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Ballistic performance of ceramic-metal composite structures

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ABSTRACT

In this study, a numerical analysis of the ballistic performance of ceramic-metal composite structures was investigated. In the analysis, the two composites consist of distinct ceramics namely alumina and boron carbide tiles supported by the aluminum plate were tested for numerical analysis. In both the structures, the size of the circular ceramic plates were 101 mm diameter and 25 mm thickness composed at the center of backed aluminum metal plates having a thickness of 25 mm and an outer diameter of 152 mm. A cylindrical tungsten projectile (76.2 mm long and 7.62 mm diameter) was impacted with 1550 m/s velocity at the center of both the composites and the behavior of the impacted ceramic-metal composites were studied through LS-DYNA solver and validated through experimental results available in the literature.

For studying the ballistic performance of the composite, different parameters were considered, namely the depth of penetration, ballistic limit and areal density of the target. The performance of ceramic immensely depends upon the yield strength of backing and front ceramic material. The numerical results have shown that the Boron Carbide-Aluminum composite had better ballistic resistance.

Keywords: Ballistics; Ceramics; Ceramic-Metal Composite; Depth of penetration.

1. INTRODUCTION

Over the decades, metals are utilized in body armours. However, the demands for lightweight armors for body protection led to the research of alternative materials. In the last few decades, non-metallic materials, such as ceramics and composites, have been gradually integrated into more efficient lightweight armors. Due to their low density, high hardness, high rigidity and strength in compression, ceramics have become widely used in armors. But, the low fracture toughness of ceramics and their tendency to fracture when subjected to high tensile stresses has directed for the improvement of composite armors in which a ceramic- faced plate is backed by a more ductile material such as a metal or a polymeric composite that can resist failure due to tensile stresses [7].

When armour-piercing projectiles impact onto composite armors, the projectiles are first shattered or blunted by the hard ceramic and the load is then spread over a larger area. The backing plate deforms to absorb the remaining kinetic energy of the projectile, delays the initiation of tensile failure in the ceramic and backing plate interface, and allows more projectile erosion.

For ballistic impact, commonly used ceramics are boron carbide, alumina, silicon carbide, Al nitride, etc. High purity alumina (Al2O3) has been widely adopted as a body armour material, primarily due to its useful combination of good ballistic properties, low costs and familiarity with associated manufacturing routes [4]. Other ceramics such as silicon carbide (SiC) and boron carbide (B4C) are stronger but are less widely employed due to both manufacturing and economic issues [3, 4].

A ballistic performance of alumina 99.5 % and 95 % backed with thick Al block against 12.7 AP projectile at velocity range 500-830 m/s was performed experimentally by Madhu et al. [2]. Ballistic performance was assessed by ballistic efficiency factor which was product of thickness efficiency and mass efficiency. The study revealed that pure alumina performed far better than alumina with other alloying element. Ballistic efficiency was function of thickness of ceramic tile and velocity of projectile.

Feli and Asgari [6] performed a finite element analysis of Alumina/Twaron against tungsten projectile on basis of LS DYNA code. Johnson Holmquist, JC and composite damage material model used to simulate the behaviour of alumina, projectile, and composite backing respectively. A ceramic with composite backing was suitable for ordinance velocity. Ballistic limit of given configuration was 470 m/s.

So, most commonly used armour material is alumina due to its advantages in terms of cost, ease of manufacturing, availability of modeling parameters. Even though boron carbide was strongest ceramic in armour application, very few studies have been carried out to investigate ballistic performance of boron carbide with metal backing. The reason might be, due to high hardness of B4C, it is difficult to find out modeling parameters by various tests.

In this paper, Ballistic performance of ceramic- metal composite structure was numerically analysed. In order to improve performance of ceramic armour system, ceramic alumina/boron carbide tile of constant thickness (25 mm) was confined inside a constant thickness (64 mm) of Aluminum as a backing plate. The projectile made of tungsten was impacted at velocity of 1550 m/s.

