Ballistic Testing and Simulation of Co-continuous Ceramic Composite for Body Armour

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A B S T R A C T

Co-Continuous Ceramic Composites, referred to as C4, have bi-continuous, interconnected and interpenetrating phases of a metal and ceramic. This bestows such composites with a higher strength to weight ratio compared with traditional composites. In this research work, a C4 composite of AA5083/SiC is fabricated for personal body armour, using gravity infiltration technique. A numerical simulation model of the C4 specimen is developed. This finite element model is utilized to simulate the DoP of a subsonic bullet into the C4 and is estimated as 1.47 mm. The C4 specimen is then, subjected to ballistic tests. A medium velocity projectile with a rated velocity of 326 m/s is used to impact the C4 specimen. The ballistic tests validate the numerical simulation with a DoP of 1.5 mm. Visual inspection reveals brittle cracks and interfacial debonding in the impacted C4. The results indicate that, such composites can potentially be utilized as low cost body armour.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| V      | velocity of the bullet (m/s) |
| F      | Impact force of the bullet (N) |
| DoP    | Depth of Penetration |
| IPCs   | Interpenetrating Composites |
| FE     | Finite Element |
| m      | mass of the bullet (x 10^-3 kg) |
| D      | distance to be travelled by the bullet for impact (m) |
| C4     | Co-Continuous Ceramic Composites |
| AP     | Armour Piercing |
| ϕ      | Diameter |

1. INTRODUCTION

Traditional composites typically consist of two constituent phases namely, a continuous matrix phase and a discontinuous reinforcement phase. Composites are used in numerous applications due to their high strength and stiffness combined with low density. In practice, these beneficial properties enable weight reduction without compromising on strength. In contrast to traditional composites, C4 consist of an interpenetrated structure of a soft, ductile metal phase and a hard, brittle ceramic phase [1], both phases being continuous. Such three dimensionally continuous composites provide a variety of desirable properties like high stiffness, low density, high thermal conductivity and high fracture toughness when compared to traditional composites [2]. These properties enable the use of C4 in numerous applications such as ballistic armour, automotive and high speed train braking systems [3, 4]. Due to its light weight [5, 6], aluminium has been widely used in conjunction with ceramics such as silicon carbide (SiC) and alumina (Al₂O₃) for body armour. Among the Al alloys, AA5083 is typically utilized in armour plates, missile components and cryogenics owing to its exceptional corrosion resistance and structural strength properties [7]. Al alloys bonded to ceramic tiles have been assessed for impact performance using 0.50 caliber AP projectiles in the velocity range of 750 to 910 m/s.

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The residual DoP in the impacted cylinders measured using X-rays indicated that, the ballistic efficiency of SiC ceramic was higher than boron carbide and alumina [8]. Advanced C4 composites have been created by immersing near net-shape silica preforms into liquid Al. Such composites have been found to possess enhanced toughness and less fragility, properties regarded as beneficial for ballistic armours [3]. Further, numerical simulations on composite armour fabricated with Al2O3 or SiC as front ceramic layer and a backing material comprising of high strength steel showed that, SiC ceramics exhibited better ballistic resistance when subjected to ballistic tests with 7.62x54 mm AP projectiles of velocity 850 m/s. It was reported that, the ceramics effectively dissipated the kinetic energy of the impact [9]. Numerical simulation and experimental ballistic studies have been performed on ceramic-aluminium targets using a blunt projectile at a velocity of 700 m/s. The behavior of the ceramic and projectile/target were modeled using the Johnson-Holmquist structural model and Johnson-Cook material model, respectively. The comparison of penetration depth of the projectile, indicated a good agreement between the simulation and experimental investigations with an error of approximately 10 percent [10]. Simulation of impact using tungsten alloy projectiles has been conducted on SiC plates shielded with three metals namely Al alloy, mild steel and Cu alloy at a velocity of 1250 m/s. In the simulation, Johnson-Cook model was adopted for the metals and Johnson-Holmquist model was utilized for the ceramic phase. The residual penetration was estimated using the difference in pre and post penetration weight of the armour. The error in DoP between the simulation and experimental results ranged from 4 to 25 percent for the three shield materials [11]. IPCs have also been produced by pressureless infiltration of an Al-8Mg alloy into Al2O3 foams in two configurations namely, ‘metal-bonded’ and ‘ceramic bonded’. The metal-bonded configuration in which Al backing plates were used for the IPC, showed better resistance to penetration when subjected to 7.62 mm AP projectiles [12]. Comparative impact studies have been conducted on interpenetrating 316L/A356 composites and its constituents using an aluminium projectile of mass 10 mg. The shielding performance was evaluated at hypervelocities of 6000 m/s. The study revealed that, the IPC exhibited the least deformation of 0.3 mm and no indication of spalling [13]. Non-linear FE models have been utilized to simulate impact behaviour of reinforced composites. Experimental ballistic tests were performed at velocities of 360 m/s with impact energies of 520 J. The FE simulations of the impact absorption and failures concurred with experimental observations on deformation behaviour with insignificant error [14].

