Experimental analysis of brazed diamond dresser using single grit scratch on zirconia ceramic

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KEYWORDS

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ABSTRACT

The overall performance of the grinding wheel is difficult to analyze, as it is a compilation of individual abrasive grit contributions. The single grit scratch test is useful to investigate the effect of the individual grit effect on the work material. A vacuum-brazed diamond dresser is developed for the single grit scratch experiment. Partially stabilized zirconia is used as work material to study the mechanics of material removal and mode of grit failure. The experiments were performed in dry conditions by varying the wheel speed, table feed, and depth of cut. The grit failure mechanism has been analyzed using a scanning electron microscope image and correlated with the induced force during the scratch test. The results show that the diamond microcracking was observed after 370 mm of grinding scratch marks. And the maximum tangential and normal force withstand by the diamond grit is 13.09 N and 19.65N, respectively.

1. Introduction

Zirconia-based ceramics with 3% yttria added (ZrO_2- 3%Y_2O_3) partially stabilized (PSZ) is one of the toughest and strongest ceramic. It is used as a thermal insulator due to extremely low thermal conductivity, and in the restoration of prosthodontics and in other biomedical applications due to chemically stable, high flexural strength/toughness and is naturally white in colour. Different researchers have suggested various methods to evaluate the material removal and grit wear during the grinding of different ceramic materials, but limited work is reported on zirconia-based ceramics (Denkena et al., 2018; Denry & Kelly, 2008; Flanders et al., 2003). Grinding of zirconia-based ceramics is done by diamond grinding to achieve the required shape and surface finish. The grinding process is expensive compared to other machining processes due to low material removal rate and high specific energy consumption. The diamond grinding of zirconia-based ceramic is relatively more expensive due to issues like the brittle mode of deformation, with localizedcovalent ionic bonding and well-organized cubical crystal structure of the material (Anand et al., 2019).

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The overall performance of the whole grinding wheel is difficult to analyze, as it is a compilation of individual abrasive grit contributions. The single grit scratch test is a useful tool to investigate the effect of the individual grit effect (Ohbuchi & Matsuo, 1991). Microscopic interaction between zirconia-based workpieces and diamond grit is analyzed in detail by indentation, scratch, and grinding tests. The effect of grit shape and different rake angles (Matsuo et al., 1989), horizontal contact scratch damage(Lee et al., 2000), fracture characteristics of diamond (Buhl et al., 2013), and many more are also analyzed. Various in-situ and post-processing tools are used to analyze different outcomes, i.e., forces data, acoustic emission signal, accelerometer, confocal data, 3D optical profilometric images, scanning electron microscopic images, etc. Mode of deformation, chip formation, groove scratch characteristics, and grit wear are significantly influenced by a) grinding parameters like table feed, wheel speed, and depth of cut and b) diamond grit geometry like grit size, shape, and orientation of its different faces, i.e., rake angle/face, side rake angle/face. In the grinding of ceramics, normal forces are much higher than tangential forces due to the brittle mode of deformation. Rubbing, chipping, and machining effects are contributing to the increase in localized temperatures and pressures at grit tip; also, dry machining condition results in the fusion of chips at the grit surface. During the single scratch experiment using a brazed diamond tool, two types of failure mechanisms are observed, a) pullout and b) micro/macro fracture of the diamond grits. During experiments, diamond grit may fracture due to overloading. It occurred due to a substantial impact on the grit during engagement with the brittle workpiece material. The consequence of such a phenomenon is that an interface brazed bond may fail, and consequently, the grit pullout occurs.

In this article, the diamond dresser is initially developed using active brazing alloy. Further, the failure mechanism of the diamond grit and the material removal mechanism of the zirconia ceramic has been analyzed using the SEM image and the force analysis.

