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

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P A P E R I N F O	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.

NOMENCLATURE

v	velocity of the bullet (m/s)	m	mass of the bullet (x 10^{-3} kg)
F	Impact force of the bullet (N)	D	distance to be travelled by the bullet for impact (m)
DoP	Depth of Penetration	C4	Co-Continuous Ceramic Composites
IPCs	Interpenetrating Composites	AP	Armour Piercing
FE	Finite Element	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 (Al_2O_3) 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 Al_2O_3 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 Al_2O_3 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 ϕ 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 800° C, 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 ϕ 100 x 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.
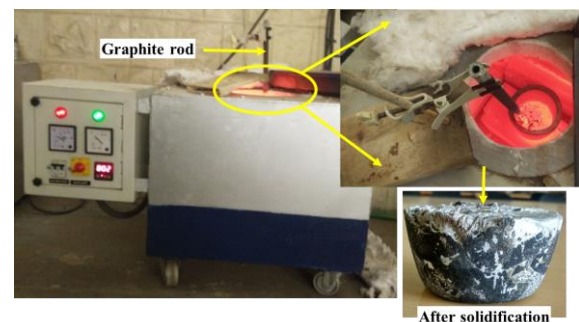

Figure 1. Induction furnace depicting infiltration and solidified composite

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 in^3	Brinell hardness tester	ASTM E10
3	Compression	1 in^3	Universal testing machine	ASTM D695
4	Toughness	55 ×10 × 10 mm^3	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/cm^3	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).

$$F = \frac{Kinetic\ Energy\ of\ bullet}{Distance\ to\ target} = \frac{\frac{1}{2}*m*v^2}{d} \tag{1}$$

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.
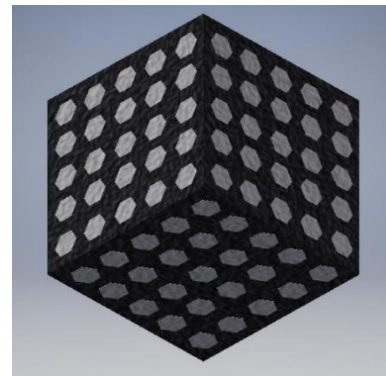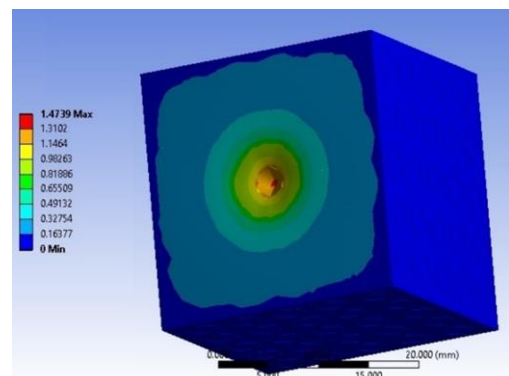

Figure 3. 3D model of interpenetrating C4

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 initating at the impact site and progressing radially outward. Further, secondary cracks were detected at the interface of Al/SiC in the vincity 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.
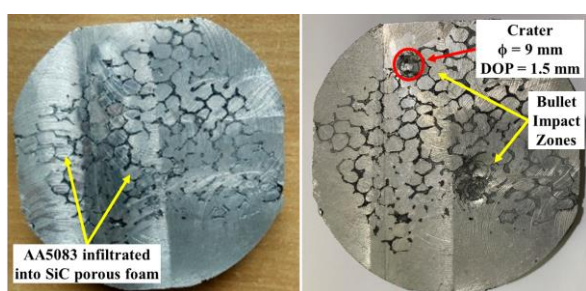

Figure 5. C4 before and after impact

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

6. REFERENCES

1.   Jiang, L., Jiang, Y. L., Yu, L., Su, N. and Ding, Y. D., "Experimental study and numerical analysis on dry friction and wear performance of co-continuous SiC/Fe-40Cr against SiC/2618 Al alloy composites", *Transactions of Nonferrous Metals Society of China*, Vol. 22, No. 12, (2012), 2913-2924. DOI: 10.1016/S1003-6326(11)61550-1

2.   Wang, Q., Zhang, H., Cai, H., Fan, Q., Li, G. and Mu, X., "Simulation analysis of co-continuous ceramic composite dynamic mechanical performance and optimization design", *Computational Materials Science*, Vol. 129, (2017), 123-128. DOI: 10.1016/j.commatsci.2016.12.009

3.   Daehn, G. S. and Breslin, M. C., "Co-continuous composite materials for friction and braking applications", *The Journal of The Minerals, Metals and Materials Society*, Vol. 58, No. 11, (2006), 87-91. DOI: 10.1007/s11837-006-0235-1

4.   Nong, X. D., Jiang, Y. L., Fang, M., Yu, L. and Liu, C. Y., "Numerical analysis of novel SiC 3D/Al alloy co-continuous composites ventilated brake disc", *International Journal of Heat and Mass Transfer*, Vol. 108, (2017), 1374-1382. DOI: 10.1016/j.ijheatmasstransfer.2016.11.108

5.   Fathya, A., Wagiha, M., Abd El-Hamida, M. and Hassan, A.A., "Effect of Mechanical Milling on the Morphology and Structural Evaluation of Al-Al$_2$O$_3$ Nanocomposite Powders", *International Journal of Engineering, Transactions A: Basics*, Vol. 27, No. 4, (2014), 625-632. DOI:10.5829/idosi.ije.2014.27.04a.14

