THE EFFECT OF SURFACE FINISH AND CAVITATING LIQUID ON THE CAVITATION EROSION OF ALUMINA AND SILICON CARBIDE CERAMICS

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The cavitation erosion of alumina (F 99.7, Friatec) and sintered silicon carbide (SSiC, EKasic F) with different surface finish was investigated at 25°C for up to 6h in distilled water as a cavitating liquid according to ASTM G32-92. The wear progress was followed by measuring the cumulative mass and volume losses. The eroded surfaces were examined for their damaged microstructure using SEM. The wear resistance of the tested ceramics, in terms of the incubation time and mass and volume losses, was improved when decreasing surface roughness. SSiC showed higher wear resistance in comparison with alumina. The results were discussed in terms of the hardness, fracture toughness, grain size, surface roughness and microstructure. In addition, the influence of oils as cavitating liquids on the erosion of tested ceramics was studied. The results indicated that water is highly erosive medium when compared with the used oils as a result of higher water vapour pressure, lower viscosity and higher density.

INTRODUCTION

Mechanical erosion of a solid material caused by cavitation is called cavitation erosion. Damage due to cavitation erosion can be found in high-speed impellers, valves, pump casings and water turbines [1-3]. Cavitation can damage and erode solid materials by the following mechanisms: generation of shock waves due to symmetric bubble implosion and formation of microjets due non-symmetric bubble implosion [4, 5]. When a cavity collapses within the body of liquid, the collapse is symmetrical. When a cavity is in contact with or very close to the solid boundary, the collapse is asymmetrical. In asymmetrical collapse the cavity is perturbed from the side away from the solid boundary and finally the fluid penetrates through the cavity and a micro-jet is formed. The microjets induce local material stress from hundred to over 1000 MPa [6]. Cavitation erosion of materials involves many factors, such as the mechanical properties of material to be tested (hardness, fracture toughness, etc.), the fluid properties (density, compressibility, gas content, vapour pressure, viscosity and surface tension) [7-9], and the flow field characterstics (geometry of the flow path, pressure distribution in the system, etc). Different factors were identified which control solid particle impact erosion behaviour: (1) particle size; (2) particle shape; (3) particle density; (4) particle hardness; (5) kinetic energy of particles; (6) particle speed; (7) impingement angle; (8) temperature; (9) target hardness; (10) target fracture toughness [7, 10-13]. Up to the present moment, the wear resistance of materials can only be determined quantitively based on parameters such as cumulative mass loss, cumulative volume loss, cumulative mean depth of erosion [14].

Damage due to cavitation may be reduced by either altering the hydrodynamic profile or by using a material that is more resistant to erosion [6,7]. Ceramics have a high hardness and excellent wear resistance, and they are considered to be prime candidates for applications which require a high resistance to cavitation erosion [11-13]. However, information on the cavitation erosion of ceramics engineering is limited. Accordingly, the objective of the present work is to investigate the effect of surface finish and different cavitating liquids on cavitation erosion of alumina and silicon carbide ceramics.

EXPERIMENTAL

The cavitation erosion of sintered silicon carbide (SSiC, EKasic F) and Al$_2$O$_3$ (F99.7; Fa. Friatec) ceramics having different surface finish were studied. The physical and mechanical properties of the invesitgated ceramics are listed in Table 1. The surface finish of the specimens was made firstly by rough grinding with 91 and 46 μm grain size of the grinding wheels, then by fine grinding with grinding wheels of 25 and 15 μm grain size. Surface roughness of the grinded specimens was measured using Hommel T 8000 (Produced by

Hommelwerke) and white-light profilometer (Micro-Prof; produced by FRT GmbH). The surface roughness is usually evaluated using statistic parameters, such as the arithmetic surface roughness (R_a), the reduced peak height (R_{pk}), The core roughness depth (R_k) and the reduced valley depth (R_{vk}). For ceramic materials, R_a alone does not provide necessary amount of information due to the large amount of surface cavities (pores and grain pull-out). Figure 1a,b represents the surface roughness of alumina and silicon carbide with different surface finish in terms of the measured statistical parameters. In general, the surface quality of the tested grinded ceramics increases with fine grinding.

Cavitation erosion resistance was measured by means of a piezoelectric vibratory apparatus in accordance with ASTM standards G32-92 [15]. The test specimen, in the form of plate with dimensions of 8×25×50 mm, was screwed to the free end of an ampli-fying piezoelectric vibrating horn. The test parameters are given in Table 2. During half of each vibration cycle, a low pressure was applied to the test specimen surface, producing cavitation bubbles. During the second half of the cycle, bubbles collapse at the specimen surface producing damage and erosion of the specimen. The cavitating liquids were presented by distilled water and two types of hydraulic oils which are FVA oil Nr.1 and FVA oil Nr.3. The chemical and physical properties of the used liquids are given in Table 3.

The cavitation test was interrupted at different intervals of time, at which the specimens were cleaned in an ultrasonic bath using isopropanol for 15 minutes, dried in an oven for 90 minutes at 125°C, cooled to the room temperature overnight in desiccator, and then weighed using a precision balance with a sensitivity of 10-5 g. The total duration of the cavitation test was 360 minutes. The mass loss results were obtained as an average of three tests. Volume loss of the eroded specimens was measured at each stage using white-light profilometer. The eroded surfaces were investigated using a scanning electron microscopy (SEM).

Table 1. Physical and mechanical properties of the investigated ceramics.

Ceramics Properties)	Al_2O_3 (F 99.7) Friatec	SSiC Ekasic F
Apparent density, ρ (g/cm³)	3.90-3.95	3.17
Mean grain size, d (µm)	7.5	1.9
Open porosity, (%)	2.3	1.0-2.2
Young's modulus, E (GPa)	385	410
Vickers hardness, HV	1670	2540
Fracture toughness, (MPa)	3.7	3.5

Table 2. Test parameters.

|	
Frequency of the ultrasonic transducer	20 ± 0.5 kHz
Peak-to-peak amplitude	50 µm ± 5 %
Depth of the specimen in liquid	12 ± 4 mm
Distance between the horn tip and the specimen surface	0.5 mm
Horn diameter	16 mm
Operating temperature	25 ± 2

RESULTS AND DISCUSSION

The effect of surface finish

The cavitation erosion progress is classified into an incubation stage, an acceleration stage, and a maximum rate stage [16, 17]. In the incubation stage, surface deformation takes place through the formation of cracks without significant mass loss. After an incubation time, the mass loss commences and proceeds at increasing rate with time of erosion. This is termed the acceleration stage which is attributed to surface hardening and crack development. The mass loss rate accelerates to a terminal value, referred to as maximum rate stage. Generally, ceramics under cavitation erosion exhibit damage by microfracture.

