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CRYOGENIC WEAR OF SELF-MATED ALUMINA: A FIRST REPORT

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ABSTRACT

The present research reports the sliding wear behavior of self-mated Al_2O_3 in liquid nitrogen under varying load (2-10 N) and rotational speed of 2550 rpm using a newly designed cryogenic tribometer. The experimental results reveal that lowest COF of 0.2 can be obtained under the selected testing conditions. Detailed SEM observation of the worn surfaces indicates that severe damage of both ball and flat takes place at cryogenic conditions by intergranular fracture. Additionally, the fine wear debris particles are observed to be entrapped inside abrasive grooves and transgranular fracture along the cleavage planes are often observed.

Key words: Cryo-tribometer, friction coefficient, wear, bearings, alumina.

1. INTRODUCTION

Friction, wear and surface failure properties of materials sliding in cryogenic liquid are of paramount importance to the development of rocket turbopumps. Cryogenic liquids are pressurized by turbopumps with rotational speeds up to 50000 min^{-1} that have to work at 20 K (LH_2) and 77 K (LN_2). The lifetime of such rocket engines is usually limited to only a few minutes and thus high wear at bearings and seals can be tolerated. In cryogenic environments, components with interacting surfaces in relative motion (tribosystems) like bearings, seals and valves cannot be lubricated conventionally by using oils and greases and thus, the use of unlubricated bearing components is critical with respect to wear and frictional heat generation[1]. Upto now, SUS440C stainless steel has been the most widely used material for the ball bearings of space mechanisms, especially for the liquid rocket engine cryogenic turbo pumps. In turbopumps of Space Shuttle Main Engine (SSME) of NASA, LE-5 and LE-7 of NASDA, the shaft bearings are operated at very high speeds like 30,000 rpm and above. These bearings are subjected to high transient axial loads, producing high contact stresses above the yield stress (~1.8GPa) of the material. A significant amount of sliding takes place between the balls and the races due to heathcote slip depending on the radii of curvature of the balls and grooves[2]. Bearing steels have high density of 7.8 gm/cc and low hardness of 7 GPa, whereas, structural ceramics like Al_2O_3, SiC, ZrO_2 and Si_3N_4 have considerably low density (3.2-6.5 g/cc) and high hardness (13-31 GPa). High rotational speed as well as longer bearing life can be achieved with the use of ceramic bearings. However, their inherently brittle nature poses a major concern for potential premature catastrophic failures. Although the tribological properties of structural ceramics at ambient and high temperature are investigated, such a study under cryogenic environment is not commonly reported in open literature.

To this end, the present study focuses on understanding the friction and wear properties of self-mated alumina, a model system consisting of brittle ceramics. Alumina have been widely used in seals and bearings owing to its low density, rigid structure and capability to retain smooth surfaces over a broad range of high stress loading conditions[3]. Lubricated and unlubricated wear tests[4-9] of alumina at room temperature reported the friction coefficient to be in range of 0.28-0.48 and wear rate was found to vary from $10^{-9} – 10^{-3}$ mm^3/N m depending on the testing conditions. This large variation in the friction coefficient and wear rates is apparently due to strong influence of the test conditions on the wear mechanisms and the occurrence of wear transitions in alumina. The sliding wear behavior of alumina is a strong function of nature and severity of contact, contact configuration, load, sliding speed and test environment. Jacob et. al[10] reports that conventional bearings and seals may operate without difficulty in liquid nitrogen and hydrogen. Recently a new high-speed tribometer (ball-on-disk testing configuration) is designed and installed at IIT Kanpur for tribological testing at high speeds (upto 36,000 rpm) in cryogenic environment. The present work reports the preliminary sliding wear tests conducted on self-mated alumina in liquid nitrogen under the varying load.

2. EXPERIMENTAL DETAILS

Cryogenic wear tests were conducted using computer controlled tribometer using ball-on-disk type of configuration in liquid nitrogen atmosphere. The samples are grounded and polished till they have roughness, Ra of 0.05 µm. The nominal dimensions of disk include 35 mm diameter, 5 mm thick and 9.5 mm diameter alumina ball. Prior to wear experiments, samples were ultrasonically cleaned to obtain clean surfaces. The load is applied to the ball, held stationary in the brass ring and placed in a specially designed ball holder and mated against the disk rotating at the desired sliding speed. The details of experimental set up can be found elsewhere[11]. The whole ball and disc assembly was immersed in liquid nitrogen during the tests. The tribological tests were conducted using normal loads of 2 N, 5 N and 10 N with rotational speed of 2550 rpm for 10 minutes. Due to extensive noise and vibrations experienced by tribometer at high load (10 N), the tests were stopped at around 5 minutes. The frictional force and normal load were continuously recorded during each test by commercial software. Detailed microstructural characterization of as-received samples (both ball and disk) and as-worn surfaces was done using scanning electron microscope (FEI). Optical microscope was used to measure the wear scar diameter of the ball and width of the circular track formed on the disk.

