Superior Sliding Wear Performance Of Pressure Slip Cast Alumina Products

P Raju[1,3], Asit Kumar Khanra[3], S Kumar[2], Y S Rao[1*], Roy Johnson[1]

[1]Department of Ceramic Processing, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, India

[2]Department of Engineered Coatings, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, India

[3]Department of Metallurgical and Materials Engineering, National Institute of Technology, Warangal, India

Research Article

Received: 06-May-2022, Manuscript No. JOMS-22-62951; **Editor assigned:** 09-May-2022, PreQC No. JOMS -22-62951(PQ); **Reviewed:** 23-May-2022, QC No. JOMS -22-62951; **Revised:** 30-May-2022, Manuscript No. JOMS -22-62951(R); **Published:** 07-Jun-2022, DOI: 10.4172/2321-6212.10.5.003.

***For Correspondence:**

Y S Rao, Department of Ceramic Processing, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, India

E-mail: ysr@arci.res.in

Keywords: Alumina; Pressure slip casting (PSC); Conventional Slip casting (CSC); Microstructure; Wear rate

ABSTRACT

Alumina (Al_2O_3) with its superior mechanical and tribological properties in combination with chemical inertness is a preferred material for wear resistant applications. In this paper, alumina sintered products shaped by Pressure Slip Cast (PSC) are evaluated for their sliding wear behaviour and compared with the same produced through Conventional Slip Casting (CSC). Due to close packing achieved through the application of pressure on the slip, the PSC products exhibit high density, which complements to enhance the hardness (15.45 ± 0.15 GPa), flexural strength (259 MPa) and fracture toughness (4.07 MPa $m^{3/2}$). The same estimated for CSC samples are 11.77 ± 0.15 GPa, 242.70 MPa and 3.73 MPa $m^{3/2}$ respectively. Owing to the above fact, the PSC alumina exhibit the wear rate as low as 2.35×10^{-18} m^3/Nm (with 0.5 m/sec at 5N load) are found to 56% less wear rate than CSC alumina. The superior wear rate of PSC alumina will have commercial implications in ceramic industry.

INTRODUCTION

Advanced technical ceramics, with their superior hardness, high temperature stability and good corrosion resistance have become potential candidates for tribological applications in various industries. Oxide ceramics, by the virtue of its low processing cost and good functionality particularly in dry sliding under high speeds, witnessed a major growth in tribology related areas [1-4]. Alumina is the most commonly used material among the various oxide ceramics in a wide range of tribology related applications such as ball milling, conveyer lining as well as various moving and rotating parts[5-7]. Koji, et al. [8] describes that a ceramic having hardness >15 GPa and fracture toughness >4 MPa $m^{3/2}$ are well suited for practical tribology applications. Also, microstructure (grain size and structure) [9-12] is considered to have significant influence on mechanical properties thus alters the wear properties. For instance, reports [13-15] suggest that grain engineering significantly improves the sliding wear performance. There is considerable number of studies performed to analyse the tribological properties of sintered alumina bodies where details from sample preparation to the wear mechanism were discussed [16-19].

In general, properties and performances exhibited by a ceramic component not only depends on the intrinsic property of the materials but also dictated by the processing history followed [20-22]. Colloidal processing of ceramics such as casting offers high homogeneity with respect to the properties of the product with flexibility to produce complex features. Reports [23,24] suggest that alumina ceramic obtained through PSC method exhibit superior mechanical properties as compared with their counterparts obtained from CSC [25]. Tribological performance of PSC alumina owing to its engineered grain structure and superior mechanical properties are missing in the existing literature. In the present study the PSC produced sintered alumina bodies were subjected to similar tribological tests evaluating their performance through sliding wear test against hard WC-Co discs. The results are correlated with the mechanical properties and compared with the CSC alumina.