Table 3. Chemical and physical properties of cavitating liquids.

| Liquids Properties)	Distilled water	FVA Oil Nr. 1	FVA Oil Nr. 3
Main constituents	H_2O	Aromatic 5 % Paraffinic 62 % Naphthenic 33 %	Aromatic 4.5 % Paraffinic 64.5 % Naphthenic 31 %
Dynamic viscosity η (20°C), (mPas)	1.002	32.060	295,100
Density ρ (20°C), (kg/m³)	998	855	877
Boiling point TS, (°C)	99.63	---	---
Flash point TF, (°C)	---	200	250
Surface tension γ (20°C), (mN/m)	72	---	---
Vapour pressure, (bar)	0.023	---	---

The microstructure and surface roughness of a material have a prominent influence on its cavitation erosion of ceramics [13,18,19]. Comparing the microstructure of a polished surface of the alumina and silicon carbide (Figure 2), it can be concluded that the microstructure of alumina consists of coarse grains of corundum (~8 μm) bonded by a glassy grain-boundary phase with large pores, whereas the microstructure of silicon carbide is a fine grains (~2 μm) and exhibits a smaller pore size. Figures 3 and 4 reveal that the surface quality of alumina and silicon carbide was improved

by finer grinding. These results are in agreement with the measurment of surface roughness parameters (Figure 1).

Figure 5a,b show the cumulative mass loss (Δm) of the tested alumina and silicon carbide ceramics with different surface finish as a function of the cavitation time. Firstly, there is a nominal incubation time, which is defined as the intercept of the maximum erosion rate on the time axis of the mass loss/time graph. In the erosion stage, mass loss increases quite linearly for both alumina and silicon carbide. It has been reported [20-22] that the diameter of the most frequently removed particles becomes larger in the erosion stage than in the incubation stage. They attributed such behaviour to the removal of many small sharply edged particles in the incubation stage under the action of single impact load, whereas during the latter stage, large striated particles were removed due to cyclic loads. The figures also show that while the nominal incubation time increases with decreasing surface roughness, the mass loss decreases with decreasing surface roughness for both of alumina and silicon carbide. Similar results
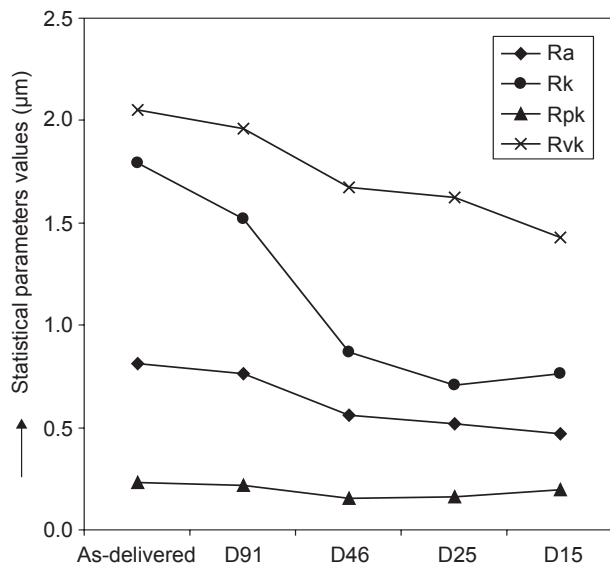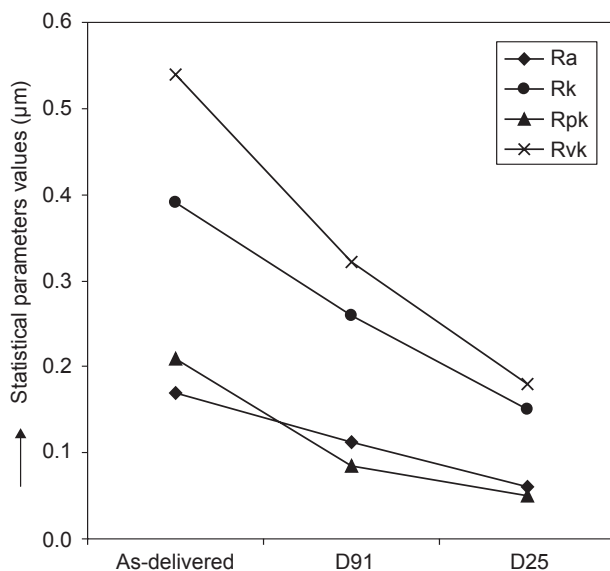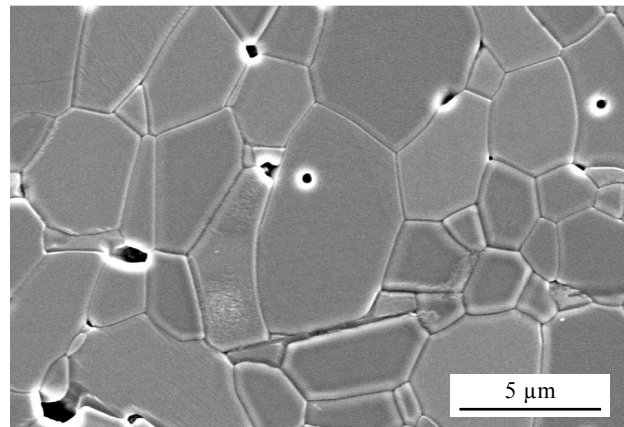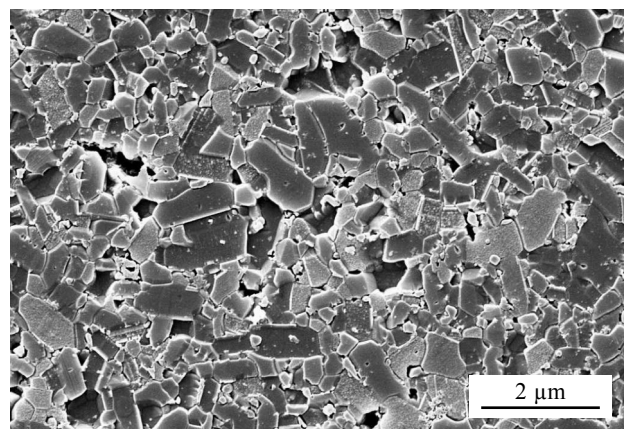

Alumina

Silicon carbide

Figure 1. Surface roughness of: a) alumina and b) silicon carbide with different surface finish in terms of statistical parameters.