2. Experimental Methods and Material

2.1. Brazed diamond dresser development

The brazed diamond dresser is developed using 35-40 mesh size natural diamond grit and Ticusil-active brazing alloy (ABA) (Prince & Izant, USA). A 6 mm diameter low carbon steel conical-shaped pin is used as substrate. The brazed diamond dresser illustrated in Fig. 1. a and b. is developed using an in-house developed vacuum furnace. The diamond dresser is brazed at 950 °C for the holding time of 10 min, and the vacuum level is maintained at less than 5.5 × 10^{-5} mbar during the process.

2.2. Workpiece setup and single grit experiment

The work material ZrO_2–3%Y_2O_3 (PSZ) with a dimension of 20 × 20 × 10 mm is flattened and polished with respect to the machine axis before conducting single grit experiments. Fig. 2. (a) illustrates the mounting of the workpiece on a dynamometer using a precision vice. The workpiece is grounded using resin-bonded diamond grinding wheel D126-B75TN69. The grinding parameters used to flatten the work material; wheel speed: 22 m/sec, table feed: 4 m/min, and depth of cut 5 µm. After that, hand polishing is carried out using a 10 µm diamond paste to increase the surface finish. The mechanical properties of PSZ are displayed in Table 1.

Surface grinder B818-III (CHEVALIER, USA) is used for the single scratch experiments. The grinding scratches are performed using a dummy aluminium wheel (180 mm diameter and 12 mm width) with a single grit diamond dresser mounted on the periphery of the wheel, as shown in Fig. 2 (b). Before each experiment, the interaction between the tool and workpiece is precisely contacted with one-micron accuracy. Different grinding parameters for single grit experiments, such as wheel speed, table speed, and depth of cut are selected as shown in Table 2.

The force components, normal and tangential forces, are measured using a Kistler-9275B dynamometer. The SEM of the brazed diamond dresser is analyzed for tool wear and interfacial bond characteristic. The height and width of

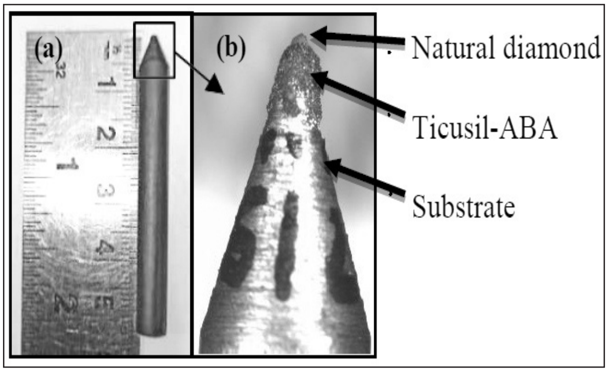

Fig. 1. (a) Vacuum brazed diamond dresser 50 mm X 6mm (L X D), and (b) Enlarged view of brazed diamond tip.

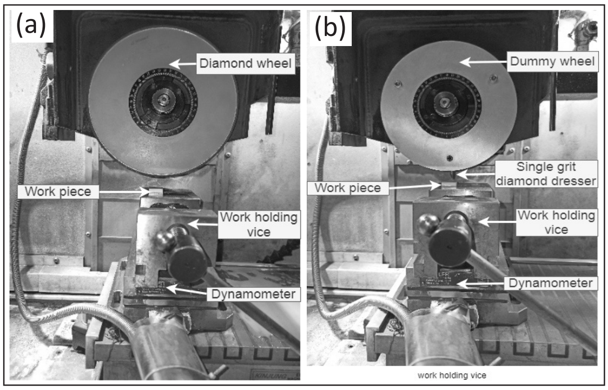

Fig. 2. Grinding setup on B818-III CNC surface grinder (a) Flattening and polishing using a diamond grinding wheel, (b) Single grit scratch wheel mounting.

Table 1
Mechanical properties of the PSZ ceramic.

Property	Value (Unit)
Density	6000 (kg/m^3)
Hardness	1300 (HV10)
Bending strength	1680 (MPa)

Table 2
Machining parameters for the single grit scratch experiments.

