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Research Paper

Experimental Investigation of Ballistic Impact Resistance of Fiber Metal Laminates Reinforced with 3D Glass Fibers

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ABSTRACT

Hybrid composite laminates consisting of layers of fibers and metal are a new generation of composites that sometimes have better mechanical properties and a greater weight-to-strength ratio than their constituent materials. 3D glass fibers have two layers of fibers on both sides with transverse links and with hollow space between the layers. In this paper, the ballistic limit of Fiber metal laminates (FMLs) including aluminum metal and polyvinyl chloride reinforced with 3D glass fibers has been investigated. Composite laminates include an aluminum layer in the middle and two composite layers on both sides. The matrix of composite layers has been polyvinyl chloride. Hand layup and hot pressing methods were used to make the samples. The ballistic limit speed of the samples was calculated with a gas gun. The results showed that the ballistic limit of the composite sample against the blunt projectile was higher than that of the hemispherical warhead projectile.

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1. Introduction

Composite materials are formed by the combination and physical mixing of two or more distinct substances, rather than by chemical reaction. In such materials, the constituent components retain their own chemical and physical properties [1]. In mechanical engineering, a composite is defined as a material consisting of two main constituents: a reinforcement and a matrix. Each component has a specific function—the reinforcement bears the load and determines the stiffness and strength of the composite, while the matrix is responsible for transferring and distributing the applied stresses [2]. Composites are generally classified according to their matrix material into metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer matrix composites (PMCs). Among them, PMCs are the most widely used because of their low density and favorable strength-to-weight ratio [3]. In PMCs, the matrix is usually composed of thermosetting or thermoplastic polymers, and the reinforcement consists of high-strength fibers such as glass or carbon fibers. Thermoplastic-based composites have gained particular attention in recent years owing to their excellent environmental resistance, ability to be reformed, high fracture toughness, good impact strength, recyclability, and long shelf life, compared with their thermoset counterparts [4–6]. Fiber Metal Laminates (FMLs) are hybrid materials consisting of alternating layers of metals—such as aluminum, magnesium, titanium, or steel—and fiber-reinforced polymer layers. Due to their lightweight structure, high specific strength, good fatigue performance, and impact resistance, FMLs are considered promising alternatives to conventional metallic materials [7,8]. In these laminates, the layers are bonded together by an adhesive. When a crack initiates in one layer, its growth is often arrested at the interface before propagating to the next layer, thereby reducing the overall crack growth rate and significantly increasing the fatigue life of the material [9,10]. Owing to these advantageous properties, FMLs have attracted considerable attention in the aerospace industry [11]. A well-known example is GLARE, which has been successfully used in the Airbus A380 aircraft [12]. Other notable types of FMLs include ARALL [13] and CARALL [14]. While metallic sheets generally exhibit high formability, reinforcing fibers have limited deformability. The fracture strain of carbon fibers is typically about 1%, while that of glass fibers is approximately 5% [15]. Plastic deformation along the fiber direction in FMLs may lead to fiber breakage; therefore, interlaminar sliding must occur to accommodate deformation in this direction. This mechanism can be promoted by increasing temperature, which softens the thermoplastic matrix. Another deformation mechanism in woven fiber layers is intralayer shear, which occurs through the rotation of fibers relative to one another [16]. Traditionally, thermosetting resins have been used as the matrix in FMLs; however, replacing them with thermoplastic matrices can significantly improve the impact resistance of these materials [17]. Furthermore, thermoplastic matrices reduce the production cycle time and enhance recyclability [18]. The mechanical properties of thermoplastic-based FMLs have been extensively studied by various researchers [19–21]. Another distinct advantage of these materials is their post-formability, meaning that they can be reshaped after fabrication [22]. Moussa et al. [23] investigated the influence of process parameters on geometric accuracy and delamination in polypropylene (PP)-based FMLs during the stamping process. They reported that increasing the forming speed leads to lower geometric errors. In another study, the same authors [24] analyzed the deformation behavior of these laminates through finite element simulations.