Figure 2. SEM micrographs of the microstructure of a polished surface of alumina and silicon carbide.
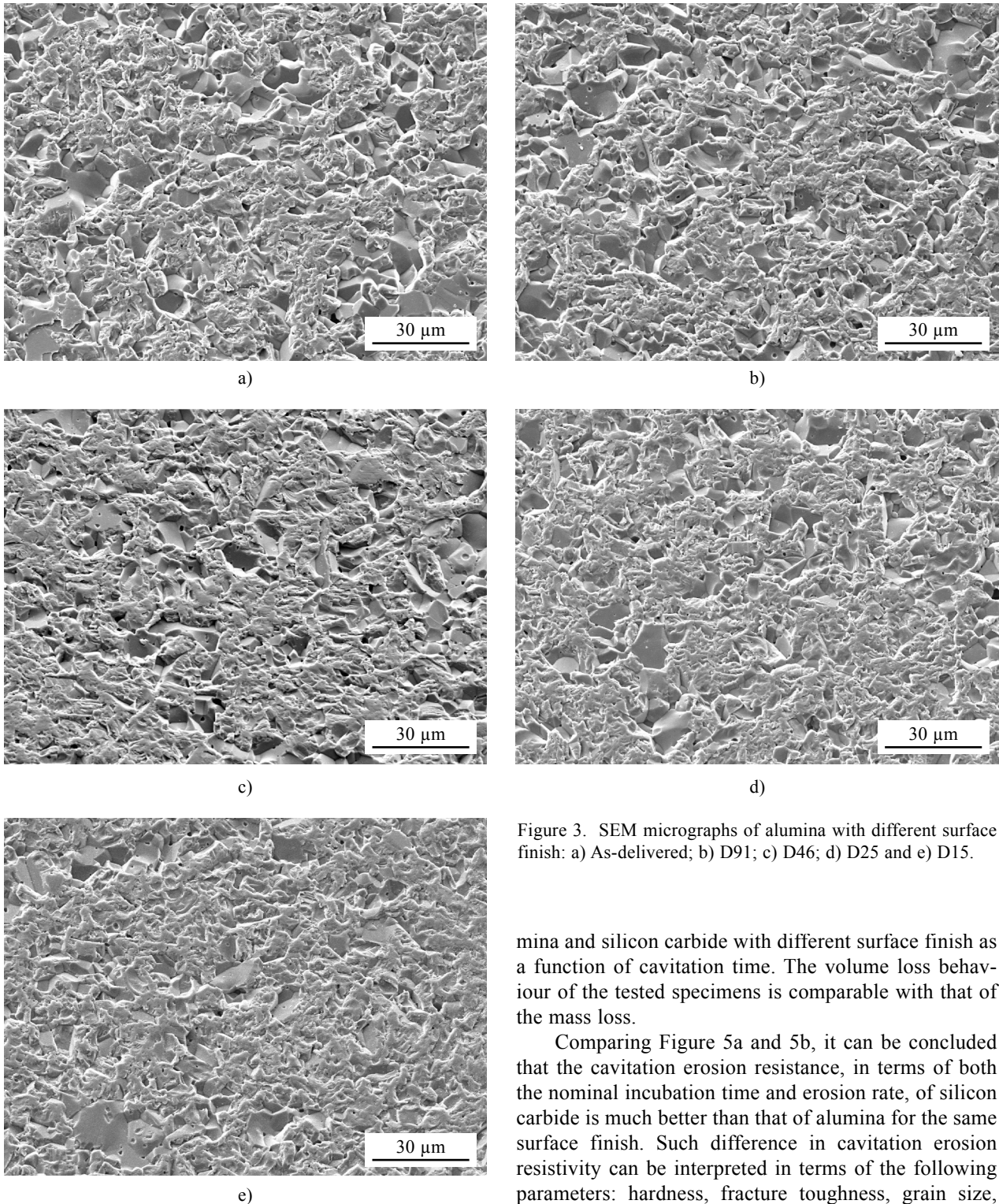
a)

b)

c)

d)

e)

Figure 3. SEM micrographs of alumina with different surface finish: a) As-delivered; b) D91; c) D46; d) D25 and e) D15.

were reported [13, 20-22] concerning the influence of surface finish as one of the factors which prolongs the incubation time. Surface roughness introduce surface defects that favour cavitation by creating stress inhomogenities [23]. Figures 6a,b represents the volume loss, determined by means of light profilometry, of alu-

mina and silicon carbide with different surface finish as a function of cavitation time. The volume loss behaviour of the tested specimens is comparable with that of the mass loss.