2. FINITE ELEMENT MODELLING

Finite element modelling was carried out in Abaqus explicit model. A quarter model was used to reduce the time required for the computation in numerical analysis. Alumina and boron carbide were considered as deformable material and discretised by using the 8 noded linear brick, reduced integration, hourglass control element and the projectile was meshed with solid element. Also, mesh at the projectile contact zone were kept finer to properly capture the failure mechanism at the contact zone. Total number of elements were 1563,76800, 416000 for projectile, ceramic and backing plate respectively as shown in fig1.

The contact used between ceramic and backing aluminum metal was Automatic_Surface_ to_ Surface and those for projectile and target was Eroding_Surface_to_Surface. The target elements were considered as master while projectile elements were considered as slave. Symmetrical boundary condition along X-axis [100011] & Y –axis [010101] were applied. A projectile was constrained in all direction except transverse motion along Z – axis. A VELOCITY_GENERATION keyword used to assign velocity to projectile.

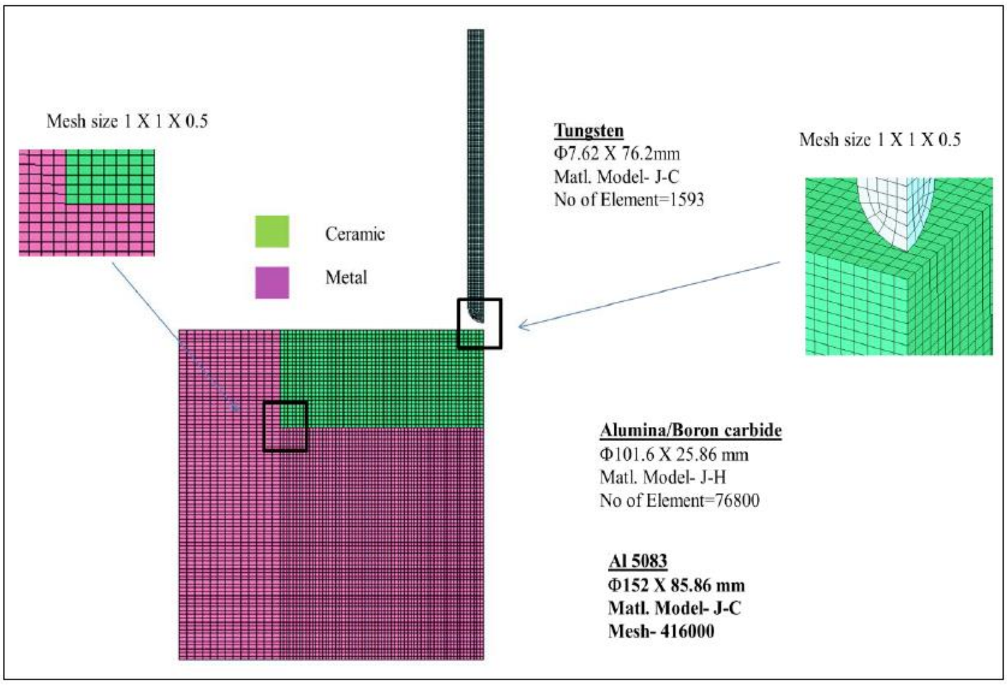

Fig. 1: Quarter model of Projectile and Ceramic-Aluminum Composite structure

3. CONSTITUTIVE MODEL

The Johnson-Holmquist material model (JH-2) is commonly used to obtain behavior of ceramics under ballistic impact. Hence in order to simulate the behavior of a targeted boron carbide and alumina ceramic material JH-2 material model was used. Response of alumina/boron carbide to various loading condition was modeled using JH-2 constitutive model, as the model incorporates large deformation of brittle material, brittle failure, high pressure effect and strain rate. Different material constants, as shown in Table 1, were used to completely describe the effect of impact on ceramic material.

3.1 JH-2 Material Model [6,16,17]

The damage material Equivalent strength is given by

$$\sigma^* = \sigma^*_i - D\,(\sigma^*_i - \sigma^*_f) \qquad (1)$$

Where σ^*_i ,σ^*_f are normalized intact and fracture strength respectively. D is damage parameter.

