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Mechanical response of discontinuous ceramic fiber reinforced metal matrix composites under quasi-static and dynamic loadings

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ABSTRACT

The quasi-static mechanical properties and ballistic impact performance of several discontinuous ceramic fiber (Saffil) reinforced Al–2% Cu metal matrix composites (MMC) are characterized. The ballistic penetration resistance of the materials are determined against a fragment simulating projectile and compared to the performance of the baseline matrix alloy. Digital image correlation with high speed photography is used to measure the full field deflection of the materials during impact. Mechanical behavior and post-mortem fracture analysis are used to relate material properties to performance in penetrating and non-penetrating impact events. It is demonstrated that the MMC materials exhibit a strong asymmetry in their tensile and compressive responses. The MMC materials are stronger in compression and the asymmetry in response increases with increasing volume fraction of fiber. It was found that the ballistic performance (V_{50}^{BL}) decreases when the volume fraction of fiber is greater than 3% due to the decrease in tensile strain to failure at higher volume fractions. In non-penetrating impacts the increased stiffness and strength with higher volume fractions greatly reduces the magnitude and distribution of plate deflection.

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1. Introduction

Ceramic fiber reinforced metal matrix composites (MMC) are being explored as lightweight alternatives to traditional structural metals. These materials can achieve high specific strength and stiffness, however, the utilization of these materials as structural design components has been extremely limited due to their characteristically low ductility and brittle fracture behavior. An attractive benefit of MMC materials is the ability to easily tune the mechanical properties of the material by controlling the volume fraction and morphology of the reinforcement phase to suit a specific application's performance requirements for stiffness, ultimate strength, and strain to failure [1–6]. Due to the success of MMC materials in improving the hardness and high temperature performance compared to the unreinforced metal matrix alloys, recent research has been mostly focused on wear [7,8] and high temperature creep [9] applications. Comparatively, little research has been conducted into the ballistic and high strain rate behavior of metal matrix composites [10–12]. High strain rate characterization is critical for developing and validating constitutive models used to predict the progressive damage and failure of metal matrix composites during a dynamic loading event such as the model presented by Deliktas et al. [11,13].

In this work the effect of volume fraction on the mechanical behavior and dynamic impact response and failure mechanisms of discontinuous ceramic (aluminum oxide) fiber reinforced aluminum alloy matrix is characterized. MMC materials were fabricated containing short fiber reinforcement over a volume fraction range of 3–30% and subjected to ballistic impact testing and compared with the base alloy. Microstructural characterization of fractured specimens and mechanical testing were used to characterize the failure mechanisms and deformation response of the materials under dynamic loading conditions.

2. Experimental

2.1. Materials

MMC materials were fabricated using an infiltration casting process by CPS Technologies (Norton, MA). The matrix alloy used was Al–2% Cu (0.01 wt% Si, 0.01 wt% Fe and 2.17 wt% Cu). The reinforcement phase was Saffil® short fiber Al_2O_3 in preforms of 4%, 7%, 15%, and 30% volume fraction. The Saffil® fiber has a chemical composition of 95–97% Al_2O_3 with 3–5% SiO_2, with a median diameter of 3.0–3.5 μm, density of 3.4 g/cm3, Young's

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modulus of 300 GPa, and ultimate tensile strength of 1.5 GPa [14]. The fibers in the pre-forms and final MMC have a nearly random in-plane (2D) orientation with very little out-of-plane (transverse) fiber content [9,15–17]. For aluminum with 2 wt% copper, the equilibrium phase diagram indicates that when the temperature drops below the liquidus line, the solid-solution phase (α) solidifies first, while most of the copper remains in the liquid form. The solid-solution (α) region (below 0.1 wt% Cu), is where the alloying atoms remain dissolved by substituting aluminum atoms in the aluminum/face-centered cubic face centered cubic (fcc) lattice. As solidification progresses, the temperature approaches the solidus and α solid phase becomes more enriched with copper. When the temperature finally drops below the solidus temperature in alloys containing less than the maximum solubility (5.65 wt% Cu), solidification is complete to the solid-solution phase condition (α). In this solid-state region below the solvus line, dispersed particles of the θ ($CuAl_2$) intermetallic precipitate in a supersaturated aluminum–copper solid solution. This however, assumes complete equilibrium. For alloys containing less than the maximum solid solubility under commercial casting conditions, the eutectic reaction can occur and $CuAl_2$ particles form during solidification of most aluminum alloy ingots and shaped castings. Under slow cooling conditions, the α solid solution contains little copper, so strength is low. The Al_2Cu intermetallic can be detrimental, depending on the extent and coarseness of the Al_2Cu particles.

Microstructures of polished Al–2% Cu and 7%, 15%, and 30% Saffil MMC materials are shown in Fig. 1, and higher magnification microstructures of the MMC materials are shown in Fig. 2. All MMC microstructures were taken perpendicular to the plane of isotropic fiber loading. The Al–2% Cu matrix microstructure consists of primary and secondary dendrites of the α (Al–Cu solid solution) phase (dark) and dispersed particles of the θ ($CuAl_2$) intermetallic precipitates and/or eutectic phase (light). The secondary dendrite arm spacing (SDAS) depends on the local solidification time and cooling rate [18]. The θ ($CuAl_2$) intermetallic phase is approximately 10 μm × 10–100 μm.