Comparing Figure 5a and 5b, it can be concluded that the cavitation erosion resistance, in terms of both the nominal incubation time and erosion rate, of silicon carbide is much better than that of alumina for the same surface finish. Such difference in cavitation erosion resistivity can be interpreted in terms of the following parameters: hardness, fracture toughness, grain size, surface roughness, and microstructure. The hardness of the surface has a strong effect on the erosion resistance of the material. The harder the material, the smaller the erosion rate. Silicon carbide is harder than alumina (~1.5 times). The dominant type of fracture depends on the toughness difference between the grains and the grain boundary phases. The grain boundaries always act as stress-concentrators, and hence fracture tends to
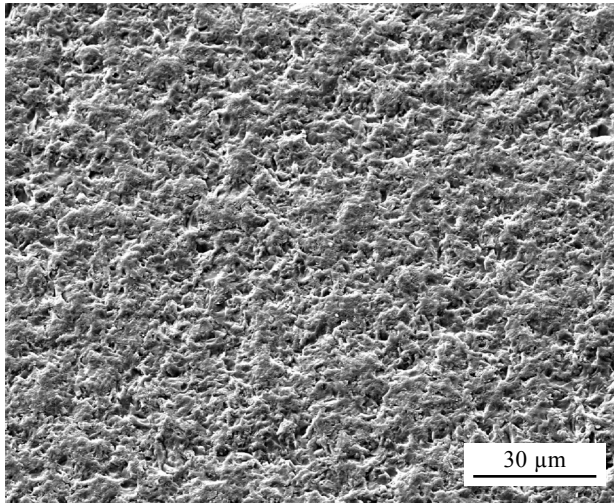
a)
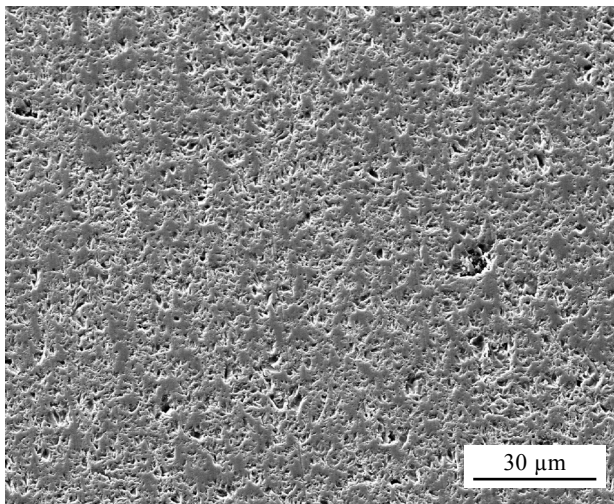
b)
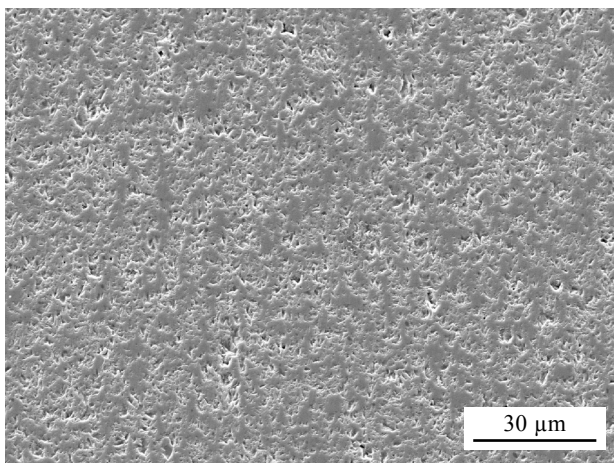
c)

Figure 4. SEM micrographs of silicon carbide with different surface roughness: a) As-delivered; b) D91 and c) D25.

occur near the boundaries in the often weaker brittle phases. They generally act as a source for the nucleation of pits and hence as the basic mechanism of dislodging. This is the case of alumina, which intially has a high amount of large pores as well as a glassy (highly brittle) grain boundary phase. The SEM observations (Figure 7a,b) indicated that the cavitating bubbles appear to attack preferentially the grain boundaries and pores either by direct impingement and erosion or by shock wave reflection on the grain boundaries resulting in inter-granular fracture. Tomlinson et al [2] and Dulias and Zum Gahr [13] found that, in pure alumina ceramics, material started to be lost at grain boundaries associated with pores, thereafter material was lost by inter-granular fracture and the removal of the whole grains.
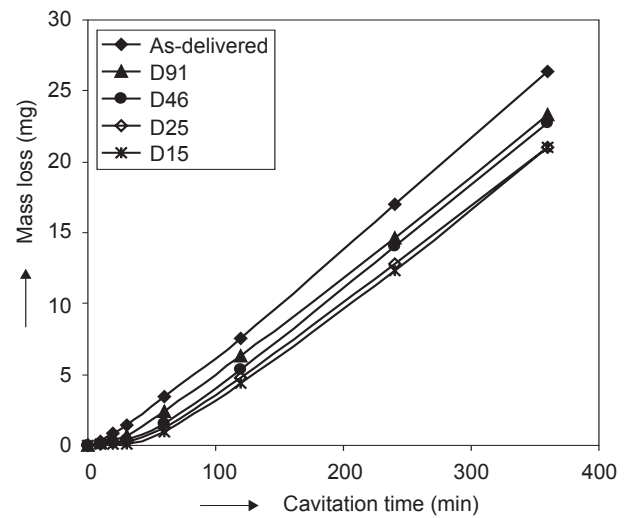
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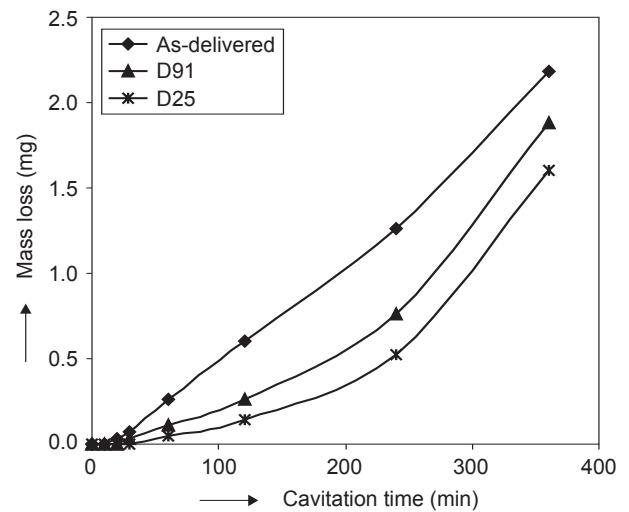
b)