MATERIALS AND METHODS

Two alumina powders in the ratio 30:70 by weight (grades MR-01 and HIM 10, M/s. Hindalco, India) with solid loadings in the range of 70-80 wt.% were mixed with Darvan (1 wt.%) (Grade 821A, acquired from R.T. Vanderbilt minerals, Inc., CT, USA) to get homogeneous distribution by mixing with deionised water. The average particle size distribution of alumina powders of grades MR-01 and HIM-10, as well as a powder mix were estimated to be 1.43 µm and 7.16 µm, and 3.16 µm respectively. The irregular morphology and size variation seen in the two grades (finer and coarser) of alumina powders are clearly beneficial in achieving a higher packing fraction and the desired interlocking of the particles [23]. To achieve the desired homogeneity and slip stability, the suspensions were wet-mixed using a pot jar mill for four hours at a rate of 20 rpm. The prepared slips of different solid loadings were subjected to the corresponding rheological measurements at different shear rates (MCR 51, Anton Paar, Austria) by concentric cone-cylindrical axial plates separated by 1.75 mm maintaining a constant temperature of 25°C.

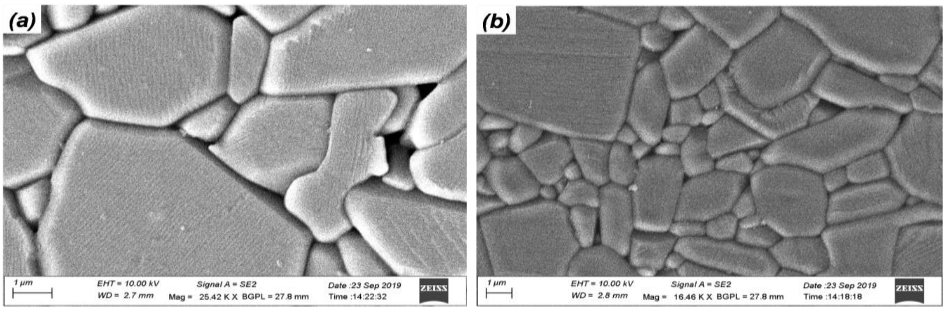
PSC was carried out on a PCS-100N machine (SAMA GmbH, Germany) with slip pressures of 5-40 bar. The details of the casting procedure can be referred elsewhere [23]. In the current analysis, the mean pressure was maintained at 80 bar at the plates. The CSC was carried out by using POP molds. The samples were dried and sintered at 1650°C in air. The final sintered densities were estimated as per ASTM C792. The micro hardness of the samples was determined using Vickers Macro Hardness Tester (ASTMC1327). Samples with dimension of 45 × 4 × 3 (L × W × d) mm^3 were used for three-point bend test (ASTM C1161) to obtain the flexural strength using the Universal Testing Machine (UTM-Intron-model 5584, UK). Ten samples were tested to get the average values and for each of the above test conditions and for this purpose 50-80 N range with a ramp rate of 0.5 mm/min were used. Sliding wear test was carried out using DUCOM pin-on-disk tester (TR-20LE-PHM400-CHM600, DUCOM Instruments (Asia), Bangalore, India) as per ASTMG99 standards. Specimens were prepared into 10 × 10 × 7 mm^3 to fit into a square pin slot. WC-Co circular disc of hardness 21 ± 0.15 GPa and 160 mm diameter with 5 mm thickness and roughness of 0.25 ± 0.01 µm was used. The loads and sliding velocities were varied from 5 N to 25 N and 0.5 m/s to 2.5 m/s respectively.

RESULTS AND DISCUSSION

The Microstructure and mechanical characterization

Figures 1a and 1b shows the microstructure of sintered CSC and PSC samples obtained using FESEM. It is evident from the images that the PSC sample exhibit close packed microstructure with interlocking of finer and coarser grains. In contrast, the CSC sample exhibit imperfections and pores (circled). The average grain sizes of CSC and PSC samples were estimated to be ~3.15 µm and ~1.75 µm respectively. It is obvious from the micrographs that the reduction in grain size enhances the mechanical properties owing to grain boundary effects. Hardness, Flexural Strength and Fracture toughness values of PSC samples were estimated to be 15.45 ± 0.15 GPa, 259 MPa and 4.07 MPa $m^{3/2}$. Whereas, the same for CSC samples were estimated to be 11.77 ± 0.15 GPa, 242.70 MPa and 3.73 MPa $m^{3/2}$ respectively. The higher values of hardness >15 GPa and fracture toughness >4 MPa $m^{3/2}$ in PSC alumina samples make them preferable candidates for tribological applications as claimed by Koji, et al. [8].

