Impact Behavior of Ceramic-Metal Armour Composed of Al_2O3-Nano SiC Composite

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Abstract: Alumina (Al_2O_3) is one of the most practical ceramics used in making ceramic-metal armours. To improve the properties of alumina, some other materials are added to it. In this paper, SiC material as Nano powder is added to alumina, and four armour samples of this new ceramic with different volume fractions (V.F.) including 0%, 5%, 10% and 15% of SiC particles are made. Their fracture toughness, bending strength and density are measured. Subsequently, it is found that the armour sample made of alumina with V.F. of 10% of SiC particles indicates more desirable properties as compared to other armour samples. Hence, the computer simulation and ballistic tests are carried out using alumina with V.F. of 10% of SiC particles and the results are compared with those of ballistic tests of pure alumina. During the simulation, it is observed that pure alumina with a thickness of 10 mm and aluminum substrate with a thickness of 4.8 mm is broken due to normal impact of a projectile with 800 m/s speed, but the new armour made of the present new ceramic is able to withstand the same conditions and no fracture is observed after the impact. The ballistic tests were also carried out using the present new ceramic-aluminum armour samples with ceramic thicknesses of 6, 8 and 10 mm, respectively to determine the smallest thickness at which the fracture occurs. It was found that the armour with a ceramic layer thickness of 6 mm did fracture, whereas the others were able to withstand the conditions of the ballistic test.

Keywords: Aluminum(Al_2O_3), Armour, Carbide(SiC), Ceramic, Silicium

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1 INTRODUCTION

Multi-layer ceramic armours are widely used to protect army instruments and infantries. In these types of armours, the front layer is made of ceramic and the back layer is made of metal, composite or Kevlar. The rough surface of ceramic usually cracks and breaks as a result of bullet impact and the remaining kinetic energy of the bullet is absorbed by a supporting layer. By deformation and breaking the bullet's head into pieces, the ceramic layer would decrease its kinetic energy and prevent the bullet's penetration deep into the armour. The basic task of the ceramic layer is to control and stop the projectile. To do this, it must have some special features and properties such as density, fracture toughness, mechanical strength and elasticity module. As a kind of ceramic, alumina is widely used for manufacturing armours.

A wide range of alumina ceramic is available on a commercial scale whose strength depends on the purity of alumina which is in the range of 88-99%. Some applications of alumina are: Cutting tools, bullet proof tiles and abrasive material. Although pure alumina has great advantages such as higher refractory and hardness, however it has some disadvantages such as low fracture toughness leading to sudden failure.

This property has limited it's use in engineering applications. In recent years, researchers have found that the incorporation of amounts of sub micrometer and nanometer SiC particles into Al_2O_3 increases the mechanical properties of this ceramic effectively [1-3] and decreases Al_2O_3 matrix grain growth. Several strengthening/toughening mechanisms have been suggested in order to explain the improvement in mechanical properties, including the residual stresses due to thermal expansion between Al_2O_3 and SiC grain, crack deflection, micro cracking and crack branching. However, the change in the fracture toughness of Al_2O_3-SiC nano composites has been controversial.

Some researchers have reported that there is no difference between the fracture toughness of Al_2O_3 and Al_2O_3-SiC nano composite. Mustafa Ubeyli et al. [4] achieved ballistic tests on alumina armours for which the thickness of aluminum back layer and the thickness of ceramic layer are 4.8 mm and 10 mm, respectively. And they observed that the projectile will penetrate at the speed of 800 m/s. In the present research different percentages of SiC are added to alumina and their properties are compared and ballistic test and computer simulations are performed using some percentages that show the best properties.

2 MANUFACTURING METHOD, SIMULATION AND TEST

In this section, manufacturing methods of adding SiC to alumina, mechanical properties obtained (fracture, toughness, bending strength and relative density), computer simulation and ballistic tests are described.

2.1. Manufacturing Method

The material used in this research is 99.6% alumina with average dimensions of less than 3μm, with the basic phase of γ- Al_2O_3. Nano powder of SiC with the basic phase of β-SiC and average dimensions of 80 nm is prepared. SiC Powder was added to alumina with a V.F. of 0%, 5%, 10% and 15% respectively, and isopropanol suspension was obtained. The suspension obtained by such method, was placed into mill chamber and was rotated at the speed of 150 rpm to achieve a homogenous mixture. The obtained slurry was discharged from the mill and was then placed into a dryer at 90ºC and was formed by a press at 20 bar for 30 seconds. The pieces were sintered at 1700ºC and at a heating rate of 10cˆ/min and simultaneous pressure of 30 MPa for 1.5 hours. At the end of the sintering process, the pieces are removed from the oven and are allowed to cool at ambient temperature.

