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Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer ☆

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ABSTRACT

With increasing threat of man-made debris in outer space, a shielding panel designed for spacecraft or satellite should withstand hypervelocity impact of debris, with speed up to 9.0 km/s. In this study, shielding performances of 2024 aluminum alloy panel, carbon fiber reinforced polymer composite (CFRP) panel and their hybrid laminates with different stacking configurations were investigated by ballistic tests of the materials impacted by Mylar flyer at 9.0 km/s. The results are supposed to guide the design of shielding laminate panel. It was found that the stacking combination of CFRP and aluminum alloy significantly reduced the peak shock pressure induced by hypervelocity impact, and the increase of the layer number enhanced the shielding performance of the hybrid laminate. The five-layered aluminum alloy/CFRP laminates resisted the impact of the flyer without perforation. Furthermore, the extent of the damage of an impacted laminate was related to the velocity profile on its free surface. The planar plate impact testing employing a Doppler laser velocity interferometer is a feasible approach to quantitatively evaluate the shielding performance of structural material.

1. Introduction

With increasing activities of outer space exploration, large numbers of flying debris are generated in outer space. The debris imposes realistic threat on orbital satellites and space shuttles. The most effective design for debris shielding is the Whipple structure [1], which is composed of a bumper and a rear wall with a standoff between them. But in some cases such as extravehicular activities, there is no space to place an external bumper, thus the structural panel should be able to resist the hypervelocity impact (HVI) of micro debris in space. When a thin panel is crashed by debris, shock waves are induced in the panel and the shocked zone endures an extremely high kinetic energy. Hence, how to reduce the shock intensity and to absorb the shock energy are essential concerns for the structural material which has the potential to be subjected to hyper velocity impacts during its in-service life.

Fiber reinforced polymer (FRP) composites have broad applications in many structural components for spacecrafts and military facilities due to their excellent mechanical properties and their feasibility in processing. Evaluation of FRP composite impacted by a projectile has attracted much attention in last two decades [2–7]. It is well known that the shielding capability of a composite material is determined by a combination of factors, including fabric texture, fiber/matrix interface strength and fiber performance, etc. Tennyson and Lamontagne [8] reviewed the results of hypervelocity impact tests conducted on graphite/PEEK laminates with aluminum spheres travelling at velocities between 2 and 7 km/s and reported that small changes in the stacking sequence had negligible effect on its energy absorbing ability. Fujii et al. [9] showed that the failure mode of CFRP laminates was determined by mechanical properties of the fibers and there was little difference in the absorbed energy for both cross-ply [0/90] laminates and woven laminates. Ramadhan et al. [10] suggested that adding aluminum layers into a Kevlar fiber reinforced polymer (KFRP) laminate improved its shielding performance. Hazell et al. [11–16] systemically studied the response of carbon reinforced plastic composite panel under different ballistic-loading conditions and Wang et al. [17] investigated the energy absorption efficiency of CFRP laminates with different thickness by experimental and numerical methods.

HVI of a projectile on a shielding panel brings in strong shock wave which leads to large deformation, phase transformation, fragmentation or spallation, and penetration of materials. The depiction of such complicated processes still resorts to the developing of in-site diagnostic technologies. The line-VISAR that measures velocities of the free surface of a shocked specimen instantaneously can provide the shock Hugoniot data of testing materials [18].

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Two-stage light gas gun can launch a projectile to a speed of 7 km/s and is commonly used for ballistic tests. However, it is infeasible to study the shielding performance of a material impacted by debris with average speed of 9 km/s. Osher et al. [19] used a 100 kV electric gun to perform HVI tests and successfully accelerated a 10-cm-square Kapton flyer plate to 3.2 km/s (4.3 g in weight) and a 1.0-cm-square, 0.3-mm-thick Kapton flyer to 18 km/s. Katz et al. [20] investigated the response of composite materials to high-speed impact using laser-driven aluminum flyer at velocities from 1 to 3 km/s. In this study, the shielding performances of 2024 aluminum alloy, CFRP panel and a series of hybrid laminates consisting of aluminum alloy and CFRP (or KFRP) were examined by means of an electric gun which can launch Mylar flyer to a velocity over 9 km/s, for the purpose of guiding the design of a shielding material. The correlation between the extent of the damage and the velocity profile of the impacted target was also investigated in this paper.