Figure 1. FESEM microstructure of the samples fabricated by (a) Conventional Slip Casting (CSC) and (b) Pressure Slip Casting (PSC).

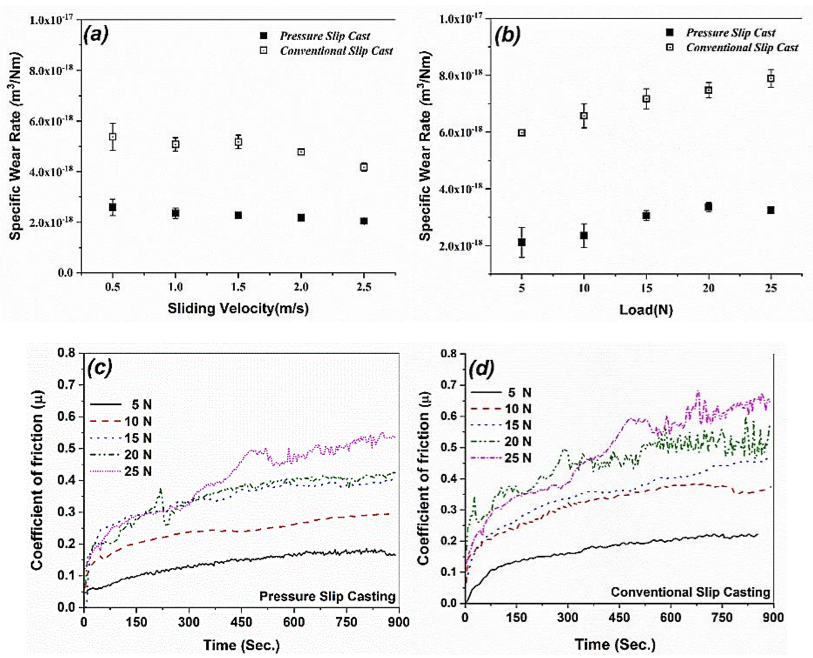


Sliding wear test

Sliding wear test was carried out for PSC and CSC alumina samples against tungsten carbide (WC) disk. Sliding wear experiments were carried out by changing the sliding speed ranging from 0.5 m/s to 2.5 m/s by keeping constant load of 10N. Another set of data was populated by changing the loads ranging from 5-25 N by keeping sliding velocity as 0.5 m/s. Normalised wear rate from each experiment was obtained from the weight loss data. Each experiment was repeated for 10 samples to obtain average value of specific wear rate and coefficient of friction (μ).