Material normalized intact and fracture strength is represented by

$$\sigma^*_i = A(P^* + T^*)^N\,(1 + C \ln \dot{\varepsilon}^*) \qquad (2)$$

$$\sigma^*_f = B(P^*)^M (1 + C \ln \varepsilon^{\cdot *}) \quad (3)$$

Where A, B, C, M, N are material constants. Stress & pressure at any instant is normalized by equivalent stress at HEL (Hugoniot Elastic Limit) & pressure at HEL respectively.

The general form of Normalized stress is

$$\sigma^* = \sigma/HEL, \quad P^* = P/P_{HEL}, \quad T^* = T/P_{HEL}, \quad \varepsilon^{\cdot *} = \varepsilon^{\cdot} / \varepsilon_0^{\cdot} \quad (4)$$

Where T* is normalized tensile strength, P* is the normalized pressure and $\varepsilon^{\cdot *}$ is the normalized strain rate.
Accumulated damage occurs during each computational step is given by equation (5). Once damage accumulation exceeds unity, material starts to failure.

$$D = \Sigma \, \Delta \varepsilon_p / \varepsilon_f \quad (5)$$

where $\Delta \varepsilon_p$ is current increment in plastic strain. ε_f is a plastic strain for fracture given as,

$$\varepsilon_f = D_1 (P^* + T^*)^{D_2} \quad (6)$$

where D1 and D2 are the material constants.

Table 1: Johnson Holmquist-2 material model parameters for Alumina and Boron carbide [5]

Parameters	**Symbol (Unit)**	**Alumina**	**Boron Carbide**
Density	ρ (Kg/mm3)	3.9E-6	2.5E-6
Shear modulus	G (GPa)	135	197
Intact strength constant	A (GPa)	0.987	0.927
Facture strength constant	B (GPa)	0.77	0.7
Strain rate constant	C	0	0.005
Facture strength exponent	M	1	0.85
Intact strength exponent	N	0.376	0.67
Max. Fracture strength ration	Sf_{max}	0.5	0.2
Hugoniot elastic limit	HEL	5.9	19
Pressure at HEL	PHEL (GPa)	2.2	8.71
Melting temperature	T (GPA)	0.15	0.26
Ref. Strain rate	ε	1	1
Damage parameter	D1	0.01	0.001
	D2	1	0.5
Max. Effective strain at failure	EFFEPS	2	2.1
Bulking constant	BETA	1	1
Failure strain	FS	1.5	1.5
Bulk modulus	K1 (GPa)	200	233

3.2 J C Material Model [6,16,17]

Backing plate Al 5083 and tungsten projectile were modeled using JC material model (Refer Table 2). In JC model yielding, hardening, plastic flow, strain rate, strain rate hardening, softening due to adiabatic heating, damage are considered.

To define the behavior of the metal under the high loading condition JC material model given as

$$\bar{\Sigma}\left(\bar{E}^{Pl}, \dot{\bar{E}}^{Pl}, \hat{T}\right) = \left[A + B(\bar{E}^{Pl})^{N}\right]\left[1 + C\,\mathrm{Ln}\left(\frac{\dot{\bar{E}}^{Pl}}{\dot{E}_0}\right)\right]\left[1 - \hat{T}^{M}\right] \tag{7}$$

A, B, C, N are experimentally determined user input constants. $\bar{E}^{Pl}, \dot{\bar{E}}^{Pl}$ are equivalent plastic strain and plastic strain rate, $\bar{\sigma}$ Von mises stress, $\hat{T}$ is dimensionless temperature and it defined as

$$\hat{T} = (T - T_0)/(T_{Melt} - T_0) \qquad T_0 \leq T \leq T_{Melt} \tag{8}$$

Once D=1, damage accumulation occurs and material failure starts.