2. Experimental methodology

The experimental configuration of the HVI testing is schematically shown in Fig. 1 [21]. A Mylar film (0.1 mm in thickness and 1.4 g/cm^3 in density) was bonded on the top of an aluminum bridge foil. When the bridge foil was applied a charging voltage over 20 kV, it exploded and a plasma was formed, driving the Mylar flying upward at a hypervelocity. Due to the restriction of the gun barrel mounted above the Mylar film, the flying film was cut to a bore-sized flyer and the flyer impacted a specimen above the gun barrel. In this experiment, the gun bore was 10 mm in diameter and 8 mm in depth, and the aluminum bridge foil was in dimensions of 10 mm × 10 mm × 0.1 mm. To eliminate the effect of the plasma pressure on the specimen, a 4-mm-length gap was introduced between the specimen and the upper edge of the barrel.

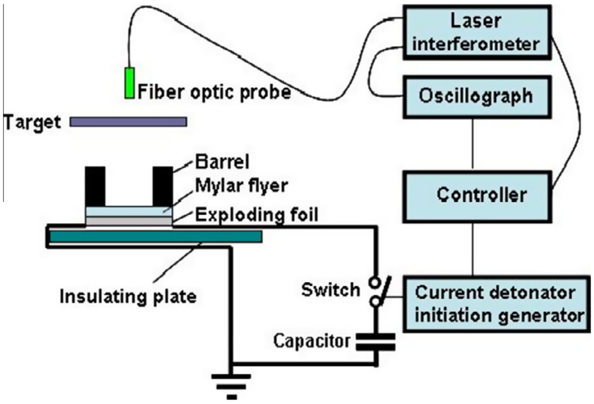


Fig. 1. Schematic configuration of the electric gun.

The flyer velocity is determined by the following equation:

$$u_f = (2kJ^n)^{1/2}(\rho_f\delta_f/\rho_F\delta_F + 1/3)^{-1/2} \tag{1}$$

Here in: u, J, ρ and δ denote velocity, the current density causing the explosion of the bridge foil, volume density and thickness, respectively. The subscript letters f and F represent the Mylar flyer and the bridge foil, respectively. k and n are Gurney constants related to the equipment. As the explosive current density J is correlated to the charging voltage of the bridge foil, the velocity of the Mylar flyer can be modulated by adjusting the charging voltage. In the experiment, the flyer was accelerated to over 9 km/s by a charging voltage of 28 kV.

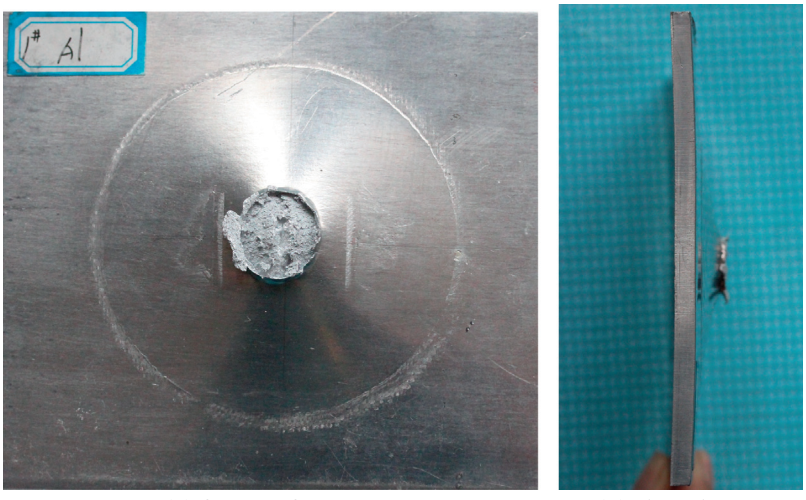
A Doppler laser velocity interferometer was used to measure the free surface velocity profile of the specimen under HVI. For the CFRP panel, a piece of 10-μm-thick aluminum film was covered on the specimen's free surface as a laser reflective surface.

3. Experimental results and discussion

3.1. HIV testing on 2024 aluminum alloy and CFRP composite

To design a shielding material with an enhanced performance of resisting to HVI of micro debris, we first studied the shock responses and damage behaviors of 2024 aluminum alloy panel and CFRP panel, respectively. The CFRP panel was fabricated by a vacuum assisted resin transfer molding (VARTM) process [22] using Bisphenol A epoxy (manufactured by Balin Petrochemical Co., China) and T300 fabric cloth (manufactured by Toray Co., Japan). The volume fraction of the carbon fibers varied in the range of 45–50%. The thickness of each specimen was 5 mm.

The photographs of aluminum alloy and CFRP panels impacted by the hypervelocity Mylar flyer are shown in Figs. 2 and 3, respectively. For 2024 aluminum alloy, a holistic deformation of the panel and a newly formed fracture surface in the free surface of the impacted zone were observed (Fig. 2). It indicates that the internal



(a) free surface (b) side view

Fig. 2. Damage of the impacted 2024 alloy panel at a collision velocity of 9.2 km/s. (a) Free surface; and (b) side view.