Parameters	Value (Unit)
Wheel Speed: V_S (m/sec)	16, 20, 24
Table feed: V_t (m/min)	4, 6, 8
Depth of Cut: a (µm)	5, 10, 15

the grooves are measured using a non-contact type confocal microscope (Micro-epsilon, Germany) and an optical microscope. SEM (Zeiss EVO-18, Germany) micrographs of the scratched groove of all experiments are analyzed for the scratch profile and modes of fracture mechanism.

3. Result and Discussion

The SEM of the diamond dresser, force analysis of the 27 scratch experiments, and the morphology of the scratched groove are discussed in detail.

3.1. Scratch force analysis

The normal force (F_n) and tangential force (F_t) of each experiment are illustrated in Fig. 3. The transverse force component due to the side rake face may present, but in the current set of experiments, the value of transverse force is significantly less compared to other forces, hence neglected in this work. The real-time data is acquired by 5070A12100 8-channel summing up the amplifier on DynoWear software. Tangential and normal forces are predominantly affected by the depth of cut and maximum principal cutting edge angle along the nose radius of the tool. It can be obtained from the following formula:

$$K_r = \cos^{-1}\left(\frac{r_\varepsilon - a}{r_\varepsilon}\right) \quad ....(1)$$

where K_r is the maximum principal cutting edge angle, r_ε is the nose radius, and '*a*' is the depth of cut. For the diamond tool nose radius r_ε = ~0.8 mm (measured through an optical microscope), as depth of cut is increased from 5 to 15 µm; the Kr increases from 6.41˚ to 11.11˚. This explains that the effect of depth of cut and grit nose radius are significant on the forces. Fig. 3. shows force data of the individual grit scratch of all experiments.

The obtained value of tangential force and normal force is in the range of 1.21-8.04 N and 2.74-16.1 N, respectively. The tangential, as well as normal forces, increase with the depth of cut; this is due

