
The Dynamic Properties of Sandwich Structures based on Metal-Ceramic Foams

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The Dynamic Properties of Sandwich Structures based on Metal-Ceramic Foams^{*}

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Abstract

The present research program has studied the fracture properties of closed pore metal-ceramic foams for their potential applications as core systems in sandwich structures. The composite foams were created at Fireline, Inc. (Youngstown, OH) using their TCON process. The microstructure and mechanical properties of two different composite foams were investigated. It has been observed that the TCON foam with a higher metallic phase by volume had better fracture properties. The investigated foam systems were also bonded between two skin materials constituted by alternating layers of thermoplastic composite and aluminum, in order to manufacture a hybrid sandwich structure. It was found that the low velocity impact properties of the sandwich structures were superior to those displayed by their constituent materials.

1. Introduction

The use of metal-ceramic foams as the core component of hybrid composite systems represents a feasible technological approach for the development of high-performance sandwich structures in the automotive, maritime, and aerospace sector. Indeed, sandwich structures are used in the transportation sector due to their high stiffness, and strength, in junction to their low weight features¹. Current sandwich structures are constituted by a core element based on aluminum honeycomb material, bonded between skin layers of composite material. Further modifications on the mechanical properties of sandwich structures have been performed by substituting either the core material or the skin layers². Indeed, whereas the skin layers have been replaced for a robust system constituted by alternating plies of composite and metal

sheets, also known as fiber metal laminates, the honeycomb core has been substituted by a low-density metal foam material. Certainly, it is widely known that metal foams are tough materials capable of absorbing impact and shock vibrations¹. They offer a unique combination of properties such as high stiffness and strength, low thermal conductivity and toxicity under fire³. Metal foams have also been used on multifunctional applications as heat exchangers and acoustic dampers. High-performance metallic foams have been used in integral armor systems for developing ballistic materials. It has been reported that they considerably reduce the dynamic deflection of backing plates⁴. Previous research works on sandwich structures based on aluminum foam have been carried out under high impact velocity conditions and it has been suggested a penetration performance similar to that offered by steel armor components, yielding impact energies up to 120J^{2,5}. Although, the use of metal foams on sandwich structures has certainly resulted on high-performance components for dynamic applications, further improvements are required to fully maximize their mechanical performance. An interesting option is the integration of lightweight metal-matrix composite (MMC) foams as the core constituent of sandwich structures. MMC foams have shown superior compressive properties than those exhibited by metallic foams, making them a promising structural material for applications in the aerospace sector⁶. An attractive feature of the MMC foams is that their mechanical properties can be particularly tailored through the incorporation of specific hollow particles⁷. It has been reported that foams based on spherical hollow particles are strain rate sensitive structures resulting on compressive strengths up to 30% higher than the displayed by metal foams⁸.

Novel MMC foams have been synthesized by a Reactive Penetration Metal (RPM) process developed by TCON-Fireline, Inc. The TCON process involves immersing a ceramic preform (typically silica, SiO_2) in a molten aluminum (Al) bath, creating an aluminum/alumina (Al_2O_3) interpenetrating phase composite (IPC). The resulting composite is approximately 65% Al_2O_3 and 35% Al. A typical image of the microstructure of the TCON IPC is observed in Figure 1.

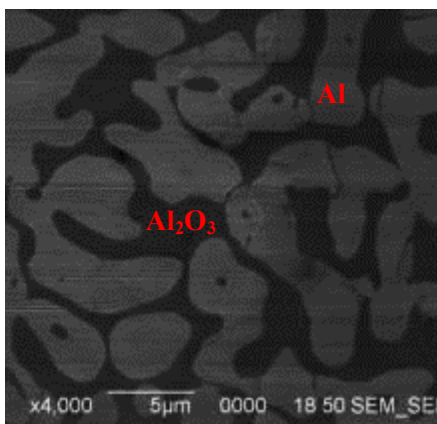


Figure 1. Scanning electron micrograph of TCON IPC. The darker phase is aluminum and the lighter phase is alumina⁹.

