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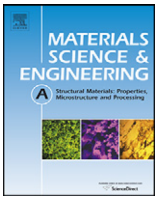

High strain rate characteristics of 3-3 metal–ceramic interpenetrating composites

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ABSTRACT

3-3 interpenetrating composites (IPCs) are novel materials with potentially superior multifunctional properties compared with traditional metal matrix composites. The aim of the present work was to evaluate the high strain rate performance of the metal–ceramic IPCs produced using a pressureless infiltration technique through dynamic property testing, viz. the split Hopkinson's pressure bar (SHPB) technique and depth of penetration (DoP) analysis, and subsequent damage assessment. Though the IPCs contained rigid ceramic struts, the samples plastically deformed with only localised fracture in the ceramic phase following SHPB. Metal was observed to bridge the cracks formed during high strain rate testing, this latter behaviour must have contributed to the structural integrity and performance of the IPCs. Whilst the IPCs were not suitable for resisting high velocity, armour piercing rounds on their own, when bonded to a 3 mm thick, dense Al_2O_3 front face, they caused significant deflection and the depth of penetration was reduced.

1. Introduction

For an armour tile to be effective, it needs both high penetration resistance and the capability of withstanding more than a single impact. Whilst a high compressive strength is a fundamental requirement for a light armour, the lack of ductility in tension is sometimes the cause for the catastrophic failure [1]. Typically, although ceramics are attractive materials for ballistic applications in terms of their abrasion resistance, which can blunt/erode the incoming projectiles and absorb the energy, hence defeating the threat, they have poor multi-hit potential, shattering after as little as one impact and needing to be replaced [2]. Such deficiencies can be at least partially addressed nowadays via the use of a mosaic approach and constraint.

On the other hand, metal matrix composites (MMCs) have been shown to display a number of useful properties for a wide range of different applications, including improved strength, stiffness, hardness, light weight, wear and abrasion resistance, lower thermal expansion coefficients and better resistance to elevated temperatures and creep compared to the matrix metal, whilst retaining adequate electrical and thermal conductivity, ductility, impact and oxidation resistance [3–5]. As a result, they are being increasingly used in applications such as aerospace and defence components [6–9].

Amongst the MMCs, 3-3 interpenetrating composites (IPCs) consisting of 3-dimensionally interpenetrating matrices of metallic and ceramic phases are interesting materials with potentially superior properties compared with traditional dispersed phase composites [10]. One of the most widely used methods to fabricate IPCs is the infiltration of molten metals into ceramic foams or powder beds [11]. Whilst infiltration under pressure, such as squeeze casting, offers high efficiency, it has difficulty in fabricating complex shaped components and risks damaging the ceramic preform. Pressureless infiltration approaches avoid these limitations [12]. By careful control of the thermo-atmospheric cycle and the use of precursor coatings, a range of molten aluminium alloys can be successfully infiltrated into a number of ceramic foam compositions, including alumina, mullite and spinel [13–15]. Properties of the IPCs have been studied by the authors, which have shown promising wear resistance, as well as flexural properties and ductility [16,17]. However, the high strain rate performance of the IPCs is yet to be studied.

The objective of the present work was to manufacture IPCs using the pressureless infiltration technique and then to evaluate their performance using both SHPB and DoP approaches. The effect of the density of the precursor Al_2O_3 foams on the subsequent high strain

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rate performance of the composites was studied and the resulting damage to the system was thoroughly assessed.

2. Experimental

2.1. Processing

The precursor Al_2O_3 foams were supplied by Dyson Thermal Technologies, Sheffield, UK. Made by gel casting an aqueous suspension of two grades of Al_2O_3 powders with mean particle sizes of 0.5 μm (CT3000, SG, Alcoa Industrial Chemicals Europe, Frankfurt, Germany), and 6 μm (MDS-6, Panadyne^{TM}, Pennsylvania, USA) in a ratio of 10 to 1, the foams measured 70 mm in diameter by 10 mm thick and had densities of 15–35% of theoretical and cell sizes in the range of 50–200 μm. An Al–8 wt.% Mg alloy, selected on the basis of previous research [15], was used as the infiltrant. Whilst full details of the process route are described elsewhere [15,18], in brief the Al_2O_3 foam samples were placed on top of similarly shaped and sized discs of the alloy, the metal–ceramic couples being contained in alumina boats. These were heated at 20 °C min^{-1} in flowing Ar in a tube furnace; the ceramic foam was infiltrated with the metal in a tube furnace at 915 °C in pure N_2. A holding time of 30–60 min was sufficient for complete infiltration. One additional series of samples was made in which individual 10 mm diameter 3 mm thick, slip cast, dense alumina discs were attached to Al–Mg/15% Al_2O_3 IPCs *in situ* during the infiltration process by providing excess metal which formed an interfacial layer between the ceramic front face and IPC backing. Microstructural observation revealed that the process worked extremely well with the foam being completely infiltrated and the ceramic facing being bonded onto the IPC with no gaps or residual porosity.