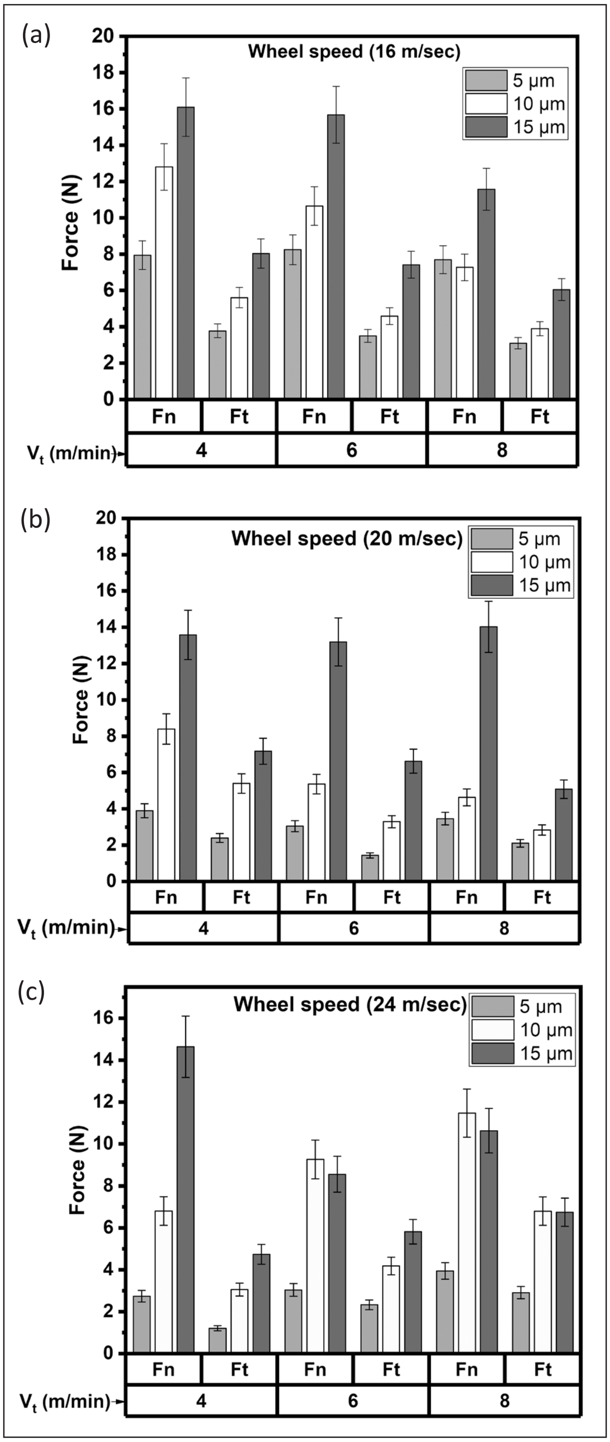

Fig. 3. Force data at differenct grinding conditions
(a) Wheel speed : 16m/sec,
(b) Wheel speed: 20 m/sec, and
(c) Wheel speed: 24m/sec.

to the following reasons: (a) The predominant ploughing and chipping mode of deformation near edges of the groove, (b) Resistance due to material hardness and (c) Coefficient of friction offered by brittle material in dry condition. At the wheel- speed 16 m/sec, forces decrease with an increase in table speed for the same depth of cut. A similar phenomenon was observed for 20 m/sec and 24 m/sec wheel speeds. At the experiment condition, V_w: 24 m/sec, V_t:8 m/min, and a: 15 µm, forces suddenly drop, which indicates that the grit wear may have started.

3.2. Grit wear analysis

Diamond grit is wear in terms of micro/macro cracking or grit pullout has been observed due to predominant rubbing and chipping action with the hard work material. The optical/SEM images of the brazed diamond grit are illustrated in Fig. 4. (a and c) before scratch test and Fig. 4. (b and d) after scratch test. SEM image of the tool after the experiment is shown in Fig. 4 (e), which clearly indicates that the diamond grit may wear out due to the microcracking effect. The total measured scratch length is approximately 370 mm using an optical microscope. The fracture due to microcracking is observed due to high thermal stresses; Fig. 4. f) illustrates the schematics of the thermal fracture mechanism of the grit. The high-stress zone due to thermal stress has been induced at the tool-chip interface/ contact length, which stands for thermal stress-induced fracture. The same has been reported by (Naskar et al., 2020).

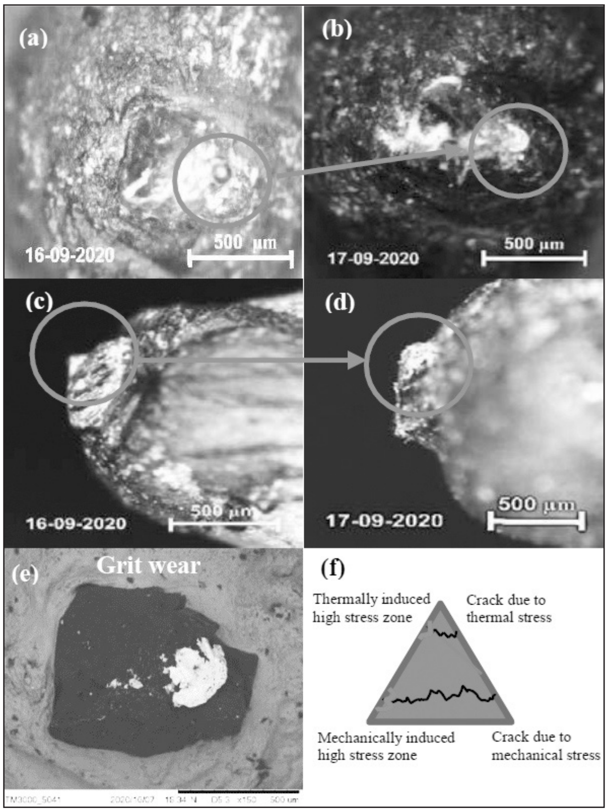

Fig. 4. Optical images of diamond dresser tip: (a, c) before scratch, (b, d) after scratch top view/side view, (e) SEM image top view of diamond grit and (f) schematics of the grit failure.

