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Solid particle erosion behaviour of high purity alumina ceramics

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Abstract

The solid particle erosion behaviour of a high purity, cold isostatically pressed ceramics, CIP-Al_2O_3, is studied in this paper. The influence of particle properties, such as hardness and shape, on erosion is examined, as well as the effect of varying the impingement angle of the erodent stream on the weight loss of alumina ceramics samples. Therefore, the erosive wear behaviour was studied at five different impact angles (30°, 45°, 60°, 75° and 90°), using SiC and SiO_2 particles as erodents.

The material loss during solid particle erosion is measured by changes in surface roughness, surface morphology and mass loss.

The surface roughness and topography of the eroded Al_2O_3 ceramics were recorded using a profilometer.

Scanning electron microscopy (SEM) was used to examine the features of eroded surfaces and to ascertain erosion mechanisms of the tested alumina samples.

The results indicate that hard, angular SiC particles cause more damage than softer, more rounded SiO_2 particles. It was found that maximum erosion by both types of particles occurs at an impact angle of 90°.

Key words : B. Electron microscopy; C. Wear resistance; Alumina ceramics; Solid particle erosion; Erosion mechanisms

1. Introduction

Alumina (Al_2O_3) ceramics is the most important technical oxide ceramic material and has the widest range of applications. Alumina (Al_2O_3) ceramics is characterized by high strength and hardness, low density, temperature stability, and high wear and corrosion resistance. These properties make ceramics useful in anti-wear applications, especially where metallic and polymeric components have proved to be inadequate. Among the engineering ceramics, alumina and alumina-based ceramics are probably the most commonly used materials in applications requiring wear resistance [1,2].

Wear is one of the most commonly encountered industrial problems, leading to frequent replacement of components [3].

Solid particle erosion can be defined as the degradation of material that results from repeated impacts of small solid particles. In some cases, it is a useful phenomenon, as in sandblasting and high-speed abrasive waterjet cutting, but it is a serious problem in many engineering systems, including steam and jet turbines, pipelines and valves carrying particulate matter, and fluidized bed combustion systems. Solid particle erosion can occur in a gaseous or a liquid medium containing solid particles. In both cases, particles can be accelerated or decelerated, and their directions of motion can be changed by the fluid [4].

The erosion occurring at impact angles between 0° and 30° is called abrasive erosion. On the other hand, if the impact angle is between 60° and 90°, the erosion is regarded as impact erosion [5].

Erosive wear occurs by plastic deformation and/or brittle fracture, depending on the material being eroded away and on operating parameters. Ductile materials will undergo wear by a process of plastic deformation in which the material is removed by the displacing or cutting action of the eroding particle. In a brittle material, on the other hand, the material will be removed by the formation and intersection of cracks that cause grain ejection from the surface of the tested material. The shape of abrasive particles affects the pattern of plastic deformation around each indentation and, consequently, the proportion of the material displaced from each impact. In the case of brittle

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materials, the degree and severity of cracking will be affected by the shape of abrasive particles. Compared with more rounded particles, sharper particles would lead to a more localized deformation and subsequently, to more localized wear [6].

The material removal during erosion depends on many interrelated factors that include properties and the structure of material, exposure conditions, and physical and chemical characteristics of erodent particles [7–18]. These factors are not independent and the system must be examined as a whole.

The erosion behaviour of brittle materials, such as alumina ceramics, cermets, has been previously studied and is found to be influenced by the properties of both erodent [7,9,14,15] and target materials [16–18].

The influence of SiC and SiO_2 particle properties as well as impact angles on the erosive wear of high purity alumina ceramics, is investigated in this paper.

2. Experimental

2.1. Characterization of alumina ceramics

The solid particle erosion experiments were performed on cold isostatically pressed CIP-Al_2O_3 with a purity of 99.8%, and the Archimedes density of 3.91 g/cm^3, supplied by Applied Ceramics, Inc., Fremont, CA, USA. The chemical composition of investigated alumina ceramics, according to the manufacturer's declaration, is given in Table 1. Al_2O_3 ceramics contains MgO as a sintering aid and the usual impurities, i.e. SiO_2, CaO, Na_2O and Fe_2O_3.

