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An experimental study on the effect of adding multi-walled carbon nanotubes on high-velocity impact behavior of fiber metal laminates

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ABSTRACT

In this paper, the effect of adding multi-walled carbon nanotubes (MWCNTs) on high-velocity impact behavior of fiber metal laminates (FMLs) was investigated. The unreinforced and reinforced FMLs with different MWCNT weight percentages of 0.25, 0.5 and 1 were manufactured and tested under high-velocity impact loading using a gas gun and a spherical projectile. Moreover, tensile tests were performed on the unreinforced and reinforced composite laminates of FMLs. Incorporating 0.5 wt% of MWCNTs into the composite laminate of FML resulted the maximum reduction of 29.8% in projectile residual velocity and the maximum increase of 18.9% in the absorbed energy during projectile perforation compared to the unreinforced FMLs. This was consistent with the tensile test results in which maximum improvements in the strength, stiffness and toughness were obtained for the 0.5 wt% MWCNT-nanocomposite. The detailed visual inspections and SEM images showed that adding MWCNTs improved the resin-fiber adhesion consequently reduced the composite delamination and matrix cracking. Conversely, MWCNTs weakened bonding between the aluminum and composite layers and allowed the aluminum layer to experience larger plastic deformation.

1. Introduction

Composite materials have been widely used in various industries such as automotive, marine and aerospace. This is because of the high static and fatigue strengths and low structural weight of composite materials compared with other materials. Composite structures can withstand under different loading conditions such as static, fatigue and creep loadings. However, due to their relatively brittle behavior, they are susceptible to impact loading [1,2].

Fiber metal laminate is a kind of structure that consists of thin metal layers and composite laminates bonded together. FML receives advantages of both of the constitutive materials including metal and composite so that weak points of them can be suppressed or limited. FMLs benefit from higher fatigue and impact damage tolerances, lower specific weight and better corrosion resistance compared to metals and composites. FMLs are categorized into several grades depending on the constitutive metal and composite materials employed in the structure. The most famous grades of FMLs are Glare, Karall and Arall in which aluminum layers are bonded with glass, aramid and carbon fibers, respectively. Researchers (e.g. [3–7]) have shown that FML can better withstand under impact loading compared to metallic or composite structures. The aluminum layers used in FML can provide deformability and increase the toughness of the structure and the composite layers can support the aluminum layers by crack bridging.

Fatt and Lin [3] compared the impact behaviors of Glare and Aluminum 2024 under high-velocity impact loading and reported 15% higher ballistic limit for Glare compared to the aluminum sheet with the same surface density. Fan and Cantwell [4] compared the impact behaviors of Glare and composite samples subjected to low-velocity impact loading. They reported significantly higher energy absorption and superior impact resistance of FML compared to the composite samples due to the combined metal plastic deformation and fiber fracture. Abdullah and Cantwell [5] showed that the presence of composite laminate in FML can increase the perforation energy three times compared to the aluminum sheet.

Some researchers [5,8] studied the effects of the size and geometry of projectiles on impact response of FMLs. Abdullah and Cantwell [5] found that the size of projectile can alter the impact response of FMLs. They showed that increasing the projectile diameter increased the maximum impact force, the maximum deflection and perforation energy of FMLs. Compston and Cantwell [8] studied the effect of projectile geometry on the impact response of FMLs under high-velocity impact loading. The results showed that impact loading using flat-front projectiles resulted higher shear stress, perforation energy and damaged

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area compared to spherical projectiles.

Introducing reinforcing phases into the matrix of composites is a method of improving mechanical behavior of polymeric composites. The reinforcing phase can be in different scales such as macro, micro and nano. The reinforcing nanofillers have attracted considerable attentions due to their outstanding characteristics. Researchers (e.g. [9–14]) have studied the effect of nanofillers on the impact behavior of composites.

Avila et al. [9] investigated the effect of adding nanoclays in glass-reinforced composites under low-velocity impact. They showed that adding 5 wt% nanoclay can increase the energy absorption at most by 48%. They also showed in another study [10] that adding nanoclays in composites can reduce the damaged area and delamination up to 22%.

Avila et al. [11] studied the effect of nanoclays on the low-velocity impact behavior of the sandwich panels consisting of two glass/epoxy face sheets and a polystyrene core. They reported improvements in the toughness and flexural strength of the sandwich panels. They obtained maximum energy absorption when 5 wt% nanoclays were employed. Uddin et al. [12] studied the effect of titanium oxide nanoparticles on the high-velocity impact behavior of sandwich panels with polystyrene core. The results showed that adding 3 wt% of titanium oxide increased the ballistic limit and energy absorption by 12% and 20%, respectively, compared to the neat specimen.

There are various nanofillers with different shapes and different materials. Carbon nanotubes are of high importance due to their exclusive mechanical and electrical characteristics. Some researchers (e.g. [15–18]) used MWCNTs to improve the resistance of composites against impact loading. Kostopoulos et al. [15] investigated the effect of MWCNTs on impact response of epoxy based composites. They reported inconsiderable reinforcing effect of MWCNTs on low-energy impact loading. However, by increasing the energy of impact loading, the effect of MWCNTs was increased. Taraghi and et al. [16] investigated the effect of MWCNTs on a Kevlar fiber-reinforced composite under low-velocity impact loading at ambient and low temperatures. They found that adding 0.5 wt% of MWCNTs improved the energy absorption of the composites by 35% when the tests were carried out at ambient temperature. While, for the low testing temperature of $-40\,^{\circ}\mathrm{C}$, adding 0.3 wt% of MWCNTs improved the energy absorption by 34%.