Figure 5. Mass loss as a function of cavitation time for: a) alumina and b) silicon carbide with different surface finish eroded in distilled water.
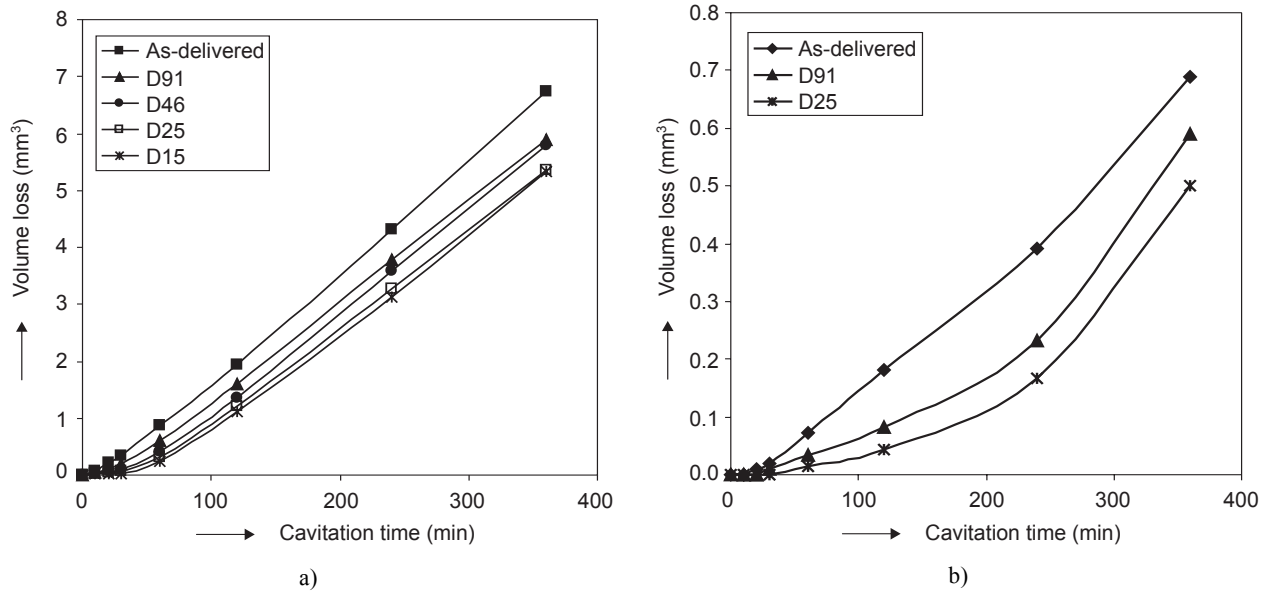
Figure 6. Volume loss as a function of cavitation time for: a) alumina and b) silicon carbide with different surface finish eroded in distilled water.
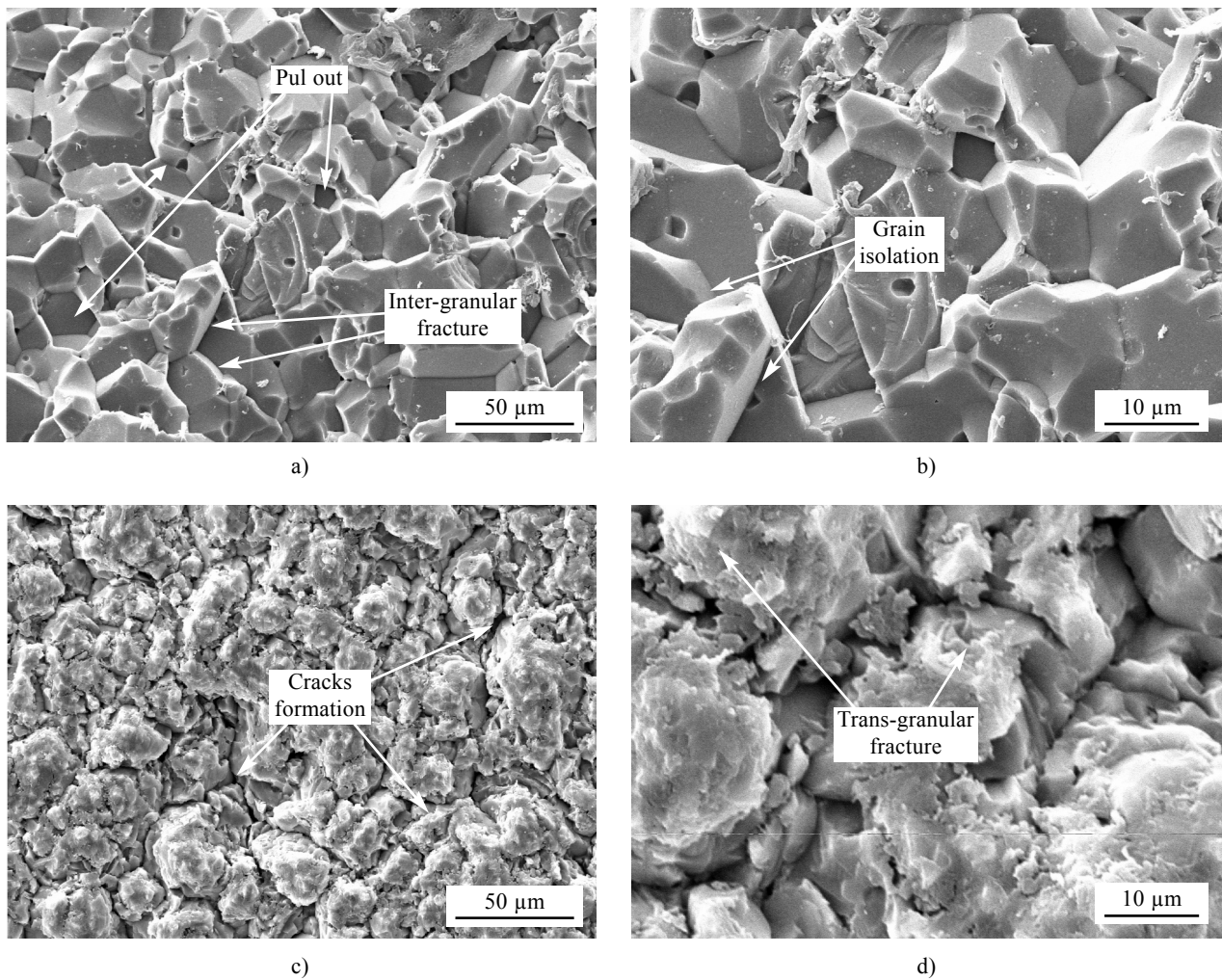

Figure 7. SEM micrographs of: a) + b) alumina and c) + d) SSiC after cavitation erosion for 6 h in distilled water.