$$D(\bar{\varepsilon}^{P}, \dot{\bar{\varepsilon}}^{P}, T, \sigma^{*}) = \sum \frac{\Delta\bar{\varepsilon}^{P}}{\bar{\varepsilon}_{f}^{\,P}(\dot{\bar{\varepsilon}}^{P}, T, \sigma^{*})} \tag{9}$$

The equivalent plastic fracture strain $\bar{E}_F^{Pl}$ expressed as

$$\bar{E}_F^{Pl}\left(\frac{\sigma_m}{\bar{\sigma}}, \dot{\bar{E}}^{Pl}, \hat{T}\right) = \left[D_1 + D_2 \mathrm{Exp}\left(D_3 \frac{\Sigma_M}{\bar{\Sigma}}\right)\right]\left[1 + D_4 \mathrm{Ln}\left(\frac{\dot{\bar{E}}^{Pl}}{\dot{E}_0}\right)\right]\left[1 + D_5\hat{T}\right] \tag{10}$$

Table 2: Johnson-cook material model parameters for Al 5083, Tungsten [5]

Parameters	**Symbol (Unit)**	**Al 5083**	**Tungsten**
Density	ρ (Kg/mm3)	2.7E-6	17.6E-6
Elastic modulus	E (GPa)	70	314
Shear modulus	G (GPa)	26.9	160
Poisson's ratio	μ	0.3	0.29
Yield stress	A (GPa)	0.167	1.506
Hardening constants	B (GPa)	0.596	0.177
Strain rate constant	C	0.001	0.016
Thermal softening constant	M	0.859	1
Hardening exponent	N	0.551	0.12
Melting temperature	Tm (K)	893	1723
Ref. Strain rate	Tr (K)	300	300
Specific heat	CP (J/Kg.K)	910	134
Damage parameter	D1	0.0261	0.5
	D2	0.263	0.33
	D3	-0.349	-1.5
	D4	0.247	0
	D5	16.79	0
Max. Effective strain at failure	EFFEPS	2	1.5
Bulk modulus	K1 (GPa)	58.3	-

4. RESULT DISCUSSION

In this paper, Ballistic performance of ceramic/metal composite structures was numerically analyzed. In order to improve multi-hit performance of ceramic armor system, ceramic alumina/boron carbide tile of constant thickness (25 mm) was confined inside a constant thickness (64 mm) Al as a backing plate. Tungsten projectile was used and impacted at velocity of 1550 m/s. The ballistic performance of the structures was analyzed by considering following parameters:

4.1 Depth of penetration of target configuration

Depth of penetration (DOP) was measured from reference top surface to end of penetration. Minimum was the DOP; better had performance of the target system. Fig. 2 shows the depth of penetration of the target configurations, when it was impacted at 1550 m/s by tungsten projectile. Fig. 2 (a) shows depth of penetration of alumina/Al was 90 mm. Fig 2 (b) shows, depth of penetration of B_4C/Al was 80 mm. Hence the B_4C/Al configuration perform better than the alumina/Al i.e. in this study Boron Carbide-Aluminum composite had better ballistic resistance.