3.3. Morphology of scratched groove

Scanning electron microscopic (SEM) images of each scratch groove have been taken and analyzed for the mode of material removal such as chipping, spalling mark, rubbing, spattering, and machining are illustrated in Fig.5. for selected scratch experiments.

At 5 µm depth of cut, rubbing action is taking place, no spatter marks are observed, and the groove looks uniform without micro-cracks. Due to such a phenomenon, specific energy at 5µm depth of cut is higher. Groove width increases with an increase in the depth of cut (10µm). The effect of that groove area increases with a little bit of chipping action at the edges of the groove and results in reduced specific energy. At a depth of cut of 15 µm, groove width increases, and more machining marks are observed at the edges of the groove. This is due to the machining by side rake edge and rake face of the grit; the material is pushed sideways to the scratch direction. The material removal is higher, and the specific energy gets further reduced. In some images, sidewall cracking marks are observed only in low wheel speed 16 m/sec and low table speed (4 and 6 m/ min) conditions. At a high wheel speed of 24 m/ sec, ploughing and cutting action is observed instead of rubbing.

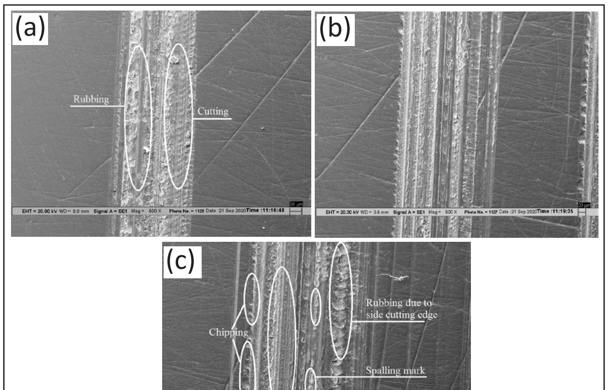

Fig. 5. Morphology of scratch groove Vw: 16 m/sec Vt: 4 m/min. (a) a: 5 µm, (b) a: 10 µm, (c) a: 15 µm.

The roughness (Ra) value of the different grooves is measured using 3D optical profilometer (Model: Zeta-20, Zeta instrument) illustrated in Fig 6. In

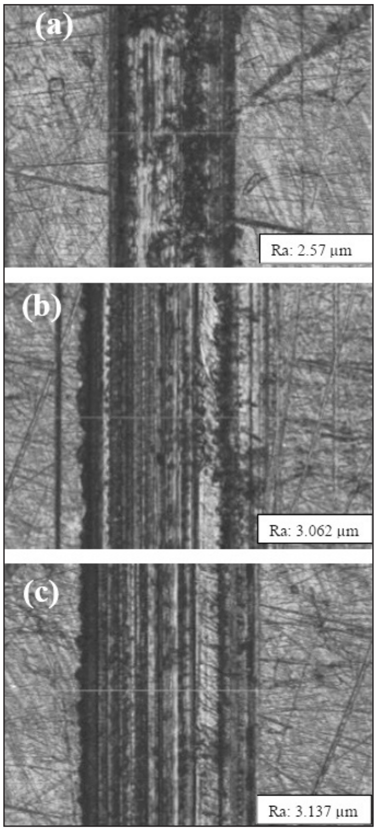

Fig. 6. 3D optical image of groove vw: 16 m/sec vt: 4 m/min (a) a: 5 µm, (b) a: 10 µm and (c) a: 15 µm.

single scratch test, measurement of Ra value inside groove is very critical as groove is in circular arc shape. Also, due to irregular geometry of the diamond grit, Ra value is different in different location. The roughness value Ra ranges from 2.57 to 3.137 µm the good roughness was observed in 5 µm depth channels while increase in the depth of cut. The roughness value increases due to rubbing and chattering action.