The TCON material is known for its impressive mechanical properties compared to its pure metallic and ceramic parts^{10,11}. The TCON process allows the modifications of the ceramic precursor and molten metal to optimize the final properties of the composites for specific applications. The TCON foams studied here had a general composition based on aluminum, silicon carbide (SiC), aluminum oxide and silicon (Si). Two samples labeled TCON A and TCON B were created using pure aluminum or aluminum alloy baths. TCON A had a precursor material consisted of SiO_2 , SiC, and hollow Al_2O_3 spheres. In contrast, TCON B's precursor consisted of a fiber material, which is a proprietary reinforcement developed by Fireline, Inc., and hollow Al_2O_3 spheres. Here,

the hollow spherical particles were added in an attempt lower the density of the foam system.

The present paper investigates the fracture properties of two different TCON foams, as well as their integration within FMLs to manufacture a new breed of sandwich structures. These sandwich structures have been subjected to low velocity impact tests and their performance has been characterized.

2. Experimental Procedure

The composites TCON A (2.566 g/cc) and B (2.378 g/cc) were developed at Fireline, Inc. in Youngstown, Ohio. The composites were received as 102 x 102 x 6.35 mm plates and test bars based on 102 mm in length, 12.85 mm in height, and 6.25 mm in thickness. Here, whereas the plates were used for studying their impact properties, the test bars were used in determining their fracture toughness and modulus of rupture. The fracture toughness was performed following the ASTM C1421-10 procedure, and the modulus of rupture, using the ASTM C133 with a support span of 77.2 mm and a strain rate of 0.5 mm/min. Low velocity impact tests were performed using a full instrumented drop impact tower. The impact force was recorded through a load cell attached to the impactor, and the plate deflection was measured using a high-speed video-camera. Here, a number of impact energies were explored to determine the perforation impact energy of the MMCs.

The as-received as well as the fractured composites were analyzed via scanning electron microscopy using a JEOL JIB 4500 multi-beam system. Elemental analysis was also investigated by using an EDAX™ Apollo SDD EDS detector. Powder x-ray

diffraction patterns were collected using a Bruker D8 Advance diffractometer with Cu-K α radiation.

3. Results and Discussion

3.1. Characterization, Microstructural Analysis and Mechanical Properties of TCON A and B

TCON A was created by immersing a SiO $_2$, SiC, and Al $_2$ O $_3$ hollow spheres precursor in an aluminum alloy. The spherical particles were added into the precursor material to create pores that imitate foam materials. It was found that some of the spheres were infiltrated by the molten aluminum. Figure 2 shows the microstructure of TCON A.

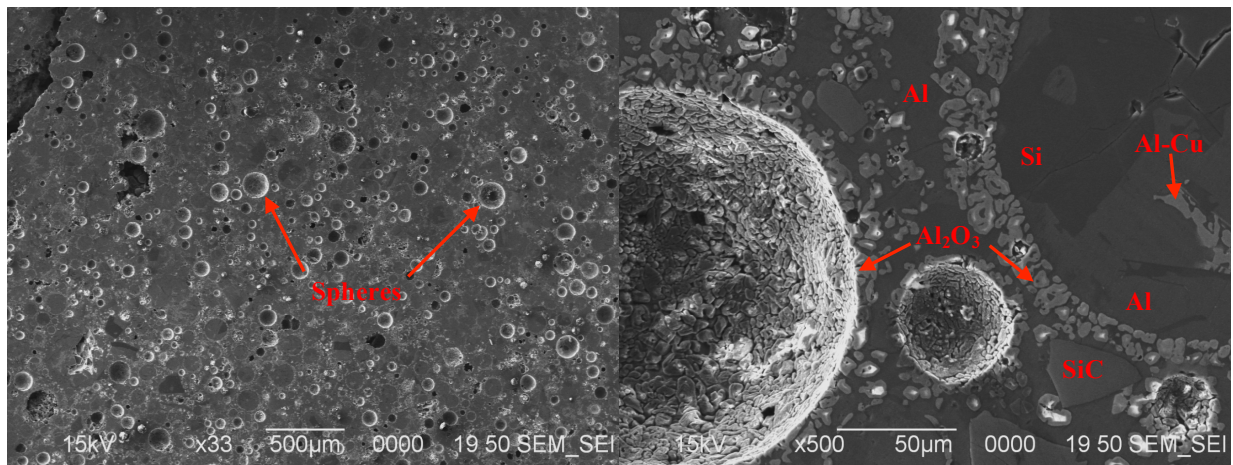


Figure 2. Scanning electron micrographs of TCON A. Left – polished cross section of TCON A showing the spherical particles. Right – Higher magnification polished cross section of TCON A showing one sphere not filled (left) and one sphere filled with metal (right) with EDS characterization.