Gresham et al. [25] studied the deep drawing of PP-based FMLs and found that increasing the forming temperature reduces sheet fracture but increases the tendency for wrinkling. Sexton et al. [26] examined the deformation and strain distribution of PP-based FMLs during hemispherical punch forming. Kalyana et al. [27] showed that heating during the forming of thermoplastic-based FMLs causes matrix melting, which facilitates interlayer sliding. Dharmalingam et al. [28], through finite element analysis, demonstrated that the optimal forming temperature for achieving maximum formability in PP-based FMLs is around 130 °C. Vollmer et al. [29] conducted both numerical and experimental studies on the deep drawing of thermoplastic-based FMLs and concluded that the drawing depth is limited by wrinkling, cracking of the outer metal sheets, and fiber breakage. Han et al. [30] developed an analytical model to predict springback in the V-die forming of thermoplastic FMLs, while Rajabi et al. [31] employed the Taguchi design of experiments method to study the influence of blank holder force and temperature on the deep drawing process of thermoplastic-based FMLs.

In this study, polymer-based composite laminates were fabricated using the hand lay-up method under a pressure of 2.5 bar and a temperature of 185 °C for 20 minutes. The polymer sheet was used as the matrix material, while aluminum sheets (Al) and three-dimensional (3D) glass fibers filled with PVC powder were employed as the reinforcing layers. The stacking sequence and fiber orientation angles of the reinforcing layers were considered as variable parameters in the fabrication process. Ballistic impact tests were performed on the fabricated laminates, and the results were compared and analyzed to evaluate the ballistic limit and failure behavior of the hybrid composites. The novelty of this study lies in the use of PVC-filled 3D glass fibers combined with an aluminum core to enhance ballistic resistance, which has not been previously reported.

2. Experimental Procedure

To fabricate the composite laminates, a commercial thermoplastic polymer (PVC) in the form of 0.2 mm-thick amorphous films was used as the matrix. In addition, the voids between the yarns of the 3D glass fabric were filled with dry white PVC powder (grade S6558) to improve interfacial bonding and uniformity. Figure 1 shows the PVC powder and the PVC film used in this study. The chemical composition of the raw materials used in this study is summarized in Table 1[33], based on standard material datasheets and supplier specifications.

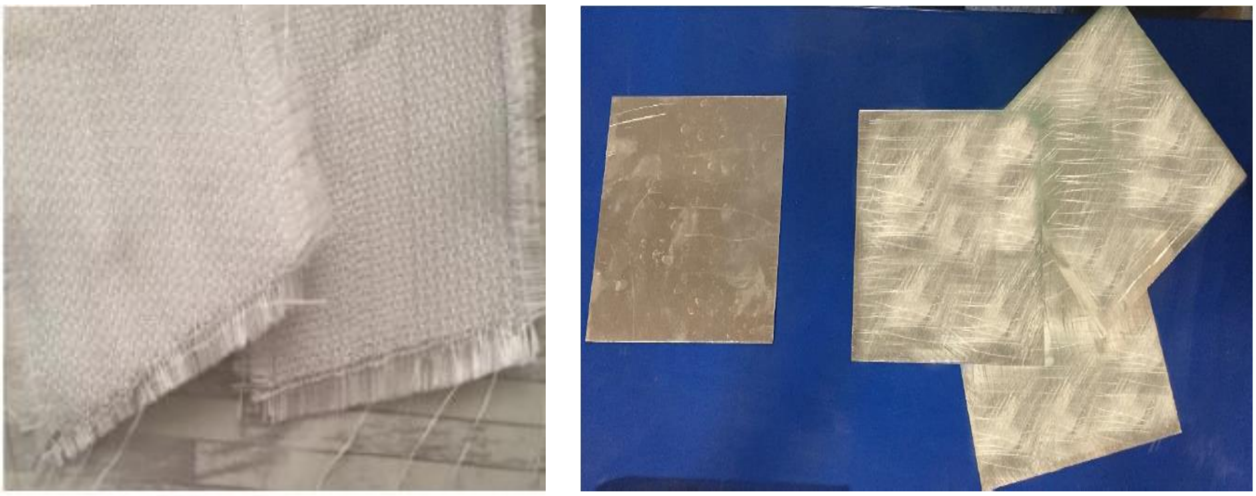
(a) (b)