Alumina ceramic disks were sintered in a gas furnace at 1650 °C. After sintering, the disks were cut into rectangular 20 mm × 20 mm × 18 mm specimens, suitable for erosion testing. Prior to erosion testing, the flexural strength (σ_{fs}), flexural modulus (E_f), hardness (*HV1*), fracture toughness (K_{IC}) and grain size of alumina ceramics were determined. For the flexural strength (σ_{fs}) and flexural modulus (E_f), alumina ceramic disk was cut into 33 rods, each with a radius of 5 mm and a length of 50 mm. The flexural strength (σ_{fs}) and flexural modulus (E_f) were determined by the three-point bend test. Results of flexural strength (σ_{fs}) and flexural modulus (E_f) are presented in Table 2. In Vickers hardness method, a diamond indenter is applied to the surface of the specimen to be tested. Thirty Vickers impressions have been made throughout the surface of the sample, using load of 1 × 9.81 N (*HV1*) during 15 s. Cracks associated with Vickers hardness impression is used for the fracture toughness (K_{IC}) determination. Fracture toughness was determined using the indentation method developed by Anstis [19]. Results of hardness (*HV1*) and fracture toughness (K_{IC}) measurements are, as well, presented in Table 2. Prior to hardness measurements all specimens were prepared by the standard ceramographic technique [20].

Table 1
Chemical composition of the tested Al_2O_3 ceramics.

Sample	wt.%					
	MgO	Fe_2O_3	SiO_2	Na_2O	CaO	Al_2O_3
Alumina ceramics	0.066	0.015	0.02	0.05	0.013	Rest

Table 2
Results for the measured hardness (*HV1*), fracture toughness (K_{IC}) and flexural strength (σ_{fs}) and flexural modulus (E_f) of the Al_2O_3 ceramics.

Sample	E_f (GPa)	σ_{fs} (MPa)	*HV1*	K_{IC} (MPa m$^{1/2}$)
CIP-Al_2O_3	254.3 ± 18.9	306.9 ± 21.4	1800	2.69

Obtained results presented in Table 2 are in conformity with results in the literature data [20,21].

Microstructure of investigated alumina ceramics was observed by means of optical microscopy on the polished and thermally etched surfaces (Fig. 1). Average grain size of investigated alumina ceramics is 9.10 μm.

2.2. Erosion wear testing

Each surface of Al_2O_3 specimens was polished in order to have a smooth surface finish. After polishing specimens were thoroughly ultrasonically cleaned with alcohol and dried in a sterilizer at 150 ± 5 °C for 4 h. The specimens were then annealed at 1200 °C for 360 min in order to eliminate residual stresses that may have occurred during machining.

Erosion test was carried out using an erosion testing apparatus (Fig. 2) where samples were subjected to erosive wear of SiC and SiO_2 particles as erodents of an average grain size of about 350 μm and 600 μm.

Detail shown in Fig. 2 is a sample supporter within an erosion testing apparatus. When placed in supporters, and after a protective drum is in place, samples are span at about 1440 rpm through the seeping beam of erodent powder. Two samples are tested (eroded) simultaneously, colliding with particles within the beam at about 24.5 m/s. Used erodent powder is then taken away by means of gravity, and stored. No subsidiary medium nor pressure is used in this testing method.

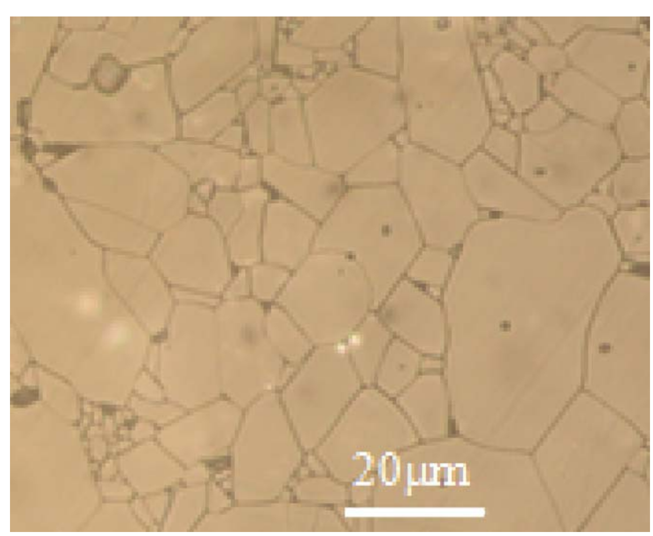

Fig. 1. Optical microscopy image of alumina ceramic microstructure after thermal etching.