Further SEM analysis on the TCON A foam, showed that the infiltration was due to cracks or holes in the spherical particles. TCON B was created using a fiber material and Al_2O_3 spheres immersed in pure aluminum metal. The microstructure of TCON B can be seen in Figure 3.

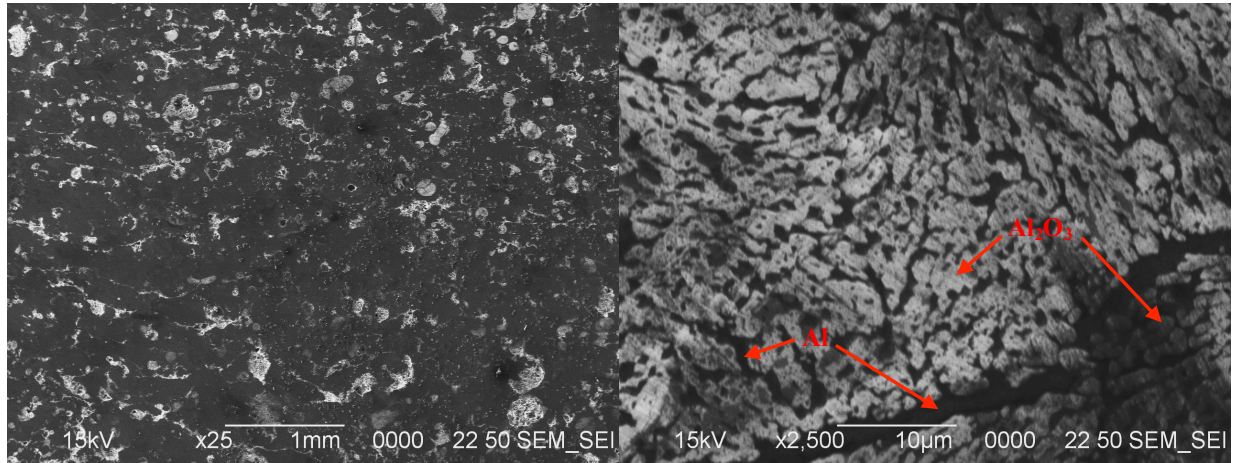


Figure 3. Scanning electron micrographs (secondary electron) of TCON B. Left – polished cross section of TCON B. Right – Higher magnification polished cross section of TCON B showing the fiber ceramic phase with EDS analysis.

Figure 3 does not show any defined spherical particles like TCON A does. This is because the spheres were added into the fibers and are visible only when the fibers are broken. It should also be noted that the TCON B foam has a much higher metallic phase by volume than TCON

A does. This is due to the high porosity of the fiber precursor material. TCON A and B were also subjected to x-ray diffraction (XRD) analysis (see Figure 4) and it was found that TCON A showed the presence of Al_2O_3 , Al, Si, and SiC, while TCON B only showed Al_2O_3 and Al. This is supported by the EDS analysis in Figures 2-3.