3. RESULTS AND DISCUSSION

3.1 Frictional Behavior

Fig. 1 shows the frictional behavior of self-mated alumina under the selected test conditions. The average friction coefficient was found to be 0.2 under the investigated conditions in liquid nitrogen environment. During first 180 seconds of testing time, COF increases to around 0.25-0.28, depending on the load. Thereafter, the frictional behavior exhibits fluctuation before attaining a rather steady frictional response. For 2 N and 5 N load, steady state COF is around 0.2, whereas the experiment with 10 N load could not be performed for 10 minutes, it was stopped after 5 minutes due to severe vibrations of gear motor, it may be probably due to the combined effect of load (10 N) and high rotational speed (2550 rpm). While critically assessing the frictional behavior, it was noted that the cryogenic fluid does not reduce COF to lower than 0.1, indicating that no significant lubrication could be achieved with LN_2. Cryogenic fluids suffer due to low viscosity, which render their contribution towards providing the significant hydrodynamic lift. The role of cryogenic fluids is to merely serve as coolants to dissipate the heat arising from the friction thereby causing reduction in friction coefficient. Severe fluctuation in frictional behavior is due to mechanical smoothening of initial surface roughness and sudden increase is attributed to the sharp asperity interactions and COF follows the decreasing trend, which is due to the flattening of asperities. Although, the effect of cryogenic cooling on reduction in friction coefficient is quite substantial, it will not be viable to eliminate the localized heating effect under high speed sliding conditions due to low thermal conductivity of alumina.

3.2 Worn surface observations

Fig. 2 (a, b, c) shows the surface morphologies of the worn track of the disk at varying load (2-10 N). Scanning electron micrograph shows the presence of faceted grains, numerous large abrasive grooves (typically 15-20 μm wide) and grain boundary cracking. The presence of fine debris particles entrapped inside the grooves clearly indicates the presence of high contact stresses (0.5-0.98 GPa) in the cryogenic environment. However, the groove depth varied from grain to grain and was controlled by the crystallographic orientation of the grain. Large variation in groove width and depth shows differential wear regions, which is also an indication of severe wear of the disk. A high wear depth of 42.5 μm has been measured from the wear disk tracks, which dictates the severity of contact in liquid nitrogen environment. Worn surface observation of the alumina ball (refer fig. 3) tested at 10 N ball shows the cleavage steps, faceted edges (indicative of transgranular fracture) and cracking along the grain boundary (intergranular fracture).

3.3 Brittle fracture of alumina in cryogenic environment

Ceramics typically possess high compressive strength and lower tensile strength, so in most of the instances, tensile stresses cause the onset of wear in a contact, especially in the mild wear regime. Tensile stresses from an asperity sliding against the counterface cause microfracture on the surface as well as subsurface cracking[12]. Slip in ionic ceramics like alumina can not occur readily due to limited independent slip systems (von mises criterion). Also, the fracture energy of alumina is expected to be very low at cryogenic temperatures, which tends to increase the propensity to cause brittle failure. In cryogenic environment, the atomic movement becomes restricted due to high stress generation at extremely low temperature of liquid nitrogen. Development of these stresses at cryogenic temperatures, clubbed with the high contact stresses applied (0.5-0.98 GPa), triggers the onset of brittle fracture in alumina. Presence of cleavage steps, faceted edges, abrasive grooves elucidates that material removal occurs by fracture process (both transgranular and intergranular mode) as well as abrasive wear mechanism of hard asperity interactions.

4. CONCLUSIONS

(a) There is no significance effect of applied load on the friction coefficient. Liquid nitrogen merely serves as coolant to liberate the frictional heat generation which causes reduction in COF.
(b) High hertzian contact stresses applied under the investigated conditions and presence of cryogenic environment triggers the brittle fracture of alumina. Material removal occurs both by transgranular and intergranular fracture.
(c) Formation of fine debris and large and deep abrasive grooves clearly indicates abrasion to be the dominant wear mechanism, due to hard asperity interactions causing severe wear.