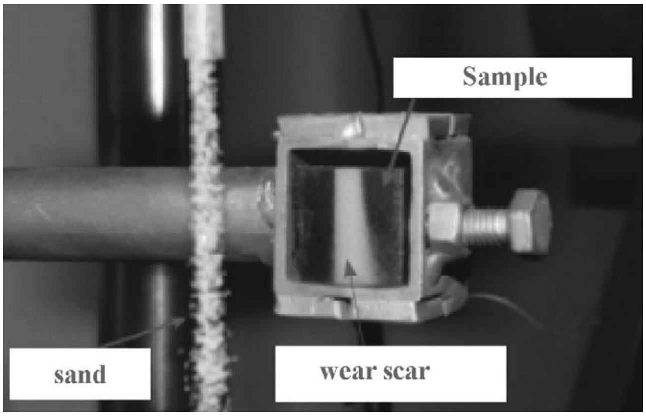

Fig. 2. Erosion testing with sand.

Table 3
Properties of erodent particles.

Erodent	Hardness (HV)	Density (kg/m^3)	Fracture toughness, K_{IC} (MPa m$^{1/2}$)
SiC	2800	3300	3.52
SiO_2	1150	2150	1.6

Each testing was timed to 13 min and 53 s (in order to achieve, roughly, 20,000 impacts per sample), and carried out at room temperature. For each of two abrasives (SiO_2 and SiC) and each impact angle test was repeated three times. Properties of abrasive particles are presented in Table 3 and SEM micrographs of used erodents are shown in Fig. 3. The SiO_2 particles were smooth, softer, more rounded while the SiC particles were sharp and angular, as seen from Fig. 3A and B.

Before and after the erosion experiments, cleaned and dried samples of alumina ceramics were weighed in an analytical balance to an accuracy of ±0.01 mg using an electronic balance. Amount of wear was determined by measuring weight loss of alumina samples. More detailed information was obtained by measuring parameters of roughness as well as by analyzing topography of eroded surfaces by SEM and profilometer. Therefore, before and after erosion, the roughness of each specimen was measured on three different tracing lanes by means of Perthometer S&P 4.5 (Feinprut Perthen GmbH, Goettingen, Deutschland). Also, the eroded surfaces were examined using scanning electron microscopy (SEM), TESCAN VEGA TS5136LS.

3. Results and discussion

Fig. 4 illustrates the erosion rates of alumina ceramics plotted against the angle of impact. The erosion rate is defined as the alumina mass loss: the difference between the specimen weights before and after the erosion experiments. Tests were repeated three times for each experimental condition.

Wear resistance, is not an intrinsic property of the material but it depends upon the set tribological system. Properties of materials tested, abrasive grit size, test conditions, equipment, and environment determine wear mechanisms [3]. In the literature on erosion, materials are broadly classified as ductile or brittle, based on the dependence of their erosion rate. Ductile materials, such as pure metals, have a maximum erosion rate at low angles of incidence (typically 15–30°), while for brittle materials, such as ceramics, the maximum is at or near 90° [4].