Fig. 1. (a) PVC powder (b) PVC film used in the fabrication process

Table 1. Results of ballistic impact tests

Material	Composition (wt.%)
PVC	C_2H_3Cl (typical commercial PVC grade)
Al 3003	Al (98.6), Mn (1.0–1.5), Cu (≤0.05), Fe (≤0.7), Si (≤0.6)
E-glass fiber	SiO_2 (52–56), Al_2O_3 (12–16), CaO (16–25), MgO (0–5)

The three-dimensional glass fibers used for the reinforcement were of the woven type, consisting of two fabric layers interconnected by vertical yarns. The glass fabric had a thickness of 3 mm, a density of 720 g/m³, and a tensile strength of 6.8 MPa. The aluminum sheet (Al 3003) used as the metallic layer had a thickness of 0.5 mm and a tensile strength of 195 MPa. Since one of the most critical factors for achieving strong interfacial bonding between the metallic and composite layers is surface preparation of the aluminum sheet [32], the aluminum surfaces were ground and roughened using a wire brush to enhance adhesion. The 3D glass fabric and the surface-treated aluminum sheet are shown in Figure2.



(a) (b)

Fig. 2. (a) 3D glass fabric (b) Brushed aluminum sheet used in the study

After surface treatment and drying of the raw materials, the following steps were performed to fabricate the laminates:

1. Filling the internal space of the 3D glass fabric with PVC powder.
2. Stacking the layers according to the desired configuration.
3. Placing the stacked layers in a hot-press machine under a pressure of 2.5 MPa and a temperature of 180 °C for 20 minutes.

The laminate configuration consisted of one central aluminum layer and two outer composite layers made of 3D glass fibers filled with PVC powder. The stacking sequence and fabrication layout of the FML sheet are illustrated in Figure 3. The hot-press machine used for fabrication is shown in Figure 4.

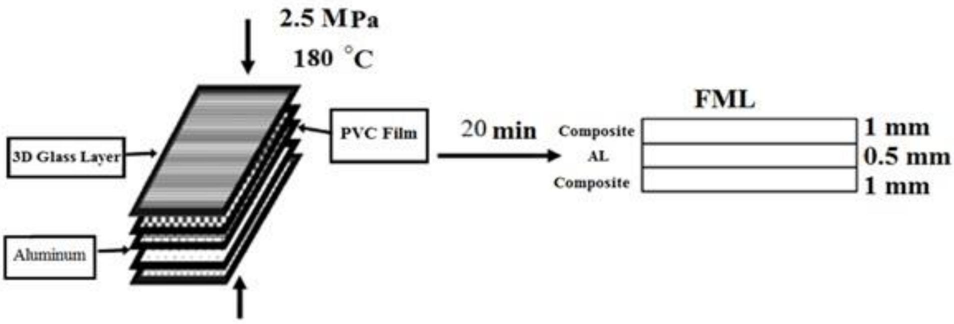


Fig. 3. Layer configuration and fabrication process of FML sheets Figure

Fig. 4. Hot-press machine used for composite fabrication

During fabrication, heating and cooling were controlled at a rate of 8 °C/min to ensure uniform temperature distribution. The gradual temperature rise led to melting of the PVC matrix, thereby improving interlayer bonding. As a result, composite laminates with a total thickness of 3 mm were produced. Figure 5 shows a sample of the laminate before and after the hot-pressing process.

Fig. 5. Composite laminate before and after the hot-pressing process

To determine the ballistic limit (V_b) of the fabricated laminates, gas-gun impact tests were carried out at the Impact Laboratory of Tarbiat Modares University. The ballistic limit velocity was calculated using Equation (1), based on the initial velocity (V_i) and residual velocity (V_r) of the projectile. The gas gun setup used in the experiments is shown in Figure 6. Two types of projectiles—flat-nose and spherical-nose—were employed to evaluate the impact response of the composite laminates. The absorbed energy was calculated using the kinetic energy difference before and after impact, as expressed in Equation (2) [34]. The absorbed energy values reported in Table 1 were calculated using Equation (2), based on the difference between the initial and residual kinetic energies of the projectile.

$$V_b = \sqrt{V_i^2 - V_r^2} \qquad (1)$$

$$E_{abs} = \frac{1}{2} m (V_i^2 - V_r^2) \qquad (2)$$