5. REFERENCES

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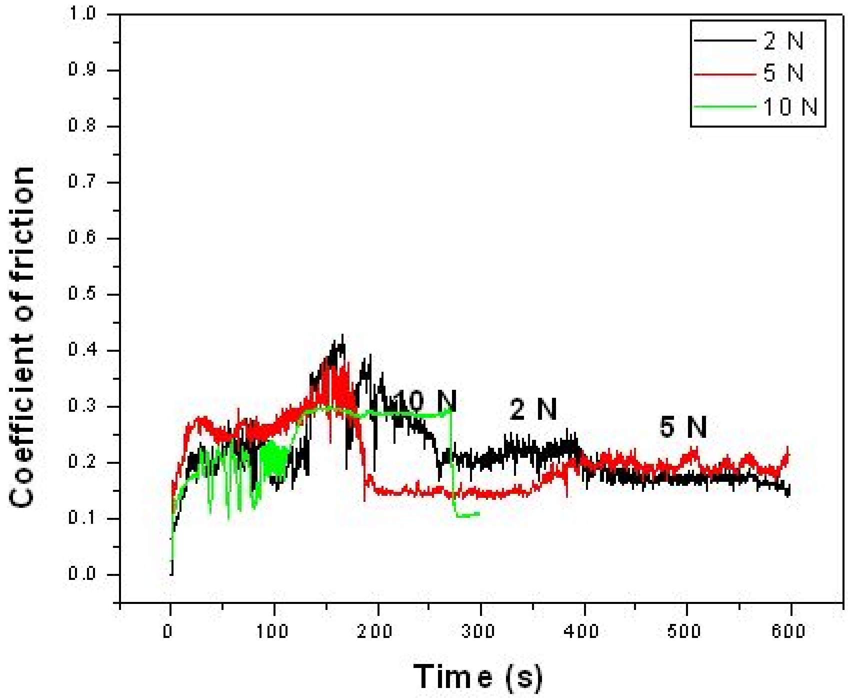
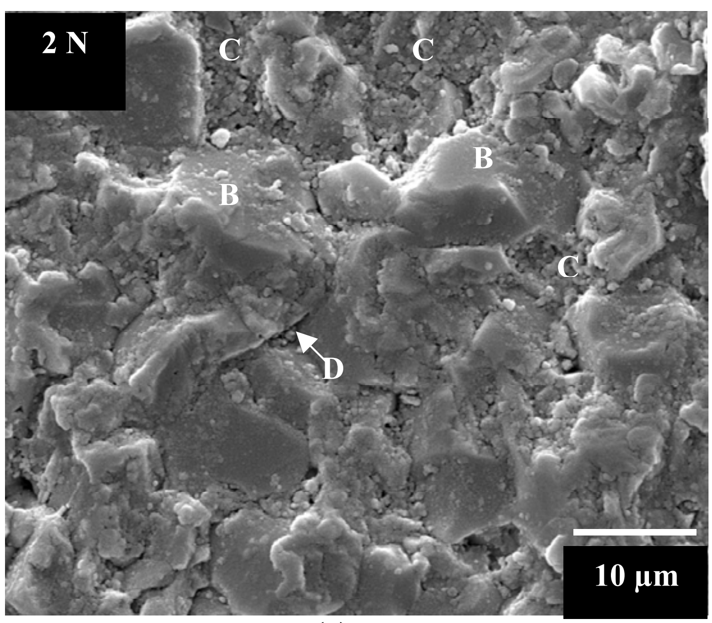
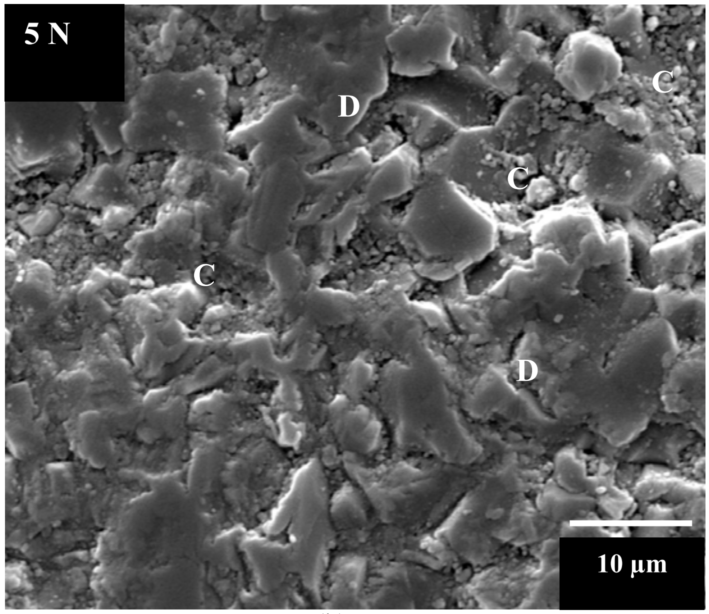