2.2. High strain rate evaluation

Initial evaluation of the high strain rate characteristics of the composites was carried out using the split Hopkinson's pressure bar (SHPB) technique, on samples measuring 9 mm in diameter and 4.5 mm in thickness. The stress–strain curve of the composite was obtained from the analysis of the incident wave, the reflective wave and the transmitted wave [19]. Three sets of strain rates were aimed to be produced by using three different apertures in the sealing plug, namely, apertures of Φ8 mm, Φ12 mm and Φ20 mm. Due to the different characteristics of the samples selected, i.e. ceramic content hence hardness, the strain rates calculated following the SHPB test varied amongst groups of samples. The Al–Mg/30% Al_2O_3 IPC, in particular, showed lower strain rates than the others whilst further attempts to achieve higher strain rates in this IPC often resulted in damage in the strain sensors embedded on the bars. The depth of penetration, DoP, ballistic evaluation of the composites was performed by Permali (Gloucester) Ltd. using 7.62 mm, steel tipped, armour piercing (AP) rounds at a velocity of 700 ± 20 ms^{-1}. The composites were glued onto an aluminium backing with a thickness of ~50 mm. The residual energy of the bullet after passing through the target composite was indicated quantitatively by the depth of penetration of the round into the backing, this was ascertained by cutting the backing aluminium in half to reveal the DoP.

2.3. Microstructure characterisation and damage assessment

For polarized light microscopy, the IPCs were ground and polished metallographically using diamond paste and then anodized using 5% fluroboric acid at 20 V for about 90 s. For Scanning Electron Microscopy (SEM) observation (1530VP FEG SEM, LEO Elektronenskopie GmbH, Oberkochen, Germany), the samples were given a final polish using 0.02 μm colloidal silica prior to observation. TEM foils (examined using a 2000FX, Jeol, Tokyo, Japan) were specifically prepared from the metal–ceramic interface using a Dual Beam Focused Ion Beam (FEI – Nanolab 600, FEI Europe, Eindhoven, The Netherlands) from both SHPB and DoP tested composites; the latter samples were produced from near the impact site.

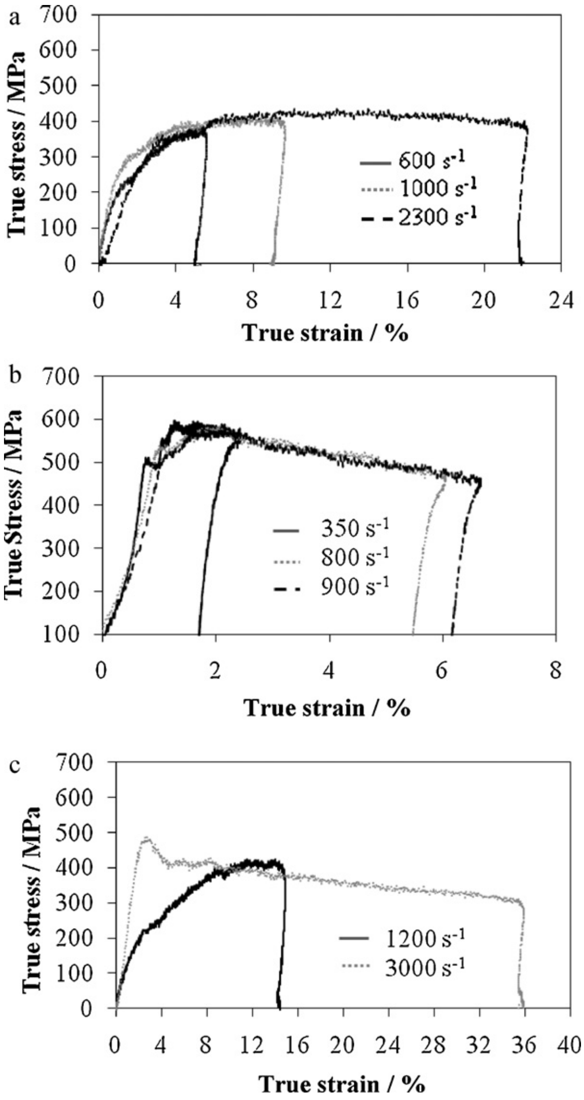

Fig. 1. True stress–strain curves of (a) Al–Mg/15% Al_2O_3, 50–100 μm average cell diameter; (b) Al–Mg/30% Al_2O_3, 50–100 μm average cell diameter; and (c) Al–Mg/25% Al_2O_3, 100–200 μm average cell diameter.

3. Results

3.1. Ballistic testing

Representative SHPB results are shown in Fig. 1. Although the IPCs contained a continuous Al_2O_3 network throughout their structure, they yielded at ~1–2% strain then displayed plastic deformation, behaviour more typical of a metallic material, and they remained macroscopically intact without shattering or falling apart. With an increase of strain rate, the yield strength of all the IPCs increased, showing strain rate sensitivity of the yield strength. For the Al–Mg/15% Al_2O_3 IPC, the curves are all of very similar shapes and the increase in the strain is purely a result of a higher impact velocity. With an increase in ceramic content in the IPC, the yield strength and the maximum true stress observed increased monotonically, obeying the role of mixture. The Al–Mg/30% Al_2O_3