In the case of alumina, material started to be lost from the glass at the glass/alumina interface, thereafter material was lost mainly through the fracture in the inter-granular glass with occasional trans-granular fracture in the alumina grains. Pohl [24] concluded that in polycrystalline materials, even a low grain boundary surface density can provide a dominant action cavitation erosion. Absence of the glassy phase in the grain boundaries of silicon carbide as well as the small pore size is responsible for its large extent of the trans-granular fracture (Figure 7c,d). Trans-granular fracture results in some parts of the grains are being worn out and consequently slower erosion. In adition, deep cracks separating one group of grains from another group were observed (Figure 7c). With respect to the effect of the grain size on the cavitation erosion, it has been found [2, 13] that the linear erosion rate of different aluminas is directly proportional to the grain size and inversely proportional to the fracture energy of the interface. The influence of fine granular microstructure of the material on the elongation of the incubation period was investigated [12, 19, 25]. Small grain size and high material density prolongs the incubation period, since the grain boundaries act as obstacles for crack propagation. Such results agreed with the results of the mass loss and the incubation time in Figures 5 and 6 . The surface roughness is known to play an important role in controlling erosion and material removal [13, 26, 27]. Figure 1 showed that silicon carbide has higher R_k value (core depth) compared with alumina for the same surface finish. This was caused by the high amount of pores and grain pull-out in alumina. Smooth surfaces have less defects and consequently exhibit better resistance to cavitation erosion.

The effect of the cavitating liquid

Figure 8 shows the effect of different cavitating liquids on the cavitation erosion of a grinded surface of alumina and silicon carbide, respectively, with 25 μm grain size of the grinding wheel. The variation of mass loss with time, for alumina and silicon carbide eroded in oil Nr.1 and oil Nr. 3 , resulted in a similar plots. After an incubation period a relatively rapid mass loss rate occurred followed by steady state of mass loss. On the other hand, the mass loss curves using water as a cavitating liquid show an incubation period followed by an acceleration period.

It is evident from Figure 8 that there is a consistency of variations between the viscosity and the relative mass loss. That is, the viscosity decrease form oil Nr. 3 to oil Nr. 1 to water (Table 3), while the relative mass loss increase fom oil Nr. 3 to oil Nr.1 to water. Under cavitation conditions water is one of the worst actors regarding equipment damage due to cavitation. Water is hard on equipment in cavitation conditions for at least two reasons: relatively high density (small molecular size and heavy molecular weight), and a sharp well defined phase change behavior. The combination of small heavy molecules and high cavity wall implosion velocities, resulting from the sharp and fast rate of phase change, leads to an extreme inertial energies as the walls of the cavity strike against each other during the implosion. Moreover, liquids with molecules larger and more complex than water, and non-homogenous liquids such as petrochemicals, are less harmful to equipment in cavitation conditions because they often have a lower density than water, their larger more complex molecular structure and sometimes non-homoge-
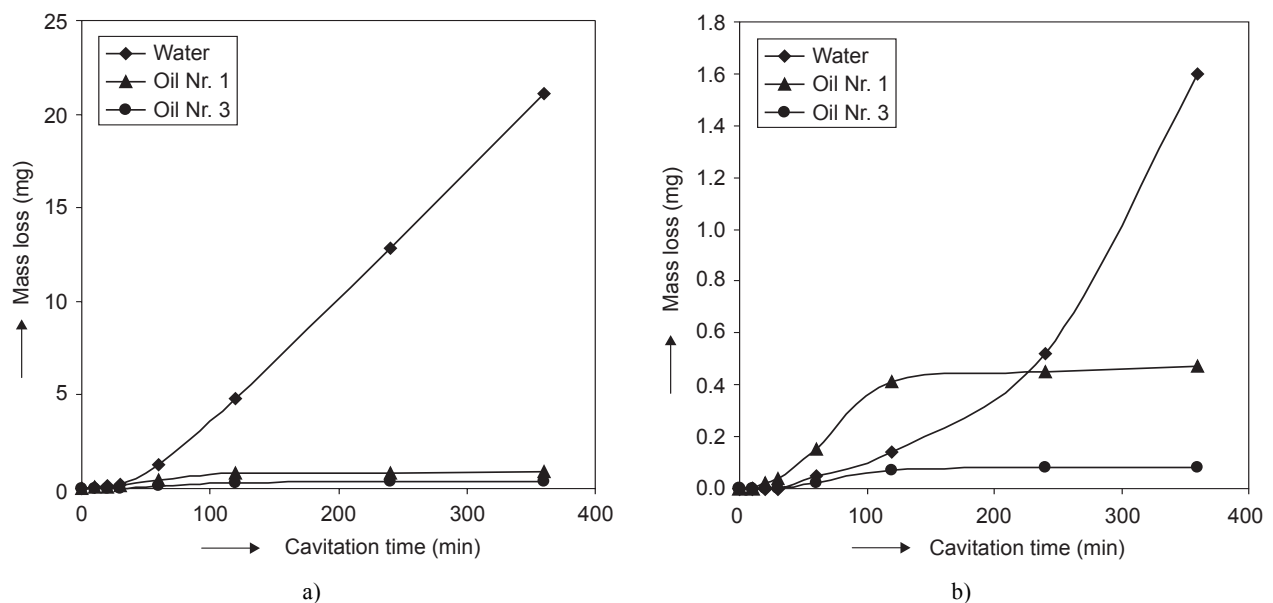

Figure 8. Mass loss as a function of cavitation time for: a) alumina and b) silicon carbide eroded in different cavitating liquids.

nous nature causes a "blurred" or less well defined phase change behavior, both of which reduce the rate of cavity creation and collapse, and therefore the amount of damage caused by cavitation is reduced when cavitation does occur. In addition, since cavitation remains from implosion of gas bubbles in the fluid, its vapour pressure is an important initiator for cavitation. Rydberg [28] found the as a temperature of 50°C the vapour pressure for water is about 0.12 bar and for mineral oil is considerably lower, approximately 1.0×10^{-8} bar. In other words, the risk for cavitation is much higher in water than in oil. Also, he concluded that the amount of air in the fluid will create different stages for the initiation of cavitation. In mineral oil, cavitation is mainly due to vaporisation of the dissolved air (gas cavitation), whereas cavitation observed in water mainly comes from boiling of water itself (vapour cavitation). The reason is that the air solubility is about five times higher for mineral oil (about 10 % volume at atmospheric pressure) than for water.