From results presented in Fig. 4 it is obvious that the erosion rates on alumina ceramic, for both erodents, increase with increasing impact angle, and thus maximum erosion rate occurs at 90° impact angle. Furthermore, alumina samples, at all impact angles, show higher rate of material loss when eroded by SiC particles (approximately by the factor of between 15 and 30). For SiO_2 and SiC particles, the erosion rates at 90° impact angle are approximately six and seven times greater,

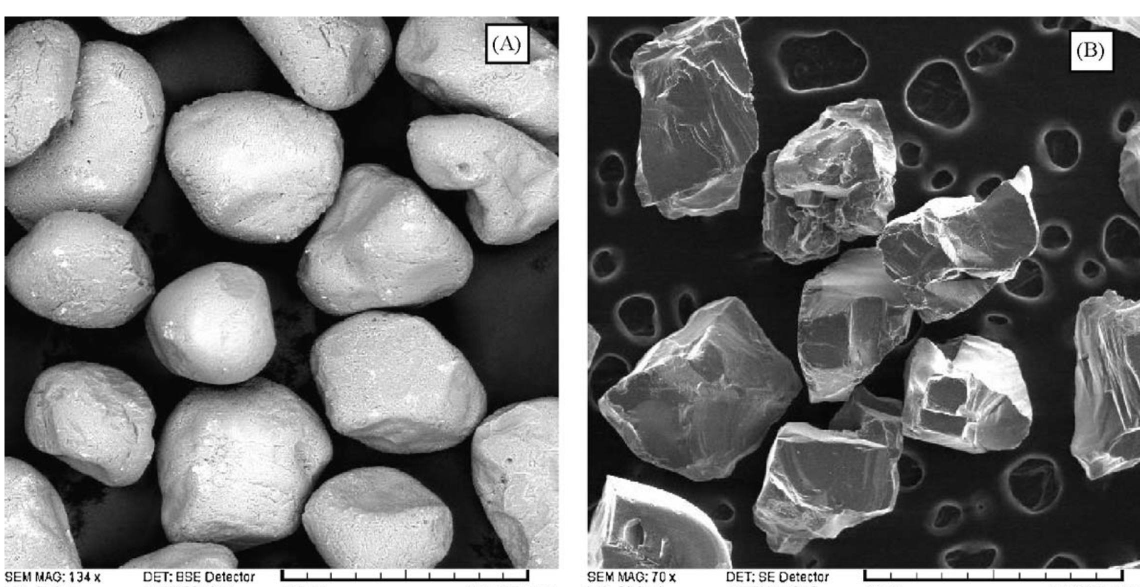

Fig. 3. SEM micrographs of erodent particles: (A) SiO_2 and (B) SiC.

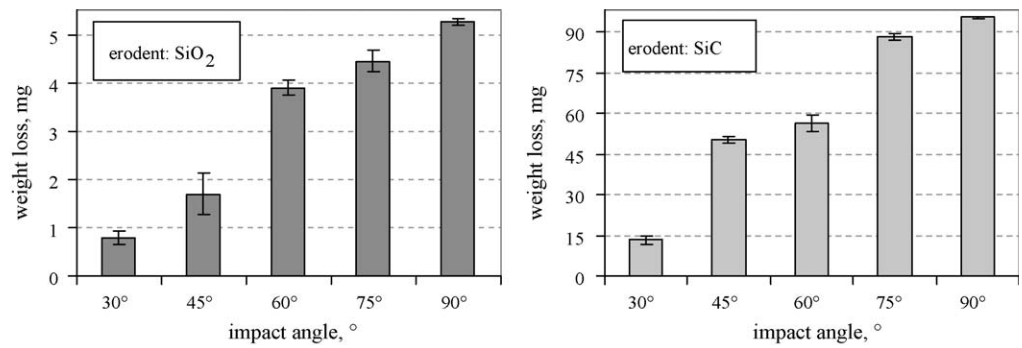

Fig. 4. Weight loss (mean value and standard deviation) for alumina ceramics after erosion tests with SiO_2 and SiC particles for different angles of impingement.

respectively, than those at 30° incidence angle. It means that erosion rate depends on properties of erodent and angle of impact. This observation is in correlation with previous research on alumina erosion mechanisms [23–25].

Surface morphology (topography and roughness) plays, or could play an important role in surface analysis after erosion by particles. Alongside weight loss, more detailed information can be obtained by measuring surface roughness after erosion.

