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DYNAMIC FRAGMENTATION OF ALUMINA WITH ADDITIONS OF NIOBIA AND SILICA UNDER IMPACT

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The addition of niobia and silica to alumina may decrease its sintering temperature to values as low as 1400 °C. The purpose of this work was to investigate the ballistic behaviour of alumina processed with such additions, by evaluating its dynamic fracture toughness under impact. Samples of a commercial alumina with niobia, silica, and magnesia additions were sintered into disk shape at 1400 °C / 3 h in order do determine their ballistic properties. For comparison, this ceramic was also submitted to sintering without additions using a conventional heat treatment of 1600 °C / 1 h before dynamic testing. Ballistic tests were carried out gluing the ceramic disks to steel plates and submitting this target to the impact of a 7.62 mm projectile fired from a rifle positioned 5 m from the target. The results showed that the alumina containing niobia and silica sintered at 1400 °C absorbed more energy during fragmentation.

INTRODUCTION

Ceramic materials such as alumina, silicon nitride, and boron carbide, among others, have been investigated along many decades as components applied to armor systems to provide protection against projectile penetration. They combine high hardness and low weight and these properties make them useful for better protection, mobility, and transportation capacity of vehicles. Figure 1 illustrates an armor system where the ceramic plate is positioned in front of the target and absorbs the initial impact of the projectile. Behind this hard and brittle plate there are other materials which should be able to plastically absorb the rest of the energy generated by the impact. Due to its low cost and availability alumina continues to be extensively used as the preferred ceramic material in armor systems. Usually the alumina without special additives is prepared using a process where the sintering temperature stays around 1600 °C. In a previous work Acchar [1] sintered at 1400 °C an alumina containing niobia, silica, and magnesia and observed that its mechanical strength was comparable to that of an alumina containg just 0.15 wt% of magnesia sintered at 1600 °C. The objective of the present work was to investigate the dynamic fracture toughness behaviour of a commercial alumina containig niobia at different percentages as well as silica and magnesia as additives, sintered at 1400 °C.

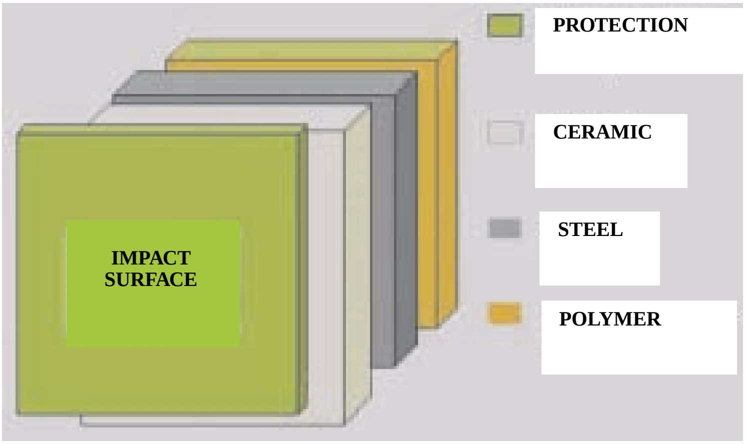

Figure 1: Example of an armor system.

MATERIALS AND EXPERIMENTAL PROCEDURES

The ceramic compositions were prepared using an inexpensive commercial alumina from ALCOA (APC2011-SG), with additions of niobia, silica, and magnesia as shown in Table 1. There, the #1 composition, without additives, was chosen as reference since it was sintered at 1600 °C / 1 h (standard procedure), for comparison purposes with the other samples sintered at 1400 °C / 3 h.

The powders of each composition were ball-milled during 8 hours and dried at 70 °C in a furnace. After that they were manually broken up using a spatula. After incorporation of 1.5 wt% of binder to provide green strength the powder mixture was pressed in a steel matrix into 57 mm diameter disks with 60 MPa pressure in a universal Instron testing machine. The pressed samples were then submitted to 350 °C / 4 h heat treatment for binder burn-out. The specimens were sintered in air in the conditions shown in Table 1. After sinterization, the samples were characterized by measuring the Vickers microhardness as well the degree of densification employing the Archimede's method.

The ballistic tests were carried out gluing the ceramic disks to steel plates and then submitting this target to the impact of a 7.62 mm projectile fired from a rifle positioned 5 m from the target, as shown in Figure 2.