The fabricated samples were tested to obtain properties corresponding to each SiC percentage. To measure the bending strength, ASTM C1161 standard was used by applying the three points method [5]. To determine the fracture toughness, according to dimensions assigned in ASTM, as shown in Fig. 1, the samples were cut and sized using wire-cut machine as a preparation for fracture toughness tests [6]. The samples were tested in uniaxial tension test apparatus. The rate of loading was set to be quite low. All the experiments were performed in the ambient temperature. The load was continuously applied until the samples were fractured.

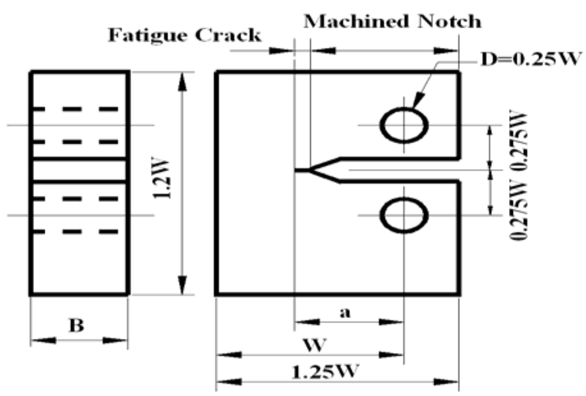

Fig. 1 Size of specimens based on ASTM standard [6]

After accomplishment of tensile test on the samples, σ_c (critical stress) relative to each load is obtained. The length of plastic effect and the length of crack in radial direction are measured using Equations (1) and (2). Fracture toughness K_{1C} is calculated for each sample and the average fracture toughness of seven measured samples is reported [6].

$$F\left(\frac{a}{w}\right)=\left[\frac{\left(2+\frac{a}{w}\right)}{\left(1-\frac{a}{w}\right)^{\left(\frac{3}{2}\right)}}\right]\times\left[0.886+4.64\left(\frac{a}{w}\right)-13.32\left(\frac{a}{w}\right)^{2}+14.72\left(\frac{a}{w}\right)^{2}-5.6\left(\frac{a}{w}\right)^{4}\right] \quad (1)$$

$$K_{IC}=\sigma_c\sqrt{\pi a}\times F\left(\frac{a}{w}\right) \quad (2)$$

where parameter 'a' and 'w' are indicated in Fig. 1. In order to obtain the density, five specimens of each sample are prepared and the density was measured using the Archimedes method.

2.2. Computer Simulation

Simulations have been performed by Ls-dyna software. In these simulations, alumina ceramic layer with nano particles of SiC and Al 2024-T6 are used as front layer and back layers, respectively. For ceramic layer modeling, MAT-JOHNSON –HOLMQUIST – CERAMICS has been used, which is the specific simulator of brittle substances and ceramics. Also, the JOHNSON COOK material model was used for the projectile. This material model is used where high strain rates are observed. The MAT-PLASTIC-KINEMATIC material model is used for aluminum sheet, implemented two dimensionally (2D).

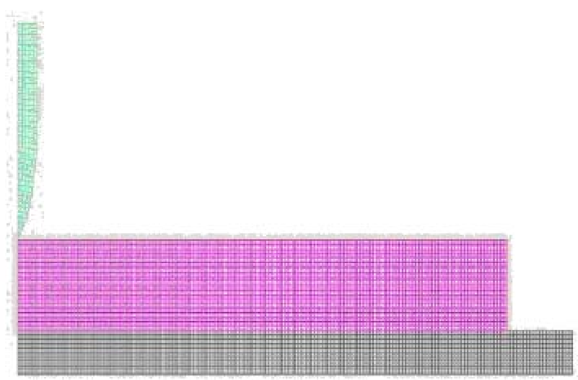

Fig. 2 Two-dimensional mesh pattern of the armour and the projectile

According to Contact-2D-automatic-Surface to Surface assumptions, a target may be impacted by a projectile in three ways as follows: impact between the projectile and ceramic, the projectile and aluminum and ceramic and aluminum. In Fig. 2 the two dimensional mesh pattern of armour and the projectile is shown.