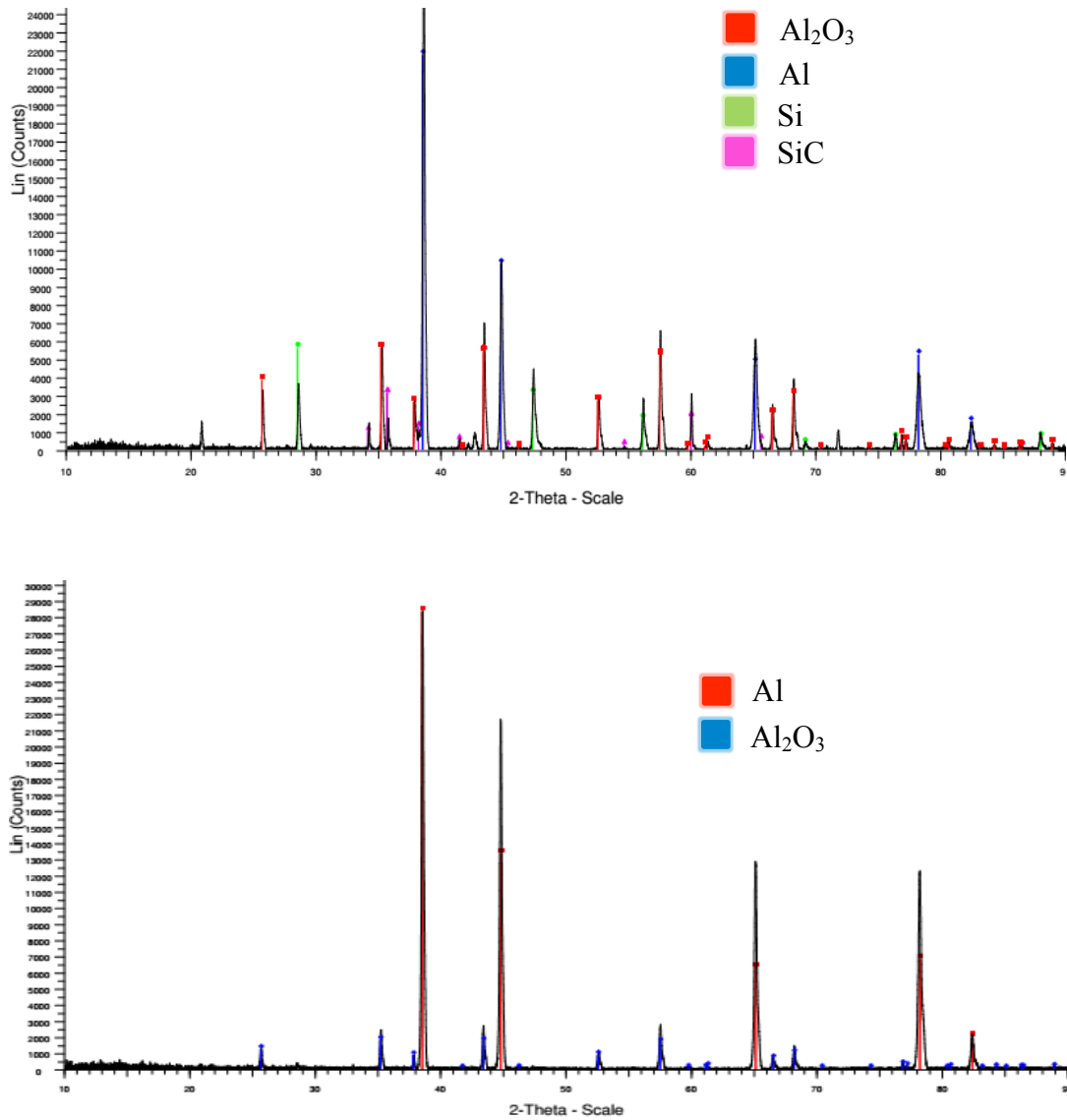


Figure 4. X-ray diffraction patterns of TCON A (top) and TCON B (bottom).

Samples of TCON A and B were subjected to a fracture toughness test (see figure 5 and 6) and a 3 point bending test to calculate their modulus of rupture (MOR). These results can be seen in Table 1.

Table 1. Fracture toughness and modulus of rupture calculated for TCON A and B.

	Fracture Toughness (MPa*m ^{1/2})	MOR (MPa)
TCON A	4.4	154
TCON B	4.7	122

The results show that the fracture toughness of TCON A and B are slightly higher than typical TCON which has a fracture toughness of 4.2 MPa*m^(1/2). The MOR of TCON A and B is also smaller than fully dense aluminum/alumina TCON which material which is approximately 120-130 MPa. The specific MOR of TCON A and B is 0.0600 and 0.0513 MPa*m³/kg respectively. In comparison the specific MOR of the foam TCON is higher than typical TCON which is 0.0400 MPa*m³/kg.