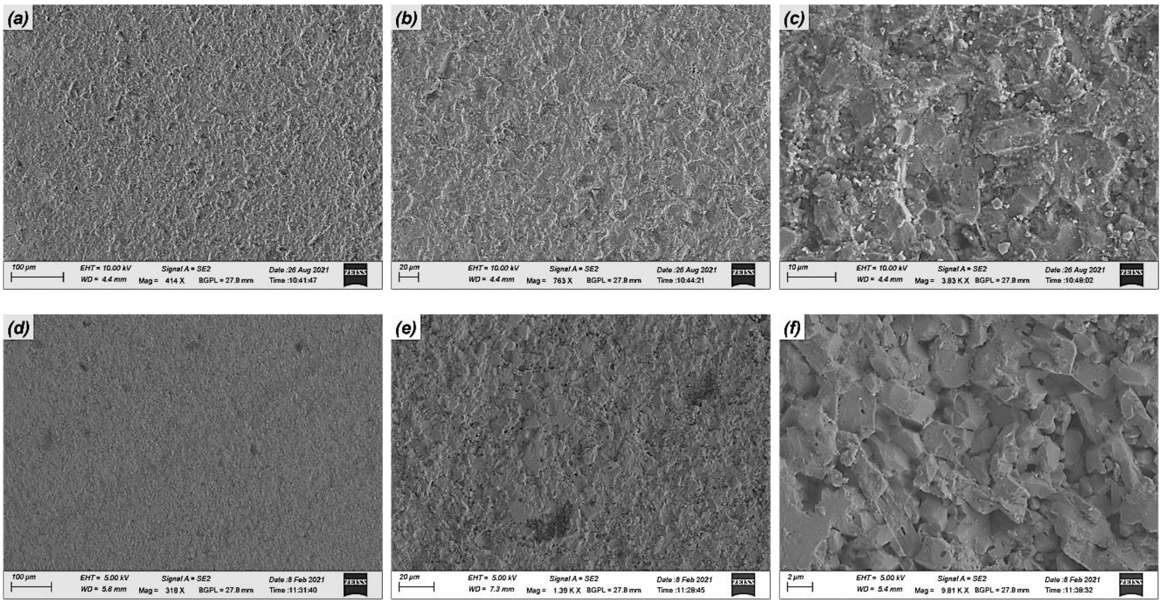
Figures 2a and 2b show the specific wear rate as a function of sliding velocity and load respectively for both CSC and PSC samples. Irrespective of sliding velocities and load, much lower wear rate was measured for the samples obtained through PSC, which is attributed to the smaller grain size and better mechanical properties as compared with the same obtained by CSC. For a sliding velocity of 0.5 m/s, the wear rate ranges from 2.35 × 10-18 m^3/Nm to 3.11 × 10^{-18} m^3/Nm and from 5.97 × 10^{-18} m^3/Nm to 7.88 × 10^{-18} m^3/Nm in the case of PSC and CSC respectively. Similar trend was obtained for the sample in varying sliding velocities. Figures 2c and 2d show the coefficient of friction as a function of sliding time for PSC and CSC samples respectively for different applied load. The fluctuations in coefficient of friction in the case of CSC samples are attributed to severe wear loss and material removal. The plot in Figure 2c (of PSC) demonstrates a mild wear mechanism, which could be due to its excellent mechanical characteristics and fine grain structure. When compared to PSC samples, CSC samples have a greater wear rate, indicating a faster debris generation and fractural behaviour.

Figure 2. Specific wear rate of samples as a function of (a) Sliding velocity and (b) Normal load for CSC and PSC samples; Coefficient of friction as a function of time for (c) PSCed and (d) CSCed samples for different loads.



In order to understand the wear mechanism, the worn-out samples were observed under FESEM. Figures 3a-3d shows the low magnification FESEM images of CSC and PSC samples undergone wear at 5N at 0.5 m/s. it is evident from the images that the smooth surface observed for PSC sample is attributed to mild wear which is in correlation with the wear data presented in Figure 2. The high magnification images presented in Figures 3b and 3c for CSC and Figures 3e and 3f for PSC provides more information. The fracture mode during sliding for CSC and PSC samples are brittle and cleavage fractures respectively. The facets shown in Figure 3f indicate smooth removal of material. Similarly, Figure 4 shows the worn-out surface observed under FESEM for CSC and PSC samples.