2.3. Ballistic Tests

For the ballistic test, ceramic armours were composed of alumina with SiC nano particles and thicknesses of 6, 8 and 10 mm respectively. The thickness of back layer was considered 4.8 mm in all cases. The armour was shot by J3 gun and the impact velocity was measured by two optical apertures. The impact velocity was reported 835±15 m/s. Each sample was shot 10 times and the total average was calculated. The complete penetration didn't occur in thicknesses of 8 and 10 mm, in thickness of 6 mm it was observed that 50% of impacts penetrate deep into the armour.

3 RESULT AND DISCUSSION

After preparing the test samples, the following outcomes were obtained from the experiments. Adding SiC nano particles to the alumina up to 10%, causes mechanical properties including fracture toughness and bending strength to be improved compared to pure alumina. In Fig. 3, variation of K_{1C} versus different percentages of SiC nano powder is shown. As can be seen in this figure, fracture toughness increases due to adding nano SiC particles up to 10%, adding more nano particles reduces fracture toughness.

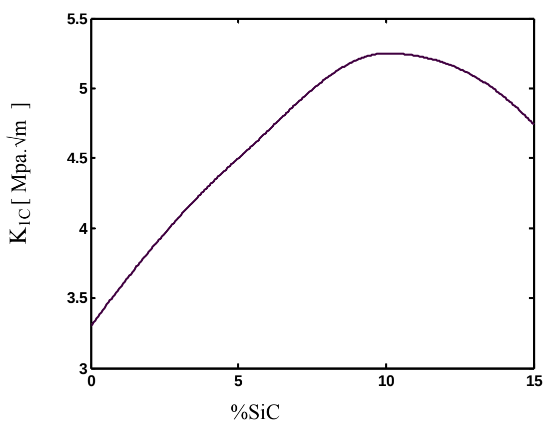

Fig. 3 Fracture toughness of nano composites vs. volume fraction of SiC

In Fig. 4, variation of bending strength versus percentage of volume fraction of SiC is investigated. As can be seen in this figure, bending strength increases due to adding nano SiC particles up to 10%, while adding more nano particles reduces bending strength.

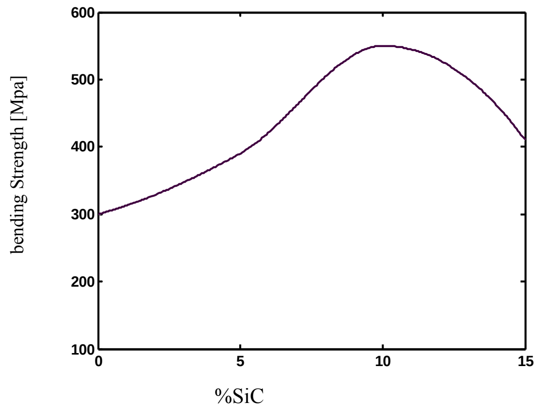

Fig. 4 Bending strength of nano composites vs. volume fraction of SiC

In Fig. 5, the effect of adding SiC nano powder to the alumina on its density is shown. As indicated in this figure, the relative density is monotonically decreased due to increasing percentage of SiC nano powder. This may result from the fact that the mobility of the nano particles of SiC are insufficient and they do not react with alumina at sintering temperature. This phenomenon will cause the boundary mobility of the grain to be decreased and the condensation of alumina is prevented consequently. Hence, by adding nano SiC particles, the condensation of alumina is decreased and consequently its relative density is also decreased.

As can be observed, by increasing percentage of SiC nano powder up to 10%, except density which is slightly decreased, the fracture toughness and bending strength are both maximized.

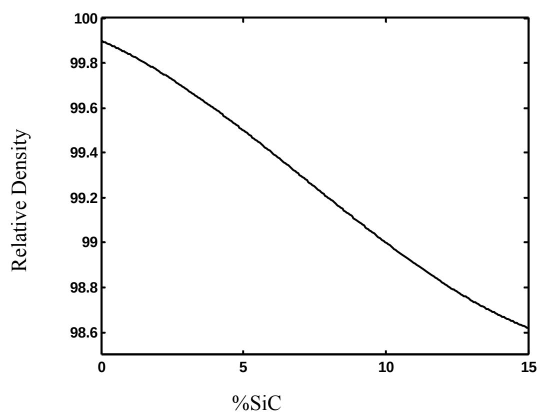

Fig. 5 Relative density of nano composites vs. volume fraction of SiC

Therefore the computer simulation is performed for alumina and SiC nano powder composite. In this simulation, the alumina and SiC nano composite is modelled as front layer and Al2024-T6 material is used to model the back layer. The thickness of back layer is considered to be 4.8 mm and the thickness of ceramic layer is considered to be 10, 14 and 20 mm. Figure 6, indicates the computer model.