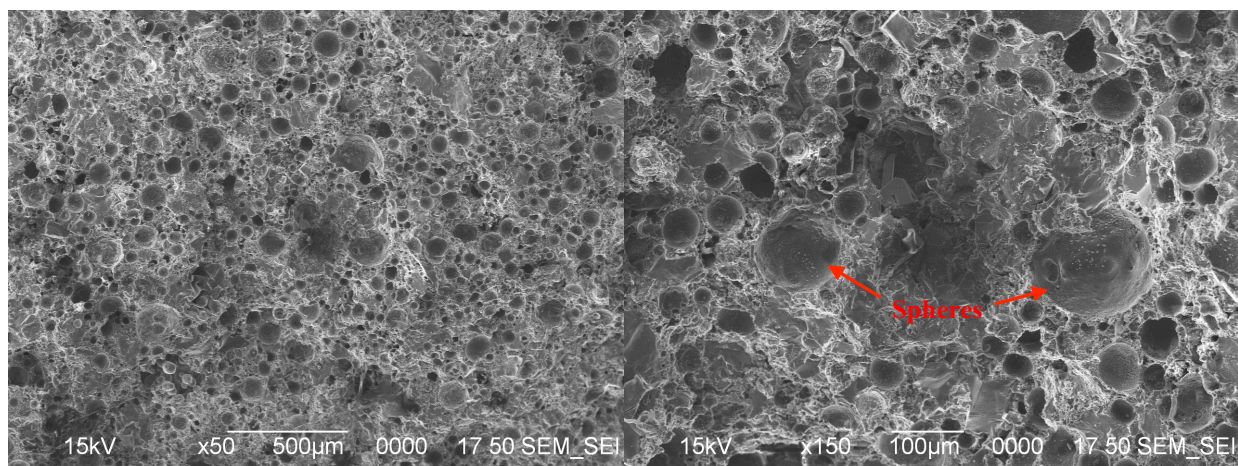


Figure 5. Scanning electron micrographs of the fracture surface of TCON A.

Figure 5 shows the fracture surface of TCON A. The micrograph shows that the crack propagates through the matrix as well as the alumina spheres. EDS analysis showed the presence of alumina on bottom of the empty spheres. The fracture surface of TCON B can be seen in Figure 6.

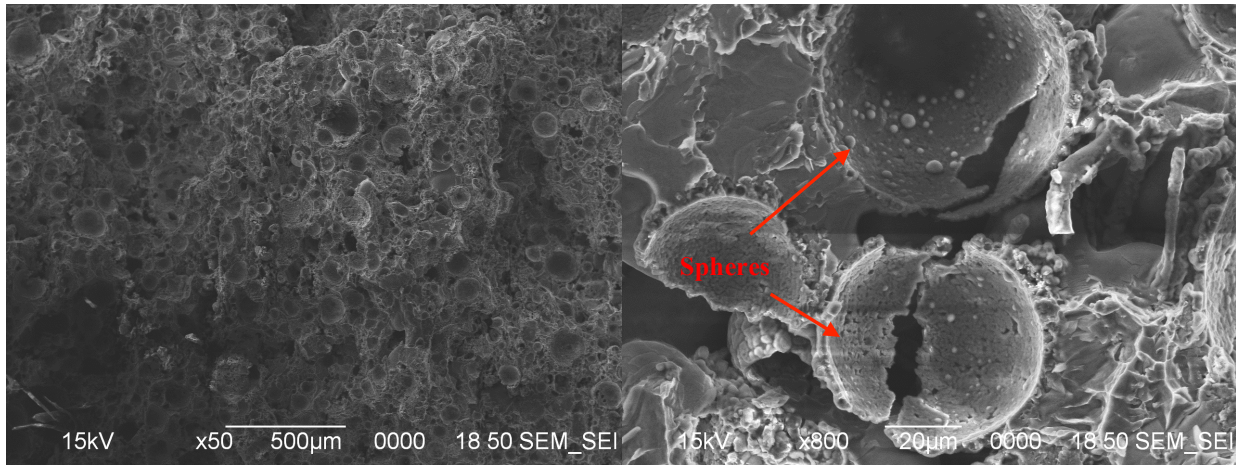


Figure 6. Scanning electron micrographs of the fracture surface of TCON B.