Zheng et al. [17] investigated the effect of adding MWCNTs on the low-velocity impact behavior of FMLs. They reported improvements in the flexural strength, modulus and impact resistance of FMLs by adding MWCNTs. Glare with 0.5 wt% of MWCNTs showed the best impact resistance. MWCNTs improved the mechanical properties of FMLs by nanotube pull-out and debonding and crack bridging. Also, addition of nanotubes reduced the entrapped bubbles inside the matrix of composite layer. However, the increased viscosity of resin due to adding CNTs gave rise to lower wetting of aluminum sheets by resin.

In this paper, the effect of MWCNTs with different weight percentages of 0.25, 0.5 and 1 on the high-velocity impact behavior of FMLs was studied. In addition to the high-velocity impact tests, quasi-static tensile tests were carried out on the composite layers of FMLs to further investigate the effect of MWCNTs on the mechanical properties of the composite layer of FML. Scanning electron microscope (SEM) technique was used to assess the distribution of MWCNTs inside the composite matrix and find the governing mechanisms. Further, the effect of nanotubes on damage behavior of FMLs under high-velocity impact loading was discussed.

2. Materials and experimental methods

2.1. Materials

The FML specimens studied in this study were made of two sheets of aluminum 2024-T3 with a thickness of 0.8 mm and a composite laminate. The composite laminates were made of six layers of E-glass woven fiber with a density of 200 g/m^2 and an epoxy resin named Epon 828 with the hardener TETA. In order to study the effect of MWCNTs on the high-velocity impact behavior of FMLs, MWCNTs (provided by Neutrino Corp. located in Iran) with outer diameter of 10–20 nm, inner diameter of 5–10 nm and length of less than 30 μm, according to the nanofiller data sheet, were added to the composite laminates. MWCNTs were functionalized with carboxyl groups for achieving higher compatibility between the epoxy resin and MWCNTs.

2.2. Fabrication of fiber metal laminates

The unreinforced and reinforced FML specimens with different weight percentages of MWCNTs were manufactured in order to study the effect of MWCNTs on high-velocity impact behavior of FMLs. The surfaces of aluminum sheets were prepared in two steps, first by washing the surfaces with soap and distilled water followed by drying and cleaning with acetone and cotton. Then, the surfaces were sanded by a sand paper with a grain size 600 followed by final cleaning with acetone. MWCNTs were dispersed into the epoxy resin with weight percentages of 0.25, 0.5 and 1. The dispersion process of MWCNTs consisted of mechanical stirring and ultra-sonication. The MWCNTs were added to the resin and the mixture of resin/MWCNTs was stirred mechanically for 30 min at a rate of 180 rpm. Then, an ultrasonic process was performed using the Bandelin sonopuls sonicator for 50 min operating at 70 W and with 1 s on/off cycle in order to reduce the generated heat from the sonication process. Moreover, during the sonication process, the mixture was placed in a water and ice mixture to reduce the mixture temperature. After sonication, the mixture was then placed in a vacuum condition for 15 min to remove the trapped air bubbles. Afterwards, the curing agent with the weight ratio of 13:100 was added to the mixture followed by mechanically mixing for 15 min at a rate of 180 rpm. Then, the trapped air bubbles were again removed from the mixture by placing the mixture in a vacuum condition. The FML specimens were manufactured by hand layup with six layers of E-glass woven fiber and two sheets of aluminum providing the stacking sequence of (Al/[Glass fiber/epoxy]$_6$/Al). The FML samples were cured under a pressure of 5 bar for 210 min at a temperature of 110 °C and post cured for 8 h at 80 °C. The dimensions of the manufactured FML samples were $100 \times 100 \times 3.2\,\mathrm{mm}^3$.

2.3. Test methods

High-velocity tests were carried out on FML specimens using a gas gun. The projectile used in the experiments was a steel sphere with a diameter of 8.7 mm and a mass of 2.71 gr. In order to facilitate comparing the energy absorption of the specimens with various MWCNT weight percentages in the course of projectile perforation, the collision velocity of projectile for all specimens was kept constant as 235 m/s. The residual velocity of projectile was measured using a chronograph having two electronic sensors. The absorbed energy was calculated as the difference between the input and output kinetic energies of the projectile. In order to ensure the repeatability of the experimental results each test was repeated at least 4 times. Fig. 1 shows the high-velocity test setup.

In addition to high-velocity impact testing of FMLs, quasi-static tensile tests were also performed on the unreinforced and reinforced composite laminates of FML samples. The composite laminates which were tested under quasi-static loading consisted of six woven glass fiber/epoxy laminas. Tensile properties of the specimens were determined based on ASTM D3039 standard [6]. Fig. 2 shows experimental setup of the quasi-static tensile tests. The tensile tests were carried out under displacement control with a rate of 2 mm/min. The dimensions of the composite laminates were $25 \times 250 \times 1.6\,\mathrm{mm}^3$.

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