Roughness (microroughness) parameters were measured before and after erosion with SiO_2 and SiC particles at 30° and 90° angles of impingement, respectively, using a profilometer. Based on obtained weight loss results, selected and presented values of roughness parameters correlate with minimum erosion rate (impact angle of 30°) and maximum erosion rate (impact angle of 90°). Three main roughness parameters were obtained from this test: *Ra* – the roughness average, *Rz* – the 10 point average of the profile and *Rmax* – the maximum between peak and valley. Value changes of the main roughness parameters (*Ra*, *Rz* and *Rmax*), in dependence of angle of impact and erodent type, are shown in Fig. 5.

Both diagrams in Fig. 5 show similar trend of changes in roughness, but one difference is obvious; samples eroded with SiO_2 at impingement angle of 30° show less roughness in comparison to starting (non-eroded) condition – as opposed to samples eroded with SiC under the same impingement angle. These point to the significance of taking the erodent particles characteristics (geometry and/or hardness) into consideration, when practical application takes place. These morphological differences of surfaces eroded with different erodent powders at the same impingement angle, become more evident if Fig. 6B and D compared. It is clear that finer SiO_2 particles had polished alumina surface to a lesser roughness (smooth, white ridges), due to plastic smearing with almost no ploughing.

Surfaces eroded with SiC particles are significantly rougher than those eroded with SiO_2 particles. In particle erosion testing, SiC and SiO_2 erodent particles of comparable particle size distribution, moving at the same velocity, was used. The major differences were in the hardness of the particles and their angularity. The SiC particles have hardness number 2.4 times higher than SiO_2 particles (Table 2) and are sharp and angular (Fig. 3A and B). SEM examination showed that harder, more angular SiC particles caused much more damage. It is established that in bulk brittle materials such as ceramics, the ratio of the particle hardness to the target-ceramic hardness (Hp/Ht) has influence on the erosion mechanisms [9,22]. When the ratio of Hp/Ht is >1, the wear mechanism essentially involves indentation-induced fracture. For lower ratios, such cracking is suppressed and the material removal occurs by less severe microchipping mechanisms. In the case of erosion studied of alumina ceramics (target-t) with SiC erodents (particles-p), the Hp/Ht ratio for this material is 1.6, with SiO_2 particles, the ratio drops to 0.6. The erosion rate is an order of magnitude higher in the former case.

In order to examine the erosion mechanism and damages, the top-view of the eroded surfaces of the samples structure was observed by SEM.

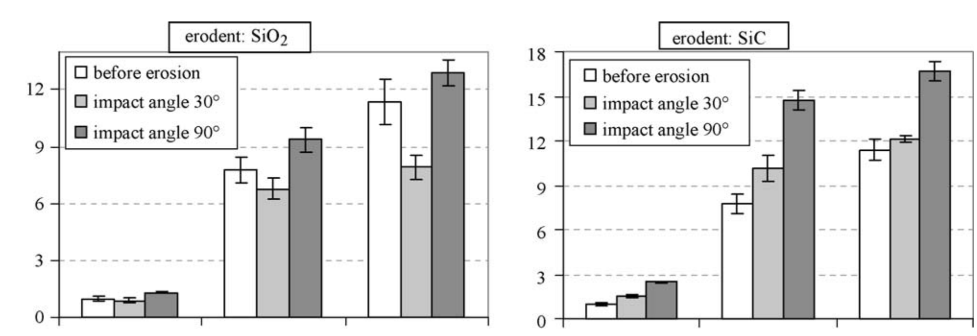

Fig. 5. Values of roughness parameters (mean value and standard deviation) of alumina ceramics before and after erosion by SiO_2 and SiC particles at 30° and 90° angles of impingement, respectively.

