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The effect of aluminum and titanium sequence on ballistic limit of bi-metal 2/1 FMLs

G.H. Majzoobi[a,*], H. Morshedi[a], K. Farhadi[b]

[a] Mechanical Engineering Department, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran
[b] Chemistry and Chemical Engineering Research Center of Iran, Tehran, Iran

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ABSTRACT

In the present study, the ballistic limit, absorbed energy and the failure mechanism of fiber metal laminates (FML) with three different arrangements of layers were investigated. Each FML specimens consisted of two metallic layers including aluminum 2024-0(Al) or titanium 6Al-4V(Ti) reinforced by E-glass unidirectional fiber and araldite/aradur5052 Huntsman epoxy resin(R). Three arrangements of FML's including Al/R/Ti, Al/R/Al and Ti/R/Al arrangements were considered in this study. The study was performed by experiment and simulation. It was shown that the ballistic limit of Al/R/Ti specimen was higher than those of Ti/R/Al and Al/R/Al specimens. Replacing an aluminum layer in Al/R/Al by a titanium 6Al-4V layer led to considerable increase in ballistic limit and the absorbed energy in both titanium FMLs. 82% and 64% increase in the average absorbed energy/thickness was observed in Al/R/Ti and Al/R/Ti specimens, respectively. It was also shown that the failure mechanism of the titanium layer changed from petalling for Al/R/Ti to plugging for Ti/R/Al.

1. Introduction

Fiber metal laminates (FMLs) have wide applications in aircraft industry because of their high mechanical properties. FML is made of metal and fiber layers that are bonded together by an adhesive such as resin and most often epoxy. Metallic layer is usually made of aluminum alloys, although magnesium, titanium, Nitinol and steel are also used in many of the investigations. Most of investigations on FMLs have been performed on monoclinic metals and less attention has been paid to the use of hybrid FMLs containing layers of different materials [1,2]. On the other hand, mechanical behavior of FMLs has been the subject of numerous investigations over the past decade. However, only a limited number of studies has been performed on the impact and ballistic behavior of FMLs. *The main objective of the current study is to explore the impact, ballistic behavior and energy absorption of hybrid FMLs made of aluminum and titanium using different arrangement of aluminum and titanium layers.* Aluminum 2024 is a light weight, relatively cheap with medium strength. Titanium is a high strength but expensive material.

1.1. Impact and ballistic behavior of FMLs

The FML have Cortés and Cantwell [3,4] investigated the fracture properties of the FMLs based on magnesium metallic layers. They showed that in low velocity impact, glass fiber/PP magnesium based FML offered a superior specific perforation resistance to that offered by the other aluminum based FMLs in the article. Pärnänen et al. [5] examined the application of AZ31B-H24 magnesium alloy in FMLs for the impact objectives. They compared the drop-weight impact testing results for 3/2 magnesium based FML with two thicknesses of 3/2 Glares (aluminum based FML). Their results indicated that the ballistic limit of the magnesium-based FML was the same as that obtained for Glare FMLs, but the cracking energy limit of magnesium based FML was lower. Cortés and Cantwell [6–8] investigated the tensile failure, structural properties and the impact responses in titanium-based thermoplastic fiber-metal laminates. They used GF/PEI and CF/PEEK composites in their investigations. A comparison between composites and the composite based FMLs demonstrated that titanium β (15-3) did not improve FMLs' impact properties due to specific impact energy. In 2007, Cortés et al. [9,10] introduced a new FML based on Nitinol (Nickel-titanium) alloy and studied its morphing and fracture properties. Khalili et al. [11] studied the mechanical properties of steel/aluminum bi-metal FMLs. They performed Charpy test on samples made of resin and GRP and also on FMLs with arrangements AAA, ASA, SAS, and SSS where S and A stand for steel and aluminum, respectively. They showed that in the presence of steel layers in FML samples the energy absorption was increased with respect to other FML samples. Seyed Yaghoubi and Liaw [12] investigated the thickness and Metal Volume Fraction (MVF) effect on ballistic Impact behavior of GLARE 5. Their

* Corresponding author.
E-mail addresses: gh_majzoobi@basu.ac.ir (G.H. Majzoobi), hamidmorshedi@yahoo.com (H. Morshedi), kfarhadi@ccerci.ac.ir (K. Farhadi).

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results showed that V50 (The ballistic limit) varied in a parabolic trend with respect to the MVF and specimen thickness. Seyed Yaghoubi and Liaw [13] examined the 3/2 GLARE FMLs of various stacking sequences by numerical simulation. They found that the cross-ply orientation had a better energy absorption than unidirectional orientations. Manikandan and Chai [14] studied four models that included monolithic ductile aluminum, monolithic brittle composite, and two aluminum and composite combinations when the ductile face or brittle face were in the impact-side. They observed that in low-velocity impact when the brittle face was in impact-side the energy absorption was higher than the other cases. Sadighi et al. [15] showed that if the aluminum layer is changed with a magnesium layer, the dent depth and perforation energy increase but this change doesn't improve the performance of the aluminum FML because the extent of damage increases and the energy/density reduces. Asaee et al. [16] introduced a new form of FMLs by using 3D fibers. Their new product impact energy absorption was good but in comparison to FMLs with woven fabrics had a lower energy absorption. Yu et al. [17] investigated the applicability of carbon fibers and propertied of aluminum alloy in FMLs. Their results showed that Carbon fiber aluminum Laminate (CARALL) had a better impact resistance in comparison to GLARE. Furthermore, in CARALLs with different aluminum alloys, namely 1060-O, 2024-T3, 6061-T6 and 7075-T6, one that had a better yield strength, had a better impact resistance. Liu and Liaw [18] studied the effect of the layers material in FML's using Al7475-T76 and Al2024-T3. Al7475-T67 has high strength and Al2024-T3 has good ductility and toughness. They showed that the latter is appropriate for low impact velocities and the former is suitable for high impact velocities.