Figure 6 shows the fracture propagation was mostly through the spherical particles supporting the superior fracture toughness of TCON B over TCON A.

3.2. Velocity Impact Testing of TCON Foam and Sandwich Structures

Both TCON A and B were subjected to low velocity impact testing. It was found that TCON A was able to absorb an impact energy up to 15.5 J without breaking and TCON B supported an energy of 70.4 J. It was also found that whereas TCON A showed a brittle fracture, TCON B showed a ductile fracture (see Figure 7).

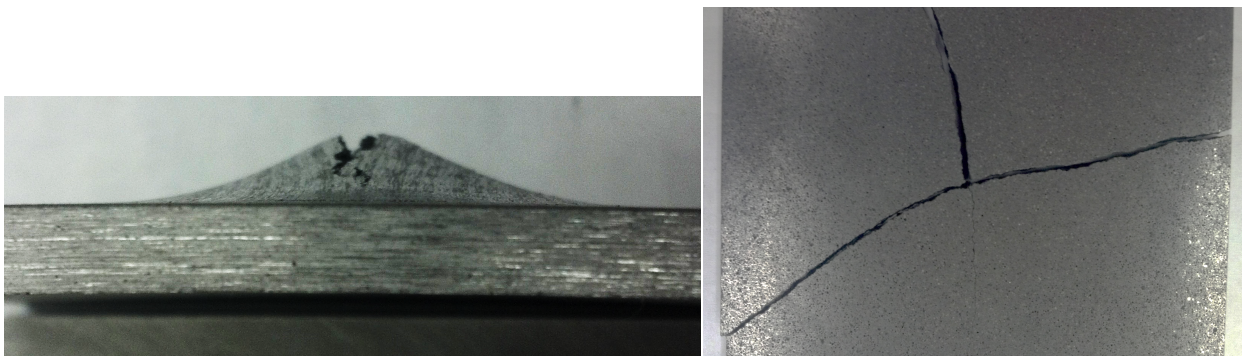


Figure 7. Images of TCON B (left) showing a ductile fracture and TCON A (right) showing a brittle fracture.

Even though TCON B showed to be a more promising material for low velocity impact events, both TCON A and B were incorporated within FML skin layers to manufacture sandwich structures. The TCON A sandwich composite was able to with stand an impact energy of 83 J without breaking. An image of the sandwich structure after absorbing energy can be seen in Figure 8.

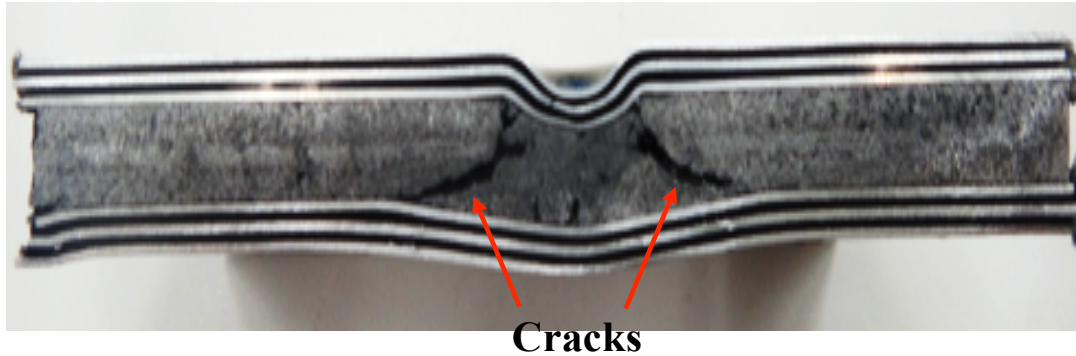


Figure 8. Image of TCON A sandwich composite after absorbing 83 J of energy.