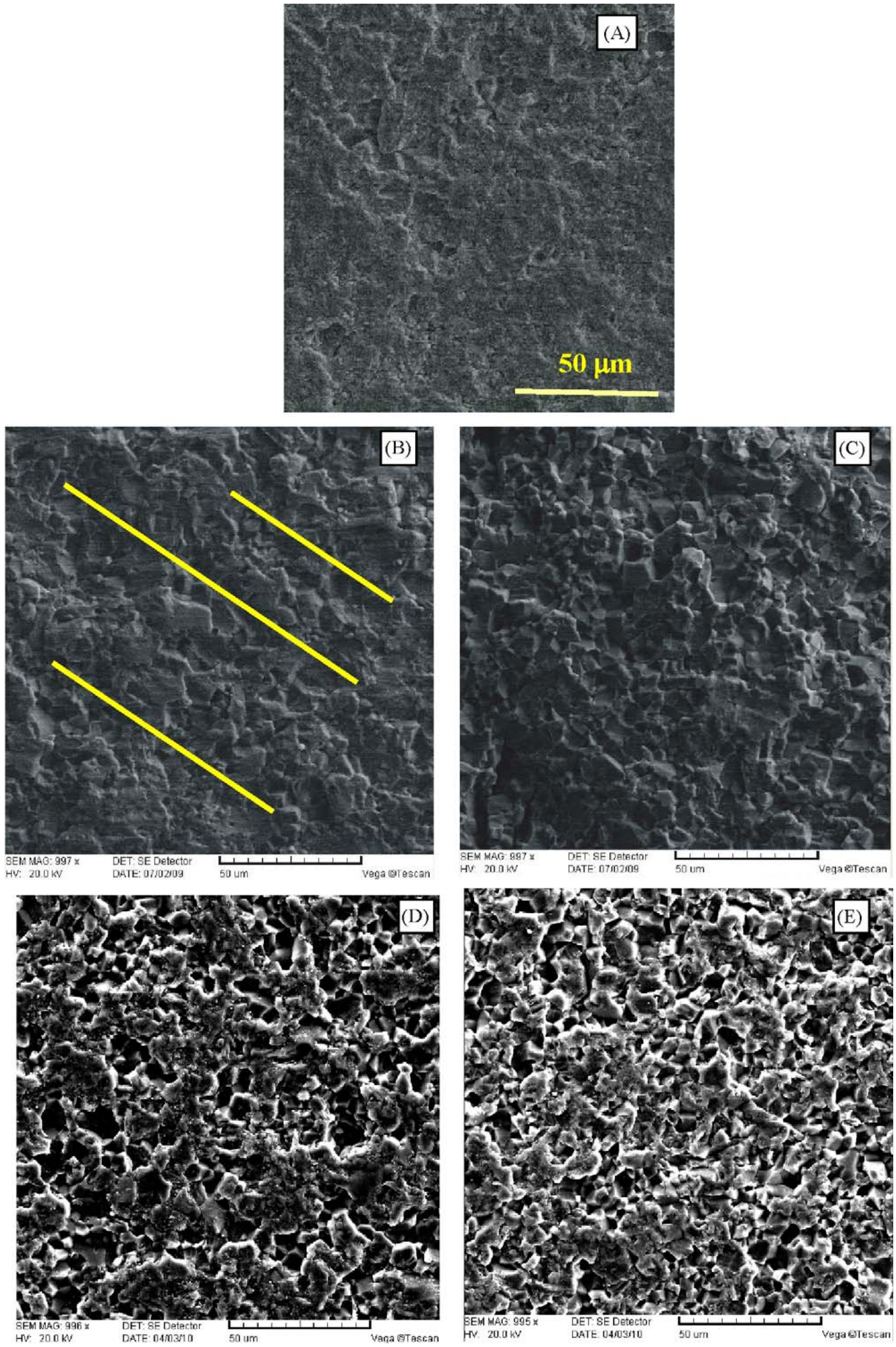

Fig. 6. SEM micrographs of surfaces of Al_2O_3 ceramics (A) before erosion; after erosion by SiC particles at (B) 30° angle of impingement and (C) 90° angle of impingement; after erosion by SiO_2 particles at (D) 30° angle of impingement and (E) 90° angle of impingement.

A comparison between the eroded surfaces of alumina ceramics after SiC particle erosion at 30° and 90° impact angles, shows two (earlier mentioned) different methods of material removal. In the case of impact angles close to 90°, the dominant material removal mechanism was grain ejection and low (but existing) plastic deformation, while in the case of acute impact angles, kinetic energy of the impinging particles contributes mainly to the ploughing mechanism. The ploughing mechanism is associated with the plastic smearing and cutting of the surface material. Ceramics is not easily plastically deformed because of their high hardness. Therefore the material removal rate is low at acute impact angles.