4. Conclusion

The single grit scratch experiments were carried out using developed vacuum-brazed diamond dresser. Brazed diamond dresser life was analyzed in terms of scratch length and the force withstand by grit onto partially stabilized zirconia (ZrO_2-3%Y_2O_3). The length of the scratch is measured by an optical microscope, and the SEM of the diamond grit and the scratch was analyzed for grit wear and scratch morphology of the work material. It can be concluded that:

No grit wear and micro-cracks at the diamond interface are observed after 370 mm of scratch length. The maximum tangential and normal force withstand by the diamond grit is 13.09 N and 19.65N respectively. However, zirconia particles are fused on to diamond tool tip during scratch experiments due to high temperature and pressure.

The forces increase with increased penetration and decrease with increased wheel speed. At constant wheel speed, forces decrease with an increase in table speed. Tangential and normal forces range from 1.21 to 13.09 N and from 2.04 to 19.65 N, respectively. The wide range is due to the large variation of the maximum principal cutting edge angle in relation to the depth of cut and grit nose radius.

Morphology of the groove reveals uniformity in scratch over the entire scratch length and non-uniformity over the scratch width due to the irregular shape of diamond grit. The rubbing action at lower depth of cut and chipping action increases at higher in-depth penetration

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References

Anand, P., Arunachalam, N., & Vijayaraghavan, L. (2019). Evaluation of grinding strategy for bioceramic material through a single grit scratch test using force and acoustic emission signals. *Journal of Manufacturing Processes, 37*, 457-469. https://doi.org/10.1016/j.jmapro.2018.12.006

Buhl, S., Leinenbach, C., Spolenak, R., & Wegener, K. (2013). Failure mechanisms and cutting characteristics of brazed single diamond grains. *International Journal of Advanced Manufacturing Technology, 66*(5-8), 775-786. https://doi.org/10.1007/s00170-012-4365-z

Denkena, B., Wippermann, A., Busemann, S., Kuntz, M., & Gottwik, L. (2018). Comparison of residual strength behavior after indentation, scratching and grinding of zirconia-based ceramics for medical-technical applications. *Journal of the European Ceramic Society, 38*(4), 1760-1768. https://doi.org/10.1016/j.jeurceramsoc.2017.11.042

Denry, I., & Kelly, J. R. (2008). State of the art of zirconia for dental applications. *Dental Materials, 24*(3), 299-307. https://doi.org/10.1016/j.dental.2007.05.007

Flanders, L. A., Quinn, J. B., Wilson, O. C., & Lloyd, I. K. (2003). Scratch hardness and chipping of dental ceramics under different environments. *Dental Materials, 19*(8), 716-724. https://doi.org/10.1016/S0109-5641(03)00018-6

Lee, S. K., Tandon, R., Readey, M. J., & Lawn, B. R. (2000). Scratch damage in zirconia ceramics. *Journal of the American Ceramic Society, 83*(6), 1428-1432. https://doi.org/10.1111/j.1151-2916.2000.tb01406.x

Matsuo, T., Toyoura, S., Oshima, E., & Ohbuchi, Y. (1989). Effect of Grain Shape on Cutting Force in Superabrasive Single-Grit Tests. *CIRP Annals - Manufacturing Technology, 38*(1), 323-326. https://doi.org/10.1016/S0007-8506(07)62714-0

Naskar, A., Choudhary, A., & Paul, S. (2020). Wear mechanism in high-speed superabrasive grinding of titanium alloy and its effect on surface integrity. *Wear*, 462-463(September), 203475. https://doi.org/10.1016/j.wear.2020.203475

Ohbuchi, Y., & Matsuo, T. (1991). Force and Chip Formation in Single-Grit Orthogonal Cutting with Shaped CBN and Diamond Grains. *CIRP Annals - Manufacturing Technology, 40*(1), 327-330. https://doi.org/10.1016/S0007-8506(07)61998-2

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