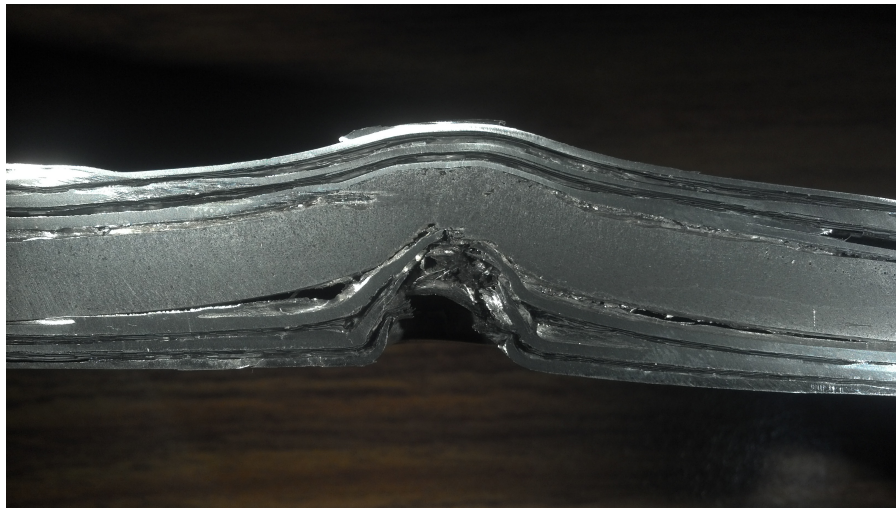


Figure 9. Image of TCON B sandwich composite after absorbing 252 J of energy.



Figure 10. Image of TCON A sandwich composite after absorbing 252 J of energy.

The figure shows that at this impact energy the sample is actually broken, but the FML skin has not been fully penetrated. In contrast, the TCON B sandwich was able to absorb 252 J of energy without breaking (see Figure 9). The figure shows that at this impact energy the foam does not show visible cracks. It was further observed that the impact energy was absorbed through a skin-core interfacial delamination. For comparison purposes, the TCON A sandwich was subject to 252 J of impact energy (see Figure 10). It was observed that at this energy sample was perforated.

Indeed, TCON B and its sandwich structure have great impact resistance, its density is larger than typical foam materials. It is appropriate to show the materials specific energy absorption. The specific energy absorption of the sandwich structures of TCON A and B are 4.6 and 9.4 Jm^2/kg . In comparison, aluminum foams were perforated at an impact energy of 130 J with a specific impact energy of $11.0 \text{ Jm}^2/\text{kg}$.² It is worth mentioning that TCON B at the specific impact energy was not broken. This implies that the TCON B

sandwich structure can absorb more impact energy without breaking. A summary of the results of the low velocity impact testing can be seen in Table 2.

Table 2. Summary of the impact energies absorbed by the foams and sandwich structures here studied.

	Impact Energy (J)	Specific Impact Energy (Jm²/kg)
TCON A	15.5	1.1
TCON B	70.4	4.6
Sandwich TCON A	83	3.0
Sandwich TCON B	252	9.4

4. Conclusions

A light weight interpenetrating phase composite was created using hollow spherical alumina particles as part of the precursor material. Two different TCON composites (A and B) were investigated by microscopy and x-ray diffraction. The fracture toughness of the TCON A and B were determined be 4.4 and 4.7 MPa*m^{1/2} respectively and the modulus of rupture was 154 and 122 MPa respectively. Sandwich composites of each TCON material and fiber metal laminates were constructed. Low velocity impact testing was completed using a drop impact tower instrument on the TCON material itself and their sandwich composites. It was found that TCON B was able to absorb more energy without breaking, and that its sandwich composite could absorb up to 252 J of energy making it a viable core impact resistant material for sandwich structures. Additional research work is currently being performed on the aforementioned foams and sandwich structures, by subjecting them to high velocity

impact tests, as well as to high strain loading rates. The outcomes of these latest efforts will be shortly disseminated in an appropriate engineering journal.

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