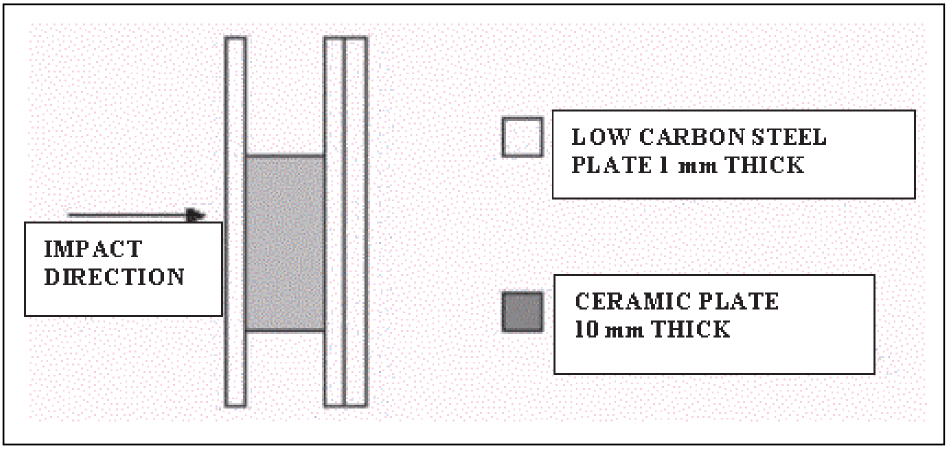

Figure 2: Target set-up showing the ceramic plate between steel plates.

The projectile velocity was measured immediately before and shortly after the impact. Based on these velocity measurements, the energy absorbed by the ceramic disk during fragmentation was determined and used to estimate the alumina dynamic fracture toughness. In this evaluation, the energy absorbed by the steel plates was computed and discounted.

Fragments of the impacted alumina were recovered and observed by scanning electron microscopy to determine the mode of fracture (transgranular or intergranular) which of the samples.

RESULTS AND DISCUSSION

Table I shows the data of microhardness, densification, energy absorption, and fracture mechanism for the investigated compositions. In this Table, if one compares the densification data for #2 sample (without additives) with the samples from #3 to # 13 (all with additives), it becomes clear that the niobia addition helped consolidation during alumina sintering under the same conditions. It is also evident that the sintering behaviour of #1 sample at 1600 °C / 1 h was worse than for most samples of alumina with additions sintered at 1400 °C / 3 h. This reinforces the role of niobia in promoting sintering at lower temperatures. Acchar [1] considered that the addition of niobia to alumina formed a second phase ($AlNbO_4$), and also mullite when in presence of silica. These components remained at the alumina grain boundaries, controlling grain growth and improving pore elimination throughout the grain boundaries and consequently increasing the sintered densities.

Home
Table of Contents

Table 1: Investigated Compositions and Experimental Results

Sample (#)	Al_2O_3 (%)	Nb_2O_5 (%)	SiO_2 (%)	MgO (%)	Sintering (°C/h)	A (HV)	B (%TD)	C (J)	D
1	100	-	-	-	1600/1	1261	84.2	1944±104	T
2	100	-	-	-	1400/3	242	64.5	1422±109	I
3	96	4	-	-	1400/3	1319	87.2	2497±43	I
4	95.2	4	0.8	-	1400/3	775	86.3	2480±45	I
5	94.05	4	0.8	1.15	1400/3	1028	89.8	2395±28	M
6	95.05	4	0.8	0.15	1400/3	994	89.0	2420±6	M
7	97.05	2	0.8	0.15	1400/3	815	86.3	2251±196	I
8	93.05	6	0.8	0.15	1400/3	1082	86.8	2251±163	M
9	92.25	8	0.8	0.15	1400/3	947	89.8	2435±88	I
10	94	6	-	-	1400/3	966	87.7	2300±199	M
11	93.2	6	0.8	-	1400/3	888	80.5	2446±19	I
12	92	8	-	-	1400/3	1307	91.2	2202±97	I
13	91.2	8	0.8	-	1400/3	761	81.1	2454±38	I

TD: Theoretical Density
A: Vickers Microhardness ; B: Densification; C: Fracture Energy Absorbed
D: Predominant Fracture Mechanism (T-Transgranular; I-Intergranular; M-Mixed)

As shown in Table 1, the results of microhardness indicated that the alumina with niobia additions was harder than the alumina containing niobia and silica. A hard ceramic face is desirable to destroy the projectile tip and thus decrease the projectile penetration power upon impact. It was also observed that in the samples with silica, the microhardness was lower but the absorbed energy was relatively high, as can be seen, for example, comparing the results for samples #3 and #4.

The alumina dynamic fracture toughness, estimated from the absorbed energy shown in Table 1, illustrates that this parameter upon impact depends on the strength of the alumina grain boundaries and the mode of fracture taking place during the ceramic fragmentation process. Therefore, for sample #2 where densification was poor, the absorbed energy was smaller due to the weak adhesion between the alumina grains as well as the high porosity present in this sample as a result of the unsatisfactory sinterization of alumina without additives at 1400 °C / 3 h.

Sample #1, sintered at 1600 °C, showed reasonable microhardness and density but lower energy absorption when compared with the samples containing niobia and silica sintered at 1400 °C. This sample also exhibited predominantly the transgranular mode of fracture, as shown in Figure 3, indicating that crack propagation and energy dissipation were low, since extensive crack branching did not take place, as would be expected in the case of intergranular mode of fracture.