In the MMC microstructures, the Saffil fibers, with a circular cross section, are clearly visible as the dark phase and the matrix appears as the lighter phase. Fiber cross sections, perpendicular to their length also visible due to random in-plane distribution previously described. In the 7% Saffil MMC the dendrite spacing is on the order of ~100 μm. The light phase is the eutectic θ ($CuAl_2$) phase and is observed to generally occur at fiber clusters. The size of the θ phase is relatively fine compared to the neat matrix alloy, on the order of ~5–20 μm. Fine porosity is also observed at fiber clusters. Given the low thermal conductivity of the alumina fibers, and the presence of the eutectic phase at the fibers and near the porosity, this porosity is most likely micro-shrinkage which occurs when liquid metal cannot reach interdendritic areas during solidification. It is caused by a combination of shrinkage and gas evolution, being the standard foundry defect for mushy-freezing alloys, such as many common aluminum alloys. As the volume fraction of reinforcement fiber is increased the dendrite spacing and size of the θ phase can be seen to decrease further. The dendrite spacing is on the order of ~10 μm in the 15% and 30% Saffil MMC. The size of the θ phase is further refined from that of the low volume fraction material to ~1–2 μm. The 15% and 30% Saffil MMC materials also show significantly more porosity at fiber clusters than the 7% and unreinforced Al–2% Cu materials.

2.2. Quasi-static mechanical testing

Quasi-static tensile testing was conducted on the Al–2% Cu matrix alloy and the four MMC materials containing 4%, 7%, 15%, and 30% Saffil® short fiber reinforcement. The MMC materials were tested parallel to the direction of dominant fiber loading to determine the in-plane tensile behavior. Flat rectangular tensile specimens of 0.5 mm thickness were tested according to ASTM D 3552 (the standard test method for tensile properties of fiber

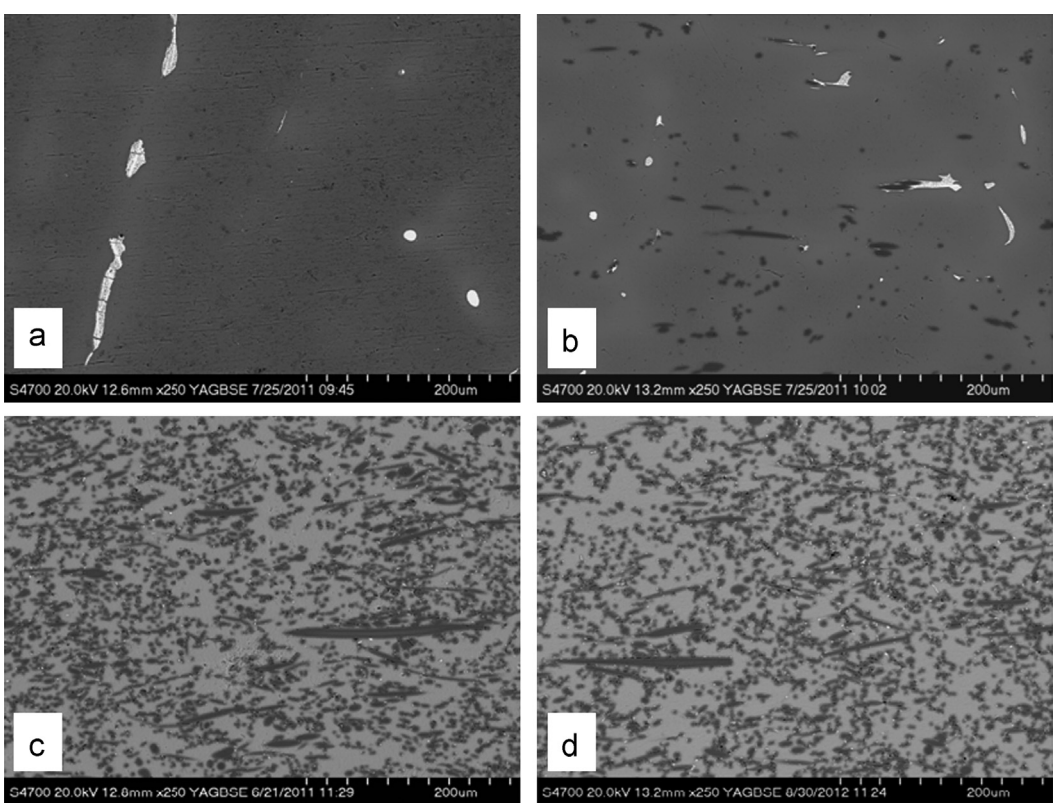

Fig. 1. SEM micrographs of polished specimens of Al–2% Cu matrix alloy (a), 7% Saffil MMC (b), 15% Saffil MMC (c), and 30% Saffil MMC (d).

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