The literature survey reveals that, many researchers have focussed on FE simulation of ballistic impact in reinforced composites or Al/SiC as discrete constituents. In contrast, the present work compares the ballistic performance and numerical simulation results of a C4 consisting of an interpenetrating network of ballistic grade AA5083 in SiC porous foam fabricated using pressureless (gravity) infiltration technique [15].

2. MATERIALS AND METHODS

2.1 Fabrication of Composite The SiC foam was initially shaped to \( \phi 100 \) mm and thickness, 15 mm in order to be accommodated in the crucible. A crucible containing the weighed, segmented pieces of AA5083 was placed in an induction furnace. The furnace was set to 800ºC, above the liquidus temperature of Al alloy. Simultaneously, the ceramic foam was placed inside another furnace for pre-heating. Subsequent to complete melting of alloy, the molten liquid was poured into the ceramic foam and allowed to infiltrate for one hour under gravity [15]. Graphite rod was used to hold the SiC foam in position.

On complete infiltration, the melt was allowed to solidify in furnace atmosphere. During solidification, the Al alloy penetrates into the pores of the SiC foam, forming the C4 as shown in Figure 1. The composite was machined out by a series of parting and milling process.

2.2 Property assessment of C4 The mechanical properties of the fabricated C4 were obtained through various tests. The testing methods and standards utilized are tabulated in Table 1.

2.3 Ballistic Testing of C4 Ballistic test was conducted on the fabricated C4 of dimensions \( \phi 100 \times 15 \) mm using a projectile from a Walther GSP Expert LR target pistol possessing a 0.22 caliber barrel. The projectile used was a steel core bullet, topped with a lead cap as shown in Figure 2. The projectile was fired from a distance of 10 m. The weight of a bullet was 40 grain with a rated velocity of 1070 fps (326 m/s), categorized as subsonic, medium velocity in ballistic testing.

![Figure 1. Induction furnace depicting infiltration and solidified composite](image-url)
TABLE 1. Properties assessed and standards utilized

| S.No | Property         | Specimen dimension | Testing Method       | Standards         |
|------|------------------|--------------------|----------------------|-------------------|
| 1    | Volume fraction  | -                  | Water displacement   | Archimedes Principle |
| 2    | Hardness         | 1 in³              | Brinell hardness tester | ASTM E10         |
| 3    | Compression      | 1 in³              | Universal testing machine | ASTM D695     |
| 4    | Toughness        | 55 x10 x 10 mm³   | Charpy impact test   | ASTM A370         |

Figure 2. The target pistol and projectile

3. RESULTS AND DISCUSSION

3.1. Numerical Analysis of Ballistic Test

The objective of this numerical simulation is to estimate the DoP of the medium velocity projectile into the composite. Towards this, the interpenetrating network of C4 was approximated as a cube and modelled using Autodesk Inventor as shown in Figure 3. This assembled geometry was imported into ANSYS Workbench.

The material properties of the metal/ceramic phases and C4 were appended to the ANSYS library as detailed in Table 2. The results of the assessed properties of the C4 are presented in Table 3. The property assessments are performed based on the testing methods outlined in Table 1.