Home
Table of Contents

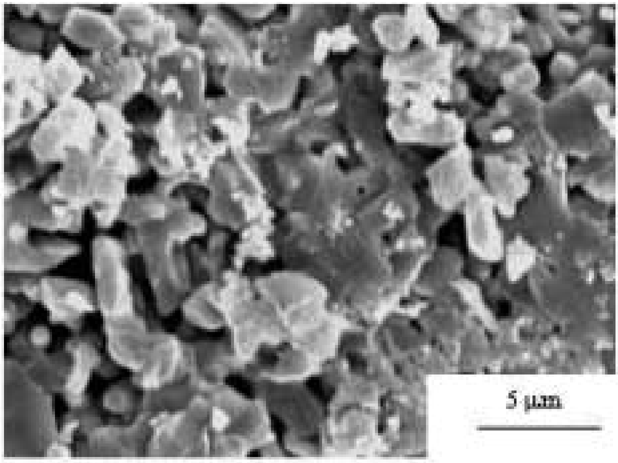

Figure 3: Dynamic fracture surface of sample #1 obtained by SEM, showing predominantly transgranular mode of fragmentation.

On the other hand, if one considers the other samples where alumina with additives were sintered at 1400 °C / 3 h, one can see that most samples exhibited the intergranular mode of fracture. For these aluminas the energy absorbed was also superior than that of #1 sample, because crack branching occurred throughout the grain boundaries, helping to consume energy and consequently resulting in better dynamic fracture toughness. Figures 4 and 5 show the dynamic fracture of samples #3 and #4 respectively, revealing a predominantly intergranular mode of fracture. Louro and Meyers [2] have developed a fragmentation model applied to brittle materials such as ceramics based on nucleation, growth and coalescence of microcracks. This model takes into account the passage of a shock wave through the target [3]. When a projectile hits the armor system, a compressive shock wave travels through the target and produces damages. Microcracks are nucleated at preferential sites such as weakly bonded grain boundaries, voids, or second phases precipitated between grains [4,5]. This probably explains why fragmentation takes place preferentially at grain boundaries as observed by scanning electron microscopy (SEM) [6] in the alumina containing both niobia and silica as additives of sintering at 1400 °C.

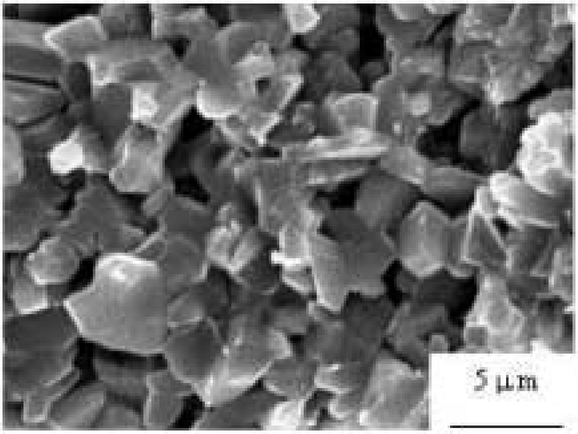

Figure 4: Dynamic fracture surface obtained by SEM from sample #3 showing predominantly intergranular mode of fragmentation.

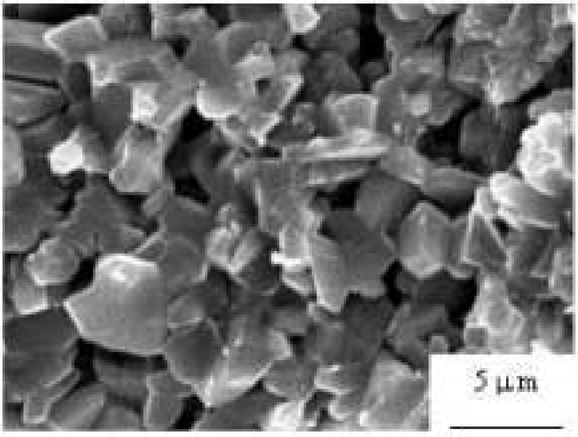

Figure 5: Dynamic fracture surface obtained by SEM from sample #4 showing predominantly intergranular mode of fragmentation.

CONCLUSIONS

1. The use of niobia and silica as sintering additives in alumina promoted better densification under sintering at 1400 °C / 3 h than 1600 °C / 1 h in the alumina without additions.
2. The presence of niobia, silica, and magnesia in alumina, generating precipitates of second phases in the alumina grain boundaries, increases the absorption of energy during impact by promoting a intergranular mode of fragmentation.
3. The ballistic performance of the alumina without additions sintered at 1600 °C was worse than the aluminas with additions sintered at lower temperature; this is attributed to the transgranular mode of fragmentation, which presented low energy dissipation upon impact.

4. The presence of niobia increased the microhardness of alumina and the presence of niobia and silica decreased its microhardness. The first effect contributed to destroy the projectile tip more efficiently and the second contributed to energy dissipation upon fragmentation.

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