As can be seen in Figure 8, the formed cavitation depends on the type of oil. The figures revealed that oil Nr.3 has significantly lower cavitation erosion compared to oil Nr. 1. This results may be attributed to the difference in viscosity, since the used oils of nearly chemical composition (Table 3). Theoretically, the higher the viscosity, the lower the effect of cavitation. The increase in viscosity led to a decrease in the rate of growth and collapse of bubbles and hence reduced erosion on the surface of the specimens [3]. A numerical solution [29] for an incompressible viscous liquid showed a decrease in bubble wall velocity for an

increase in viscosity. In addition, the difference in the density of the used oils may be had a role. The results of the volume loss (Figure 9) confirmed the obtained results of the mass loss. SEM observation (Figure 10) indicated that the surfaces of alumina and silicon carbide are much more eroded in distilled water as compared with the oils. It is obviously that some areas still preserve their original surface after cavitation using oil Nr. 1 and oil Nr.3.

CONCLUSIONS

The cavitation erosion of alumina (F 99.7, Fa. Friatec) and sintered silicon carbide (SSiC, Ekasic F) ceramics having different surface finish in distilled water was investigated. The used ceramics showed an incubation stage followed by an erosion stage. The nominal incubation time increased with decreasing surface roughness, since surface roughness introduces surface defects that favour cavitation. For the same surface finish, SSiC showed higher erosion resistance as compared with alumina due to its higher hardness, higher fracture toughness, lower surface roughness, and finer granular microstructure. In addition, two types of oils were used as cavitating liquids. The results indicated that water is the worst cavitating liquid, in comparison with the tested oils, as a result of its small molecular size and heavy molecular weight, high vapour pressure, low viscosity and air solubility. The eroded surfaces were investigated using SEM.
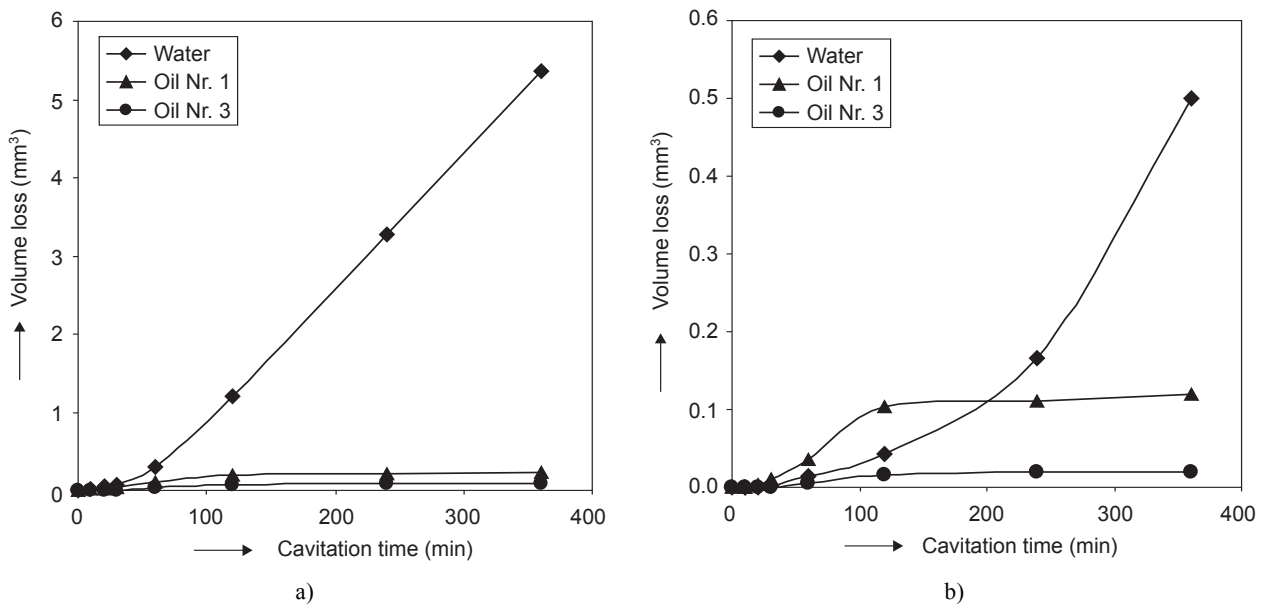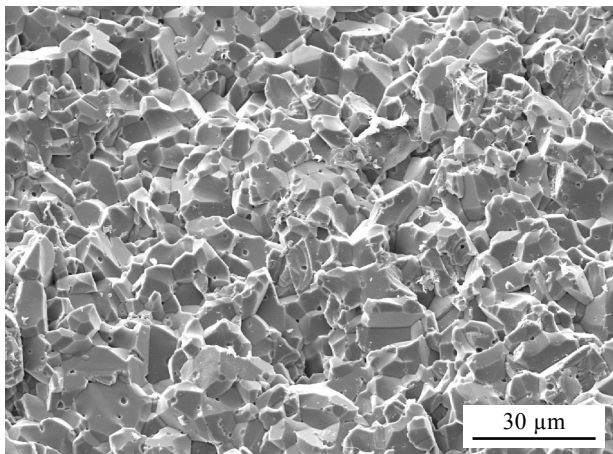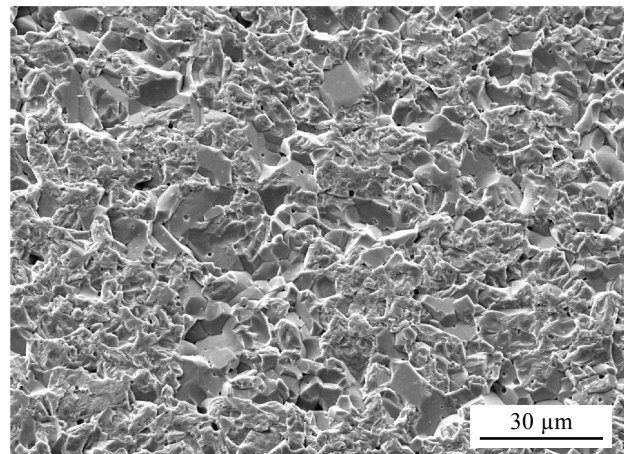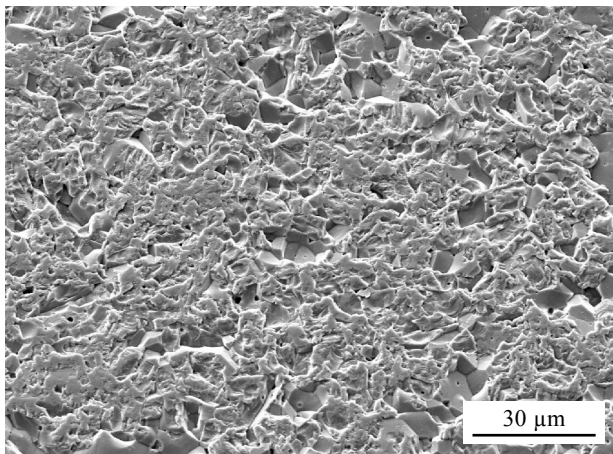