At impact angles close to 90°, the material removal rate is high. Ceramics has low fracture toughness, and therefore cracks readily propagate to form a crack network propagating across the grain boundaries. The subsequent impacts will easily

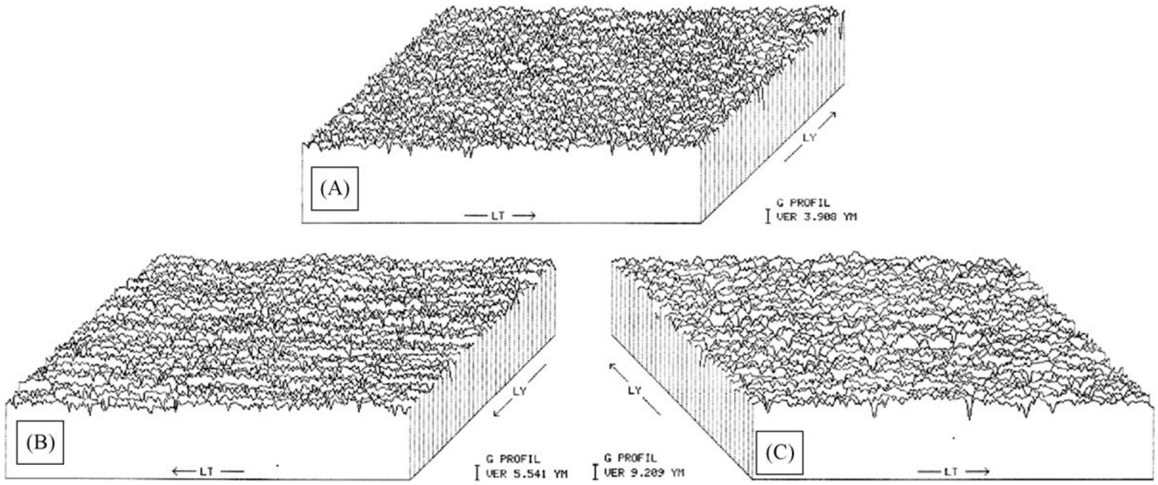

Fig. 7. Surface topographies of surface of Al_2O_3 ceramics (A) before erosion, after erosion by SiO_2 particles at (B) 30° angle of impingement and (C) 90° angle of impingement.

remove the surface material via the ejection of the upper layer grains.

The wear tracks shown in Fig. 6B are the result of the ploughing of the erodent particles on the sample surface. The damage patterns observed in the wear tracks are mainly grain dislodgment and some isolated plastically deformed regions.

Again, Fig. 7 confirms earlier stated explanations of erosion mechanisms, but in this case through recorded topography of surfaces in question. Whereas Fig. 7C shows perceptible areal disorder and roughness, in Fig. 7B grooves stretching across the surface are evident.

4. Conclusions

Erodent particles of different materials can cause different erosion rates and mechanisms. Based on the solid particle erosion studies of alumina ceramics, the following conclusions have been drawn:

- The erosive wear performance of alumina ceramics is dependent on the impingement angle. The general observation is that erosion rate increases with the increase in the impact angle. It was found that maximum erosion by both particles takes place at impact angle of 90°.
- Alumina ceramics shows a significantly higher erosion rate when eroded with SiC than with silica particles. This may be explained by the influence of particles shape and hardness of particles compared to the test material as target.
- It is shown that angular and harder SiC particles cause more damage than more rounded and softer SiO_2 particles.
- Eroded surface morphology is mostly dependent on the size and shape of eroding particles. Alumina surfaces eroded with SiO_2 at impingement angle of 30° show less roughness in comparison to starting (non-eroded) condition – as opposed to samples eroded with SiC under the same impingement angle. It is clear that finer SiO_2 particles had polished alumina surface to a lesser roughness (smooth, white ridges), due to plastic smearing with almost no ploughing.
- The SEM studies of worn surfaces have revealed wear mechanism as such.

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