6.   Munasir, N., Triwikantoro, T., Zainuri, M., Bäßler, R. and Darminto, D., "Corrosion Polarization Behavior of Al-SiO$_2$ Composites in 1M and Related Microstructural Analysis", *International Journal of Engineering, Transactions A: Basics*, Vol. 32, No. 7, (2019), 982-990. DOI: 10.5829/ije.2019.32.07a.11

7.   Gurgen S.,"A Numerical Investigation on Oblique Projectile Impact Behavior of AA5083-H116 Plates", *Politeknik Dergisi*, Vol. 22, No. 2, (2019), 293-301. DOI: 10.2339/politeknik.403994

8.   Kaufmann, C., Cronin, D., Worswick, M., Pageau, G. and Beth, A., "Influence of material properties on the ballistic performance of ceramics for personal body armour", *Shock and Vibration*, Vol. 10, No. 1, (2003), 51-58. DOI: 10.1155/2003/357637

9.   Chabera, P., Boczkowska, A., Morka, A., Kędzierski, P., Niezgoda,T., Oziębło, A. and Witek, A., "Comparison of numerical and experimental study of armour system based on alumina and silicon carbide ceramics", *Bulletin of the Polish Academy of Sciences*, Vol. 63, No. 2, (2015), 363-367. DOI: 10.1515/bpasts-2015-0040

10.   Moslemi Petrudi, A., Vahedi, K., Kamyab, M.H. and Petrudi, M., "Numerical and experimental study of oblique penetration of a blunt projectile into ceramic-aluminum target", *Modares Mechanical Engineering,* Vol. 19, No. 5, (2019), 1253-1263.

11.   Luo, D., Wang, Y., Wang, F., Cheng, H., Zhang, B. and Zhu, Y., "The influence of metal cover plates on ballistic performance of silicon carbide subjected to large-scale tungsten projectile", *Materials and Design,* (2020), 108659. DOI:10.1016/j.matdes.2020.108659

12.   Chang, H., Binner, J., Higginson, R., Myers, P., Webb, P. and King, G., "Preparation and characterisation of ceramic-faced metal-ceramic interpenetrating composites for impact applications", *Journal of Materials Science*, Vol. 46, No. 15, (2011), 5237–5244. DOI:10.1007/s10853-011-5461-4

13.   Poole, L.L., Gonzales, M., French, M.R., Yarberry III, W.A., Moustafa, A.R. and Cordero, Z.C., "Hypervelocity impact of PrintCast 316L/A356 composites", *International Journal of Impact Engineering,* Vol. 136, (2020), 103407. DOI:10.1016/j.ijimpeng.2019.103407

14.   Signetti, S., Bosia, F., Ryu, S. and Pugno, N.M., "A combined experimental/numerical study on the scaling of impact strength and toughness in composite laminates for ballistic applications", *Composites Part B: Engineering,* (2020), 108090. DOI:10.1016/j.compositesb.2020.108090

15. Prasanth, A.S. and Ramesh, R., "Investigation of Surface Roughness and Tool Wear in End Milling of Al7075-SiC Co-continuous Composite", in Materials Design and Applications, *Advanced Structured Materials*, Vol. 65, (2017), 315-327. DOI:10.1007/978-3-319-50784-2_24

16. Basyir, A., Bura, R. O. and Lesmana, D., "Experimental consideration of projectile density and hardness effect on its penetration ability in alumina target", *Journal of Defense Acquisition and Technology*, Vol. 1, No. 1, (2019), 9-15. DOI:10.33530/jdaat.2019.1.1.9

17. Rollings, L., Mcdonald, S., Roy, M. and Withers, P., "An investigation into the interface behaviour of an aluminium/silicon carbide fibre metal matrix composite", European Conference on Spacecraft Structures, Noordwijk, Netherlands, (2018).

Persian Abstract

چکیده

کامپوزیت های سرامیکی همزمان با هم ، که از آن به C4 یاد می شود ، دارای مراحل دو جداره ، بهم پیوسته و متقابل انتقال فلز و سرامیک هستند. این امر باعث می شود چنین کامپوزیت هایی با نسبت استحکام به وزن نسبت به کامپوزیت های سنتی بیشتر باشند. در این کار تحقیقاتی ، یک کامپوزیت C4 از AA5083 / SiC با استفاده از تکنیک نفوذ گرانش برای زره های بدن شخصی ساخته شده است. یک مدل شبیه سازی عددی از نمونه C4 تهیه شده است. این مدل المان محدود برای شبیه سازی DoP یک گلوله فرعی به C4 استفاده می شود و ۱.٤۷ میلی متر تخمین زده می شود. نمونه C4 سپس در معرض آزمایش های بالستیک قرار می گیرد. یک پرتابه با سرعت متوسط ۳۲٦ متر بر ثانیه برای تأثیرگذاری بر نمونه C4 استفاده می شود. آزمایش های بالستیک شبیه سازی عددی را با DoP 1.5 میلی متر اعتبار می دهد. بازرسی بصری ترک های شکننده و جداسازی سطحی در C4 تحت تأثیر را نشان می دهد. نتایج نشان می دهد که ، چنین کامپوزیت ها به طور بالقوه می توانند به عنوان زره بدن کم هزینه استفاده شوند.