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Ballistic impact behavior of woven ceramic fabric reinforced metal matrix composites

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ABSTRACT

In this paper, the effect of weave architecture on the ballistic impact response of woven fabric metal matrix composites (MMC) is investigated. The ballistic limits, V_{50}^{BL}, of four different composites are experimentally determined and post impact characterization is used to investigate the damage mechanisms active during dynamic loading. Numerical modeling implementing an elastic–plastic orthotropic material model with hydrostatic pressure dependent yield surface is used to model the pressure dependent response of the MMC during impact to predict the ballistic limit, and to offer insight into the damage mechanisms occurring during dynamic loading of woven fabric reinforced MMC. The correlation between laterally constrained compression testing and ballistic performance is investigated for use as a screening tool to enable rapid evaluation of the relative ballistic performance of potential fabric MMC weave and composite designs as a potential alternative to full scale ballistic testing. It was found that the fabric architecture has significant effect on ballistic performance and through thickness shear strength of the MMCs. It was found that 3D woven MMC is 13% and 40% lower in terms of ballistic limit and through thickness shear strength respectively, than its 2D counterpart. Furthermore, the numerical results successfully predict the ballistic limit of a 2D fabric reinforced MMC within 6% of the experiment and are used to qualitatively elucidate the experimentally observed damage mechanisms.

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1. Introduction

Ceramic fiber reinforced metal matrix composites (MMC) combine the high stiffness and high strength of ceramics with the plastic dissipation energy capacity of metallic alloys which offers promise as lightweight alternatives to traditional high strength monolithic metallic alloys. These materials have the added benefit of tunable properties in which mechanical properties, such as Young's modulus, tensile strength, and elongation, can be altered to meet design requirements by varying the volume fraction of reinforcement phase [1–4]. Unidirectional continuous fiber reinforced MMC offer the greatest increase in stiffness and strength in the longitudinal direction [5,6]. However the resulting transverse properties are typically poor [7,8], which is remedied by designing laminated cross ply or woven fabric structures.

The majority of the mechanical characterization of continuous unidirectional alumina fiber reinforced aluminum that has been reported in the literature has focused on studies of the strength and deformation mechanisms of the composite loaded along the fiber axis at quasi static strain rates [5,6,9–11], and comparatively little literature exists on the behavior of woven fabric MMC [8,12], or under high strain rate dynamic loading conditions [7,13]. Most examples of the ballistic impact behavior of MMC that have been previously studied are for particle reinforced MMC [14,15] and short fiber reinforced MMC [16,17], with comparatively little reported for fabric MMC. The ballistic impact behavior of MMC has received less attention in the literature than fiber reinforced polymer matrix composites of which many examples can be found annually, e.g. Refs. [18–20]. The complex interaction of dynamic stress waves during ballistic impact provides the opportunity to simultaneously observe the high strain rate loading response under various triaxialities including tension, compression, and shear. As such, the experimental characterization of deformation and failure mechanisms during ballistic impact of fabric reinforced MMC is

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critical for designing high performance lightweight structures and for developing and validating constitutive models used in modeling tools [21–23] used to predict the performance of composite structures in service conditions involving penetration and perforation.

In this paper, the effect of weave architecture on the impact response of four different woven fabric MMCs is investigated. Numerical modeling is used to offer insight into the damage mechanisms occurring during ballistic impact of woven fabric reinforced MMC. In addition, laterally constrained compression testing is used to measure the fiber shear strength and through thickness crush strength of the MMC. The correlation between this data and the results of ballistic limit testing is investigated for use as a screening tool to enable rapid evaluation of the relative ballistic performance of potential fabric MMC weave and composite designs as a potential alternative to full scale ballistic testing.