Figure 9. Volume loss as a function of cavitation time for: a) alumina and b) silicon carbide eroded in different cavitating liquids.
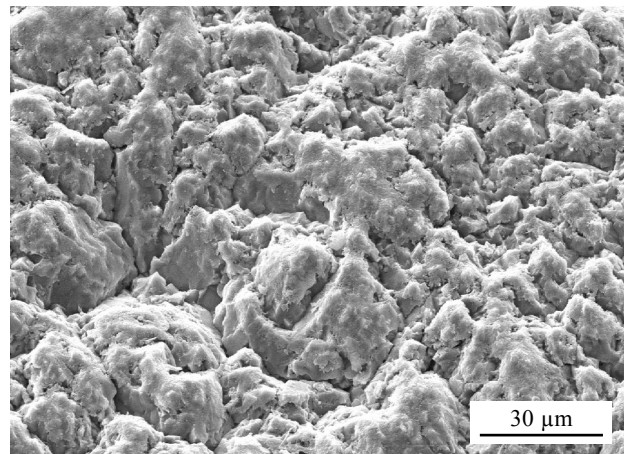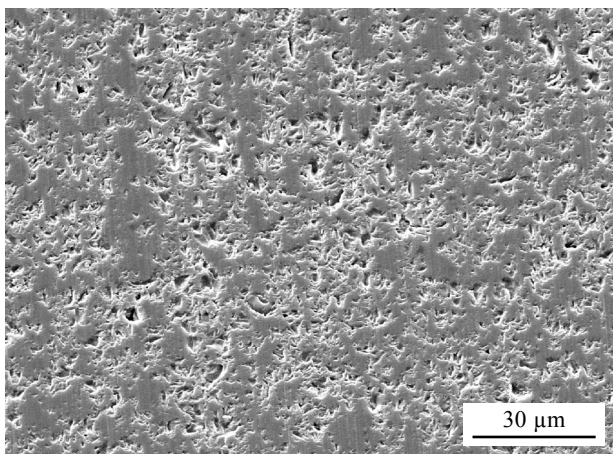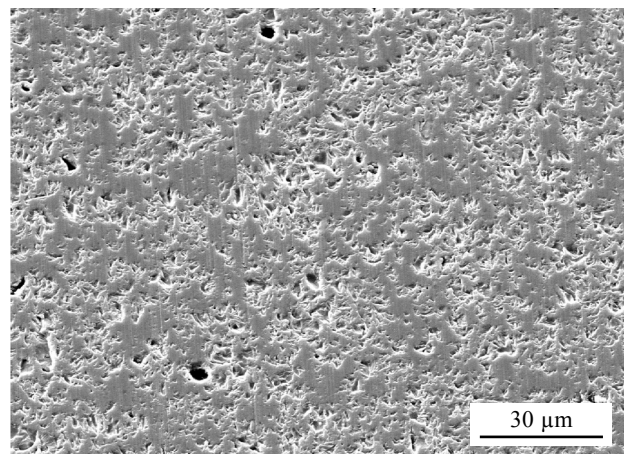
a)

b)

c)

d)

e)

f)

Figure 10. SEM micrographs of : a), b), c) alumina and d), e) f) silicon carbide silicon eroded for 6 h in: a), d) distilled water; b), e) FVA Oil Nr. 1 and c), e) FVA Oil Nr. 3.

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VLIV KVALITY POVRCHU A KAVITAČNÍ KAPALINY
NA KAVITAČNÍ EROZI KORUNDOVÉ
A KARBIDOVÉ KERAMIKY

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Kavitační eroze oxidu hlinitého (F 99.7, Friatec) a slinutého karbidu křemíku (SSiC, EKasic F) s různou jakostí povrchu byla zjišťována při 25°C po dobu 6 hodin v destilované vodě jako kavitační kapalině podle ASTM G32-92. Po procesu opotřebení následovalo měření kumulativní ztráty hmoty a objemu. Poškození erodovaných povrchů bylo prozkoumáno pomocí SEM. Odolnost proti opotřebení zkoumaných keramických hmot ve smyslu inkubační doby a ztráty hmoty a objemu byla lepší při nižší drsnosti povrchu. SSiC vykazoval vyšší odolnost opotřebení ve srovnání s oxidem hlinitým. Byly projednány výsledky tvrdosti, lomové houževnatosti, velikosti zrn, drsnosti povrchu a mikrostruktury. Dále byl zkoumán vliv olejů jako kavitačních kapalin na erozi zkoušené keramické hmoty. Výsledky ukázaly, že voda je ve srovnání s použitými oleji vysoce erozivním médiem, což je důsledek vyššího tlaku vodní páry, nižší viskozity a vyšší hustoty.