Failure mechanism of FMLs under impact or ballistic test is also an important issue in their ballistic characterization. Kpenyigba et al. [19] has argued that in plugging failure mode, the energy absorption capacity is higher than in petalling failure mode for Monolithic single layered plates. In double layered FML's, however, the situation is different. In fact, 2-ART specimen failed in petalling mode absorbed more energy than 2-TRA specimen which failed in plugging mode. The reasons for this discrepancy is believed to be due to bending of titanium layers and delamination.

The focus of the study is to find the best arrangement of 2/1 Al-Ti FML for high velocity impact applications. The FMLs fiber/resin layer is made of E-glass fiber and epoxy resin/hardener type 5052 araldite/aradur and the metallic layers are made of aluminum or titanium. The ballistic behavior of the FMLs are determined by experiment and the energy absorption is computed by numerical simulation.

2. Materials & specimens

2.1. Materials

In the present study, two types of metals, titanium 6Al-4V (Produced by TIMET Company) and aluminum 2024-0 (produced by Arak Aluminum producer) in the form of sheet were used. Titanium and aluminum sheets had 1 mm and 0.84 mm thicknesses, respectively. The reinforcing layers were made of E-glass unidirectional fiber (purchased from dealers in Iran) and araldite/aradur 5052 epoxy resin made by Huntsman company. Three arrangements, as specified in Table 1, were considered for preparing the test specimens. A typical arrangement is schematically shown in Fig. 1. The first series of specimens, 2-ARA, consisted of two aluminum and a fiber layers. The second series, 2-ART, were made of an aluminum, a titanium and a fiber layers. In these specimens, the front face of the FML was made of aluminum and the rear face was made of titanium. In the third arrangement, the 2-TRA specimens, the rear and front face materials swapped their positions. The FML's were fabricated at ambient temperature under 10 bar pressure. In fabrication process, layers were cut in the size of $9 \times 9\ cm^2$. Then, aluminum and titanium layers' faces were prepared after removing oil, abrading and rinsing with high pressure water for bonding to the fiber layers before laminating. Hand lay-up method was used to manufacture the specimens. In fabricating process, pressure was applied to remove extra resin after layers were laid-up. Gelation step was accomplished in 8 h at 20 °C.

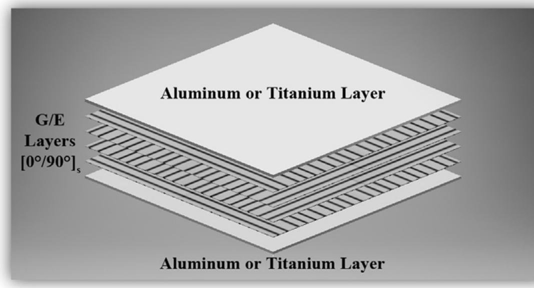

Fig. 1. Schematic view of a FMLs specimen.

Table 1
Ballistic tests' description.

Code	Panel arrangement	Number of tests
2-ARA	$A/[0/90]_s/A$	10
2-ART	$A/[0/90]_s/T$	4
2-TRA	$T/[0/90]_s/A$	4

In this work, the projectile used for ballistic tests was made of steel and had a blunt cylindrical shape. The mechanical properties of the steel are given in Table 2. In order to minimize the deformation of the projectiles, they were hardened by heat treatment. The metal layers were treated according to ASTM D2651before FMLs fabrication. As seen in Fig. 1, four [0°/90°] of G/E plies were used in the laminates.

2.2. Test apparatus

The ballistic tests were carried out on a light gas gun illustrated in Fig. 2. The impact and residual velocities of the projectiles were measured by speed sensor. The gas gun was able to launch the projectiles of 10 g at the velocities up to several hundred m/s. The gas gun was equipped with a fixture for holding the specimens (see Fig. 3). The design of fixture allowed to create built in and simple supports for the specimens and also to quickly set up the specimen for ballistic test.

3. Experiments

The arrangements of the specimen's layers were provided in Table 1. As the table indicates, the first series of specimens consisted of two aluminum and one fiber layers. Fig. 4(a) demonstrates the section of a typical 2-ARA specimen after ballistic test. As the figure suggests, the failure mode of the rear layer (aluminum) shown to be a petalling (tearing) type while the front layer (aluminum) exhibits a shearing failure mode. The protuberance around the hole at the impact side, caused by the spring back behavior of the delaminated aluminum ply and also, from the initial stress wave propagation. The perforation diameter of the rear layer is larger than the diameter of the projectile.

Table 2
Projectile characteristics.

Description	Unit	Value
Density	[kg/m^3]	7850
Young modulus	[GPa]	210
Poisson's ratio		0.3
Diameter	[mm]	6
Length	[mm]	18