TABLE 2. Properties of constituent elements

| Property          | Unit   | AA5083 | SiC |
|-------------------|--------|--------|-----|
| Density           | g/cm³  | 2.85   | 3   |
| Young’s Modulus   | MPa    | 73100  | 2.76|
| Poisson Ratio     | -      | 0.33   | 0.14|
| Bulk Modulus      | Pa     | 7.166E+09 | 1.277E+09 |
| Shear Modulus     | Pa     | 2.748E+09 | 1.210E+09 |
| Tensile Yield Strength | MPa | 215   | 14   |
| Tensile Ultimate Strength | MPa | 320   | 240  |

TABLE 3. Assessed properties of C4

| S.No | Property     | Result                      |
|------|--------------|-----------------------------|
| 1    | Volume fraction | AA5083=75%, SiC=25%        |
| 2    | Hardness     | 91 BHN                      |
| 3    | Compression  | 588 MPa                     |
| 4    | Toughness    | 17 J                        |

This numerical model was approximated as a static structure and was meshed with an element size of 1 mm. Fixed supports were modelled on all the faces of the cube except on one face. Since the DoP is directly proportional to the impact kinetic energy [16], the impact force of the medium velocity projectile was modelled on this face, in accordance with Equation (1).

\[ F = \frac{\text{Kinetic Energy of bullet}}{\text{Distance to target}} = \frac{1}{2} \cdot m \cdot v^2 \cdot \frac{1}{d} \]  

where, \( m \) and \( v \) refer to the mass and velocity of the bullet, respectively. The term ’\( d \)’ denotes the distance to be travelled by the bullet for impact.

This impact force of the projectile was applied to the numerical model and the analysis revealed that, the maximum DoP of the projectile into the composite was 1.47 mm as shown in Figure 4.

Figure 3. 3D model of interpenetrating C4

Figure 4. Maximum deformation from ANSYS
3. 2. Inference from Ballistic Test In order to validate the simulation, ballistic tests were performed. Figure 5 shows the C4 composite before and after projectile impact. Though fragmentation of the C4 was not observed, it exhibited brittle fracture with cracks initiating at the impact site and progressing radially outward. Further, secondary cracks were detected at the interface of Al/SiC in the vicinity of impact site, suggesting the occurrence of debonding at the interface [17]. The maximum DoP and the diameter of the crater produced due to projectile impact were ascertained as 1.5 mm and 9 mm, respectively. This indicates that the fabricated C4 of AA5083/SiC can be used to defeat medium velocity projectiles with assured conformance.

![Figure 5. C4 before and after impact](image)

4. CONCLUSION

In this study, a C4 composite was fabricated with AA5083 and SiC as the metal and ceramic phases. Tests to assess its suitability for body armour were performed by means of numerical simulation and practical ballistic tests using a subsonic projectile. The values of DoP of both the tests were proximate to each other. Additionally, brittle fracture and debonding along the interface were observed on the C4. Further tests under high strain rate conditions utilizing AP projectiles at high velocity regimes can be explored in order to assess the suitability of AA5083/SiC C4 composites as affordable alternatives for body armour.

5. ACKNOWLEDGEMENT

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Persian Abstract
چکیده
کامپوزیت‌های سرامیکی همزمان با هم، که از آن به C4 یاد می‌شود، دارای مرحله‌های جدیدی، به‌هم پیوسته و متقابل انتقال فلز و سرامیک هستند. این امر باعث می‌شود کامپوزیت‌هایی با نسبت استحکام به وزن بالاتر نسبت به کامپوزیت‌های سنتی باشند. در این کار تحقیقاتی، یک کامپوزیت C4 از AA5083 / SiC یافت شد. این کامپوزیت با نسبت محاسباتی به ورق نسبت به کامپوزیت‌های سنتی مشابه بوده‌است. در این کار تحقیقاتی، یک کامپوزیت C4 به عنوان یک مدل شبیه‌سازی انتقال گرانش برای یک گلوله فرعی به سایر مدل‌های سازی C4 مورد استفاده قرار گرفت. یک سطح نفوذ C4 با سرعت متوسط ۳۲۶ متر بر ثانیه برای تأثیرگذاری بر نمونه C4 استفاده شد. نتایج نشان می‌دهد که C4 به عنوان یک کامپوزیت هوا به طور بالقوه می‌تواند باعث افزایش استحکام شکننده و جداگانه سطحی در C4 تحت تأثیر را نشان دهد. نتایج نشان می‌دهد که C4 به عنوان یک کامپوزیت هوا به طور بالقوه می‌تواند باعث افزایش استحکام شکننده و جداگانه سطحی در C4 تحت تأثیر را نشان دهد.