
| Hardness, Vickers 200 gm (HV\(_{0.2}\)) | 1400 | 983 | 1066 |
| Elastic modulus (E), GPa | 370 | 137 | 86 |
| Fracture toughness \( (K_{\text{IC}}) \), MPa m\(^{1/2}\) | 5 | 1.719 | 1.955 |
Tangential and normal grinding forces were measured during the grinding experiments. A piezoelectric dynamometer (KISTLER 9254) connected to charge amplifiers (KISTLER 5015A) and oscilloscope (Agilent DSO X 2014A) were used for measuring the grinding forces. Eight passes were taken for each set to obtain steady state forces. Chips were collected on a carbon tape for the last pass and were studied under a scanning electron microscope (Zeiss EVO 18). Surface integrity and ground surface topography were studied under SEM. Average surface roughness ($R_a$) of the ground surfaces was measured using 3D contact type profilometer (Taylor Hobson Intra). Residual stress of the ground surfaces was measured by $\sin^2 \Psi$ method using a high-resolution X-Ray diffractometer (PANanalytical Empyrean) equipped with a Cu-Kα target ($\lambda_{Cu} = 1.54$ Å) at higher angle (between 108° and 145°).

3. Results and discussions

Raw data of the tangential and normal grinding forces was analyzed by a user-developed MATLAB code and average grinding forces are determined. The processed data is shown in figure 2. Figure 3
shows the variations in specific grinding forces with wheel speed. It clearly shows that normal grinding forces are greater than tangential grinding forces. Specific grinding forces for sintered alumina are greater as compared to the forces in coatings. This is prominent in case of specific normal force. This can be attributed to greater density and cohesion strength of the sintered material than that of the coatings.

An increase in wheel speed leads to a reduction in the maximum uncut chip thickness as noted in equation 1 [21].

\[ h_m = \left[ \frac{3}{4} \frac{v_w}{\tan \theta} \frac{v_x}{a} \right]^{1/2} \] (1)

The variation in specific grinding forces with maximum uncut chip thickness is shown in figure 4. With an increase in uncut chip thickness, the grit load increases leading to an increase in grinding forces. This has been reported in the grinding of metallic alloys [22]. But the same trend is not observed in the grinding of alumina and alumina coatings in the present study. This can be attributed to micro brittle fracture being the predominant mechanism of material removal in the grinding of ceramics and ceramic coatings.
Figure 4. Variation of specific grinding forces with uncut chip thickness

Figure 5 shows the variations in the grinding force ratio, $F_N/F_T$ with wheel speed. Sintered alumina exhibited higher force ratio in the range of 4 – 8 as compared to that in alumina coatings with a range of 1.5 – 6. The cohesion strength of particles in sintered ceramic is higher than that in plasma sprayed ceramic coatings due to the defects in plasma spraying process [18]. This higher cohesion strength leads to higher grinding force ratio in sintered alumina.

Figure 6 shows the variations in grinding force ratio with $h_m$. An increase in uncut chip thickness usually results in an increase in force ratio in the grinding of metallic alloys [22]. This trend is not observed in the present study due to the grinding mechanism being primarily micro-brittle fracture as compared to ploughing, rubbing and shearing in grinding of metallic alloys.
Specific grinding energy ($u_g$) is the energy required to remove a unit volume of material. It consists of contributions from ploughing, rubbing and material removal by shearing and/or micro-cutting in the grinding of metallic alloys. In the case of ceramic grinding, micro-brittle fracture is the dominant mechanism of material removal [23]. The variations in $u_g$ with wheel speed is shown in figure 7. Specific grinding energy in all the experiments has been observed to be low (less than 5 GJ/m$^3$) in the present study. This can be attributed to the material removal mechanism being primarily micro-brittle fracture.

Figure 7. Variation of specific grinding energy with wheel speed

Specific grinding energy is observed to increase with decreasing uncut chip thickness ($h_m$), as shown in figure 8. This can be attributed to increased contribution of rubbing at lower values of $h_m$
Figure 8. Variation of specific grinding energy with uncut chip thickness

Figure 9 shows the SEM images of the ground surfaces at 160 m/s wheel speed. Crushing on the ground surfaces clearly shows that micro-brittle fracture is the predominant material removal mechanism in the coatings. However, some amount of micro-cutting has been observed on the ground surface of sintered alumina. Bifano et al. have proposed that there exists a critical grit depth of cut \( d_c \) below which the material removal mechanism in grinding changes from micro-brittle fracture to shearing or micro-cutting \([24]\). The critical depth of cut can be estimated using equation 2.

\[
d_c = 0.15 \left( \frac{E}{H} \right) \left( \frac{K_{1C}}{H} \right)^2
\]  

(2)

Where \( E \) is the elastic modulus, \( H \) is the hardness and \( K_{1C} \) is the fracture toughness of the ceramic.

The critical grit depth of cut is calculated using equation 2 as 0.505 \( \mu \)m for sintered alumina and 0.0678 \( \mu \)m for NS 500 and 0.0431 \( \mu \)m SFP 500.
Grinding chips are studied using SEM and are shown in figure 11. Chips are observed to be crushed and not sheared. This confirms the material removal mechanism to be mainly micro-brittle fracture.

Average surface roughness ($R_a$) across and along the grinding direction has been measured. Figure 12 shows the 3D surface profile and the variations in $R_a$ with wheel speed. No specific trend is observed.
between $R_a$ and wheel speed. Surface roughness across the grinding direction is higher than that along the grinding direction. This indicates some amount of micro-cutting action along with micro-brittle fracture. Pure brittle fracture would result in similar surface roughness across and along the grinding direction. Surface roughness for sintered alumina is found to be lower than that for the coatings.

Figure 12. (a) 3D surface profile of sintered alumina ground at 160 m/s wheel speed, (b) Variations in average surface roughness with wheel speed

Figure 13 shows the residual stresses on the ground surfaces. Sintered alumina, upon grinding, is stress-free and coatings showed tensile residual stresses on the ground surface. This shows that grinding has caused significant damage on the surface of the coatings as compared to sintered ceramic. Residual stress is also lower at higher wheel speed for all the materials indicating less surface damage at higher wheel speeds.

Figure 13. Residual stresses on the ground surfaces at 40 m/s and 160 m/s wheel speed

4. Conclusions

Grinding forces and specific grinding energy of both sintered alumina and alumina coatings are very low compared to that of metallic alloys. This is due to the material removal mechanism being predominantly micro-brittle fracture instead of ploughing, rubbing and micro-cutting. Grinding forces are higher for sintered alumina as compared to that of the plasma sprayed alumina coatings due to higher cohesion strength and lower material defects in sintered alumina which also resulted in higher force
ratio in sintered alumina. SEM images of the ground surface and the grinding chips at high speed did not show any micro-cutting action, but the differences in average surface roughness along and across the grinding direction indicated micro-cutting action along with micro-brittle fracture as the grinding mechanism. Surface roughness is lower in sintered alumina as compared to alumina coatings. The ground surface of sintered alumina is found to be stress-free, whereas tensile residual stresses are observed on the ground surfaces of plasma sprayed coatings. Grinding residual stress is less at high wheel speeds indicating less surface damage in high-speed grinding.

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