2. Experimental

2.1. Materials

An inert gas pressure infiltration casting process by CPS Technologies (Norton, MA, USA) was used to produce fabric reinforced aluminum metal matrix composite plates of 0.25″ (6.35 mm) nominal thickness. The matrix alloy used was aluminum with 2% copper (0.01 wt% Si, 0.01 wt% Fe and 2.17 wt% Cu). The fabrics were woven using rovings consisting of continuous Nextel 610™ (3M, St. Paul, MN, USA) alumina (Al_2O_3) fibers. The ceramic fiber is greater than 99% α-Al_2O_3 with a diameter of 10–12 μm, density of 3.9 g/cm^3, tensile modulus of 380 GPa, and tensile strength of 3100 MPa [24]. Four fabrics with different weave architectures were produced to investigate in the present study. They are shown schematically in Fig. 1. The first fabric (0/90 3 K) consists of a 2D fabric with plies of 3000 denier rovings in an 8-harness satin weave configuration. All plies were laid up such that the rovings were in a 0/90 configuration prior to infiltration. The second fabric (0/90 20 k) consists of 20,000 denier rovings woven in a 2D plain weave configuration which were laid up such that all rovings were in a 0/90 configuration. The third weave architecture (85/15) consists of 2D fabric plies with 85 percent of the fibers in the warp direction and 15 percent in the fill direction. The warp rovings were 20,000 denier and 3000 denier rovings were used for the fill. The final weave architecture investigated was an orthogonal 3D woven design with an X:Y:Z ratio of 46% zero: 47% fill: 7% Z (through thickness). In the 3D weave material the zero and fill rovings were 20,000 denier and the Z rovings were 3000 denier. This fabric is the 3D counterpart to the 0/90 20 K 2D fabric. The final volume fraction of fiber in the as-cast MMCs was 30–32% for all three 2D fabric reinforced materials and slightly higher at 42% for the 3D woven materials. The slight variation in the 2D materials is due to non-uniform compression of the fabric layers during infiltration with the molten aluminum. The 3D woven material has a higher volume fraction of fibers due to the addition of the 7% of fibers in the Z direction. Also the 3D fabric does not compress as much as the 2D fabric plies during infiltration due to the enhanced structural rigidity augmented by the Z fibers in the through thickness direction. A polished microstructure normal to the plane of weave of the 0/90 3 K fabric reinforced MMC is shown in Fig. 2 to illustrate typical infiltrated yarn and fiber structure observed in these materials. In the lower magnification micrograph the warp and weft yarns can be seen, while in the higher magnification micrograph the fibers in the sub-yarn structure can be seen. In both materials, regions of porosity (black) can be observed particularly at fiber-matrix interfaces. Formation of micro-porosity in this case is likely due to micro shrinkage which occurs when liquid metal cannot reach interdendritic areas during solidification and is a commonly observed defect in mushy freezing alloys.

2.2. Ballistic impact testing

Ballistic impact testing was conducted on all MMC materials to determine the effect of weave architecture on the ballistic limit and dynamic deflection of the targets. The MMC targets were 0.2032 m (8 in.) in length, 0.2032 m in width, and 0.00635 m (0.25 in.) thick and were mounted on a square frame and clamped rigidly 1 cm on all sides. The MMC targets were impacted by 0.30 caliber fragment simulating projectiles (FSP) launched from a smooth bore gas gun with a plastic sabot. The target stand is located 0.5 m from the gun muzzle. The velocities of the projectiles were determined by a high speed video camera shooting at 100,000 frames per second perpendicular to the flight path of the projectile at the point of impact. The projectile impacted on the target surface with less than five degrees of obliquity. The shot locations on each target were carefully spaced to ensure that the ballistic performance of the target from one impact was not affected by the damage caused by

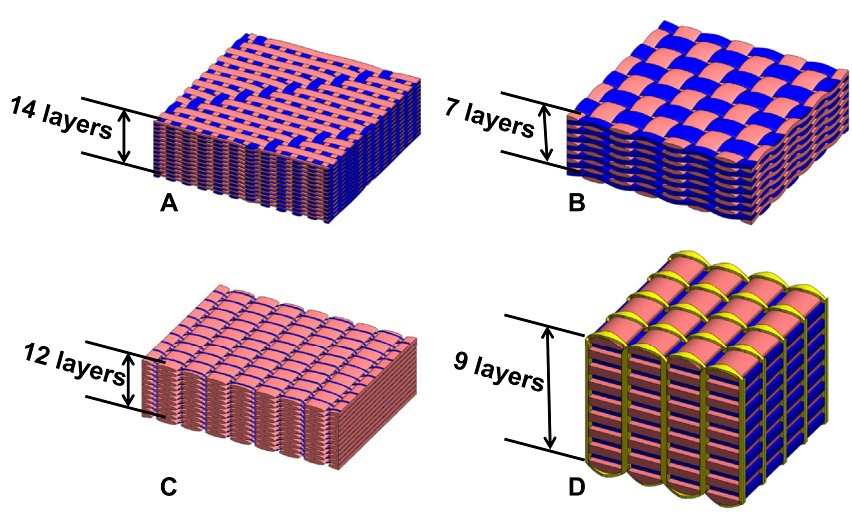

Fig. 1. Schematic (not to scale) of the four ceramic weave architectures used as reinforcement in the MMCs investigated in this paper: 0/90 3 K (A), 0/90 20 K (B), 85/15 (C), and orthogonal 3D weave (D).