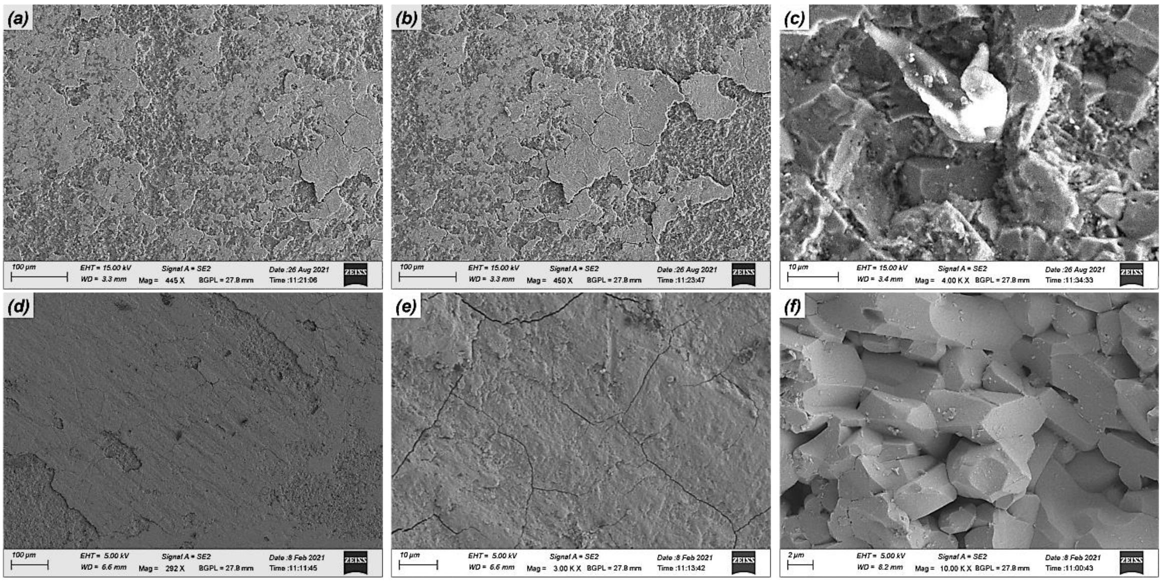
Figure 3. Low magnification FESEM images of the worn out surfaces of (a) CSCed and (d) PSCed samples; High magnification images of CSCed (b and c) and PSCed (e and f) at 5N normal load and 0.5 m/s sliding velocity.



In contrast with the images shown in Figures 3, 4a-4d shows the low magnification images of CSC and PSC samples undergone wear at high loads (25 N). The adhesive film type layer was observed in both the samples. However, PSC sample exhibit continuous layer whereas the CSC sample shows highly brittle layer formation. High magnification image presented in Figure 4e (PSC) shows randomly generated cracks. Still the formed layers are intact with the sub-surface indicate the superior adhesion of the layer. Further magnification in the locations from where the layers were removed indicates the failure mode of CSC and PSC. The results are in agreement with that presented in Figure 3. A careful observation of CSC samples (Figures 3c and 4c) reveals that increasing load severely removes the worn-out layers and leaving behind roughened surface. The roughness seems to be in direct proportionality with the load. Similarly, from the high magnification FESEM images for PSC samples (Figures 3f and 4f), it is evident that the facets obtained for higher load is clean without any debris.

It is understood from the wear data of the CSC and PSC samples that the wear mechanism is smooth and gradual when the normal load is low. The formation of adhesive layer is not observed in both the cases from the FESEM images for low loads. In contrast, increasing the normal load, gradually forms a layer probably formed by entrapped worn out debris between WC-Co disc and the surface of the alumina sample during wear test. This adhesive layer is fragile in the case of CSC whereas, the layer is intact in the case of PSC, which is evident from the microstructures. The superior wear resistance performance of PSC samples than that of CSC is mainly attributed to their enhanced fracture toughness. In severe wear region in the PSC sample, the deterioration of mass loss showing that the small debris are formed and fracture behaviour shows both inter-granular as well as trans-granular. Wear rate is found to be in good correlation with the mechanical properties of both the samples and accordingly PSC samples exhibited an enhanced wear resistance of 56% in comparison to the CSC samples.

Figure 4. Low magnification FESEM images of the worn out surfaces of (a) CSCed and (d) PSCed samples; High magnification images of CSCed (b and c) and PSCed (e and f) at 25N normal load and 0.5 m/s sliding velocity.



CONCLUSION

Pressure Slip Cast (PSC) Alumina with 75 wt% solid loading exhibits structural integrity with its a higher density of 98.5 % theoretical density as compared to the relatively low density of 97% obtained through traditional casting (CSC). The refined grain structure with minimum defects/pores as achieved by PSC thus enhances the mechanical properties hardness, flexural strength and fracture toughness determined to be 15.45 ± 0.15 GPa, 259 MPa and 4.07 MPa $m^{3/2}$ respectively making them suitable for wear resistance applications. The PSC samples showing the wear rate as low as 2.35 × 10^{-18} m^3/Nm (with 0.5m/sec at 5N load) are found to exhibit 56% less wear than that measured in CSC samples. The mechanical and microstructural behaviour of the results are discussed and correlated. The improved wear rate of PSC alumina will have commercial applications in the ceramics industry.