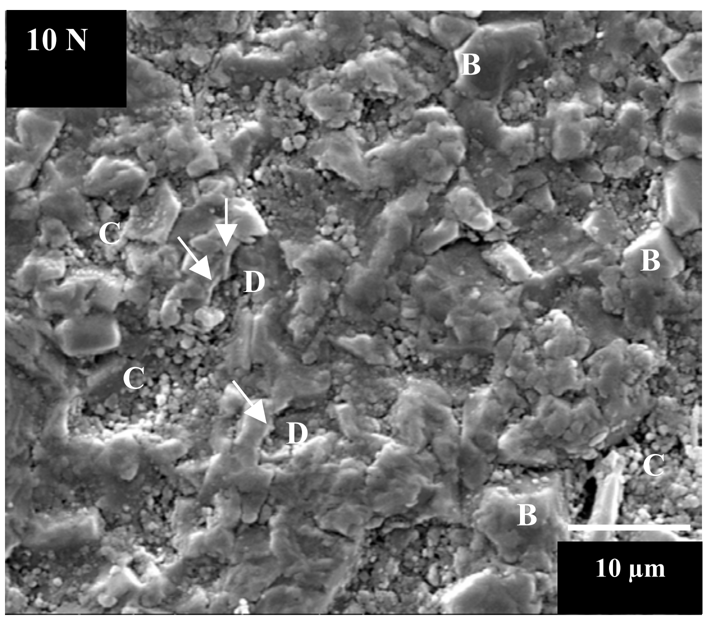
Figure 1: Comparison of friction coefficient under varying load (2-10 N) in liquid nitrogen



(a)



(b)



(c)

Figure 2. SEM micrographs of worn surfaces of circular tracks of the disk at 2N, 5 N and 10 N showing (B) Faceted edges (C) Grooves with Fine debris entrapped (D) Intergranular cracking.

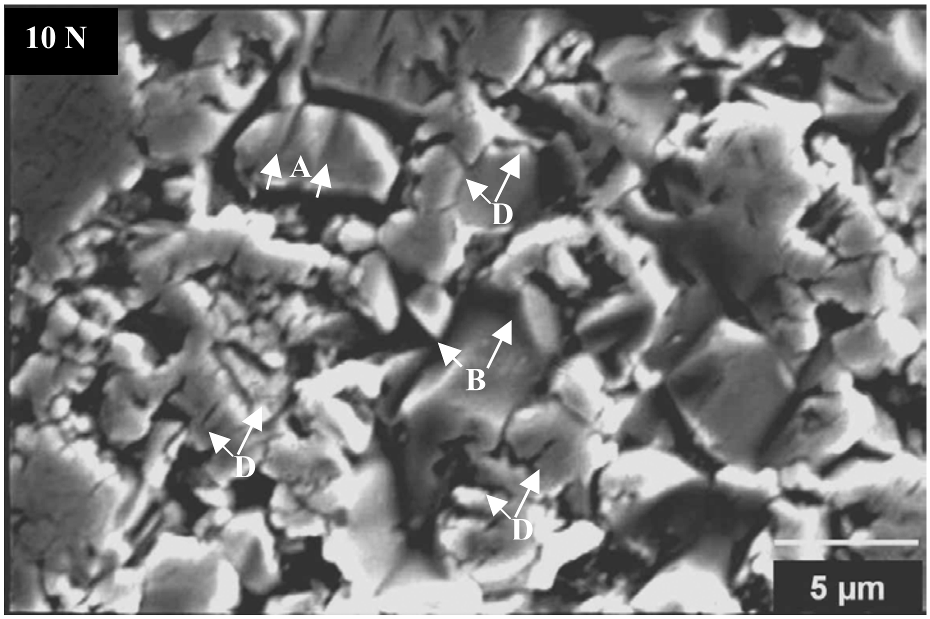


Figure 3. SEM micrograph of the wear scar of the ball at 10 N loads showing (A) Cleavage Steps (B) Faceted edges (D) Intergranular cracking.