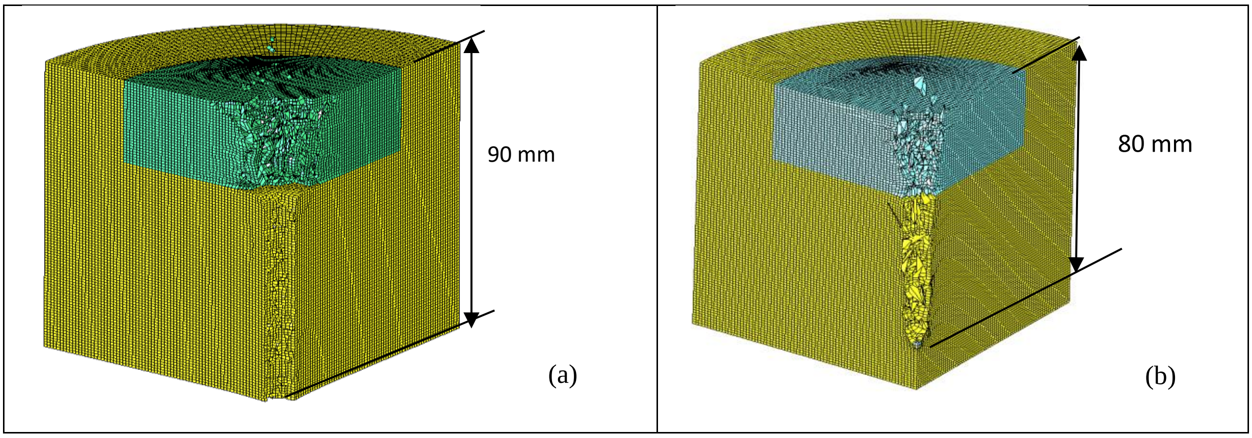

Fig. 2 Depth of penetration when tungsten projectile impact at 1550 m/s on (a) Al2O3 /Al 5083 (b) B4C /Al 5083

4.2 Ballistic limit

Ballistic limit is a maximum velocity a target can sustain with 50 % probability of perforation. It was an average of 10 shots velocities, out of which five shot just perforated and remaining five were stopped by target. The more would be the ballistic limit; the better would be the ballistic performance of target configuration. In this study, the ballistic limit was calculated for tungsten projectile and it was found that B_4C/Al outperformed compared to the Al2O3 /Al. This was due to higher yielding value at failure of B_4C as compare to Al2O3. Ballistic limit was 44 % higher in case of B4C/ Al as compare to Al2O3 / Al.

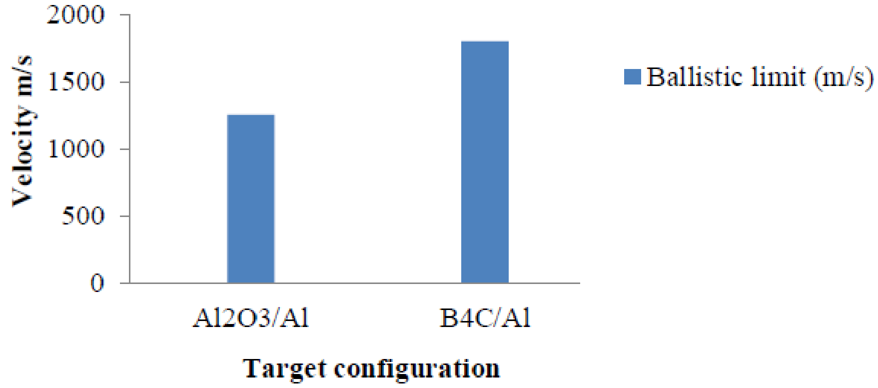

Fig. 3: Ballistic limit of composite structures

4.3 Areal Density

Areal density is mass per unit area of target system. For constant thickness configurations, areal density is best parameter for comparison in terms of weight.

$$\text{Areal density} = \sum \rho_i h_i \tag{11}$$

where ρ is density of component, h is thickness of component and i is no. of components.

Al2O3 / Al areal density was calculated as 270.3 X 10^{-6} whereas B4C/ Al areal density was 235 X 10^{-6}. Hence Al2O3 / Al areal density was found to be 14% higher than B4C/ Al.

5. CONCLUSION

This paper presents the numerical study of the ballistic performance of ceramic-metal composite structures. In the investigation, the two different composites consist of ceramics namely boron carbide and alumina tiles supported by the backing aluminum plate were used. In both the structures, for studying the ballistic performance of the composite, two main parameters were considered, namely the depth of penetration and ballistic limit.

- Depth of penetration in the Al2O3 / Al configuration is more than compare to the B4C/ Al target.
- B_4C/Al outperformed compared to the Al2O3 /Al. This was due to higher yielding value at failure of B_4C as compare to Al2O3. Ballistic limit was 44 % higher in case of B4C/ Al as compare to Al2O3 / Al.

In this study, considering above parameters in account, the Boron Carbide-Aluminum composite shows better ballistic performance than the Alumina-Aluminum composite.

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