REFERENCES

1. Javad K, et al. Investigation of the surface integrity, flexural strength on the grinding of alumina for biomedical applications. Int J Precis Eng. 2021;67:110-122.
2. Barkallah R, et al. Mechanical properties and wear behavior of alumina/tricalcium phosphate/tatania ceramics as coating for orthopedic implant. Eng Fra Mech. 2021;214:107399.
3. Lu X, et al. Tribological behavior and mechanism of high proportion of ceramic particles reinforced Al composite. J Mater Res Technol. 2021;15:4931- 4939.
4. Xue-feng Y, et al. Wear properties and microstructures of alumina matrix composite ceramics used for drawing dies. Ceram Int. 2009;35:3495-3502.
5. Changxia L, et al. Microstructure and wear performance of alumina/graphene coating on textured Al_2O_3/TiC substrate composites. J Eur Ceram. 2021;41:1430-1451.
6. Yang C, et al. Friction and wear behavior of alumina-based ceramics in dry and lubricated sliding against tool steel. Wear. 1992;157:263-277.
7. Zum Gahr KH. Modelling and microstructural modification of alumina ceramic improved tribological properties. Wear. 1996;200:215-224.
8. Koji K, et al. Wear of advanced ceramics. Wear. 2002;253:1097-1104.
9. Rolf W, et al. Wear behavior of α-alumina in hot steam at high contact pressure. Wear. 2018;404-405:22-30.
10. Singha RR, et al. Improved sliding wear-resistance of alumina with sub-micron grain size: A comparison with coarser grained material. J Eur Ceram. 2007;27:4737-4743.
11. Godino IP, et al. Modelling the wear evolution of a single alumina abrasive grain: Analyzing the influence of crystalline structure. J Mater Process Technol. 2020;277:116464.
12. Hsu SM, et al. Wear prediction of ceramics. Wear. 2004;256:867-878.
13. Xiong F, et al. The effect of test parameters on alumina wear under low contact stress. Wear. 1999;236:240-245.

14. Mark G, et al. Real time measurement of wear and surface damage in the sliding wear of alumina. Wear. 2017;377:1866-1876.
15. Lidija CU, et al. Solid particle erosion behavior of high purity alumina ceramics. Ceram Int. 2011;37:29-35.
16. Haiyue X, et al. Densification mechanism and microstructure characteristics of nano- and micro-crystalline alumina by high-pressure and low temperature sintering. J Eur Ceram. 2021;41.
17. Xiong F, et al. The effect of test parameters on alumina wear under low contact stress. Wear. 1999;236:240-245.
18. Ravi kiran A, et al. Effect of contact pressure and load on wear of alumina. Wear. 2001;251:980.
19. Zeng P, et al. Characterisation of the wear mechanisms in retrieved alumina-on-alumina total hip replacements. Wear. 2017;376-377:212-222.
20. Luo HH, et al. Wear resistance of reaction sintered alumina/mullite composites. Mater Sci Eng. 2008;478:270-275.
21. Vinay K, et al. Wear testing and characterization of alumina ceramic to predict erosion rate. Int J Mech Prod. 2016;4:10.
22. Moreno R, et al. Colloidal filtration of silicon nitride aqueous slips, part ii: slip casting and pressure casting performance. J Eur Ceram. 1999;19:49-59.
23. Rao YS, et al. Pressure slip casting: a novel process for producing alumina bodies with superior green density. Interceram-Refractories Manual 1. 2013:218-220.
24. Salomani A, et al. Pressure casting offers possibilities for technical ceramics. Am Ceram Soc Bull. 2000;79:49-53.
25. George VF, et al. Colloidal processing: Enabling complex shaped ceramics with unique multiscale structures. J Am Ceram Soc. 2017; 100:458-490.