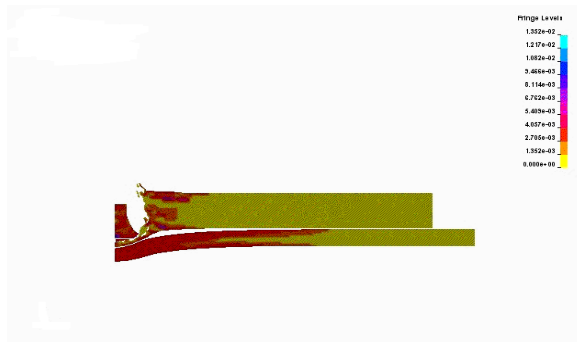

Fig. 6 Simulation of penetration of projectile armour

Figure 7, indicates the velocity of the projectile (cm per microseconds) versus time (microseconds). It was observed that in 122 microseconds after the impact, the velocity of the projectile reduces from 815 m/s to zero. While if pure alumina is used in the same armour with the same dimensions, according to the test data reported by Obeyli (on which the present computer simulations are based) perfect perforation must occur. This is due to the fact that the alumina ceramic with SiC particles absorbs more energy than the back metal layer. Of course, the size of the SiC particles are not modelled in the simulations and only their volume fraction is considered in the material properties.

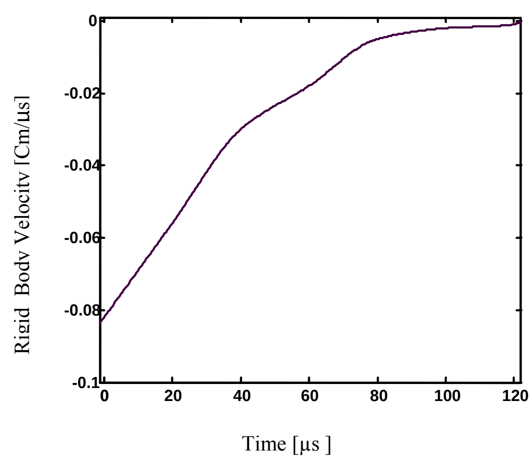

Fig. 7 Variations of projectile speed during penetration

As observed from the simulations, perfect perforation does not occur in armour with 10 mm ceramic of alumina with SiC nano particles and back layer of 4.8 mm. According to the findings by Obeyli et al in ballistic tests, on an armour with 4.8 mm alumina back layer and alumina ceramic layer of 10 mm thickness, in most test cases, the projectile with velocity of 800 m/s perforates the armour, but according to the computer simulations by changing the ceramic layer with alumina and SiC nano particles, in addition to weight reduction due to less density, the projectile cannot perforate the armour and in the other case, it causes the dishing of the back layer to be decreased as shown in Table 1. For this reason, the ballistic tests were performed on alumina (including 10% SiC nano particles) with thicknesses of front ceramic alumina layer of 6, 8 and 10 mm and thickness of the back layer of 4.8 mm and impact velocity of 835 ± 15 m/s.

Table 1 Dishing value of back layer of armour

Thickness of ceramic (mm)	dishing of back layer in alumina armour (mm)	dishing of back layer in alumina with 10% ceramic armour (mm)
10	Complete penetration	10
14	5	2
20	3	0.75

Table 2 Comparison of dishing values due to ballistic tests on armour with different thicknesses for alumina ceramic layer

Thickness of ceramic layer (mm)	10 mm	8 mm	6 mm
dishing	12 mm	17 mm	Complete penetration

Each test was repeated 10 times using a J3 gun and the average of measured data was calculated. In thicknesses of 8 and 10 mm, no perfect penetration occurred but in thickness of 6 mm, it was observed that in 50% of impact tests, the projectile perforates the armour. Table 2 indicates values of dishing in these three armour structures.

4 CONCLUSION

1- By increasing the percentage of SiC in alumina up to 10%, fracture toughness and bending strength are increased, but adding more SiC particles causes the fracture toughness as well as bending strength to be decreased.
2- As compared to pure alumina, alumina ceramic with 10% of SiC nano particles shows improved ballistic behaviour.
3- Using this ceramic causes its density to be decreased and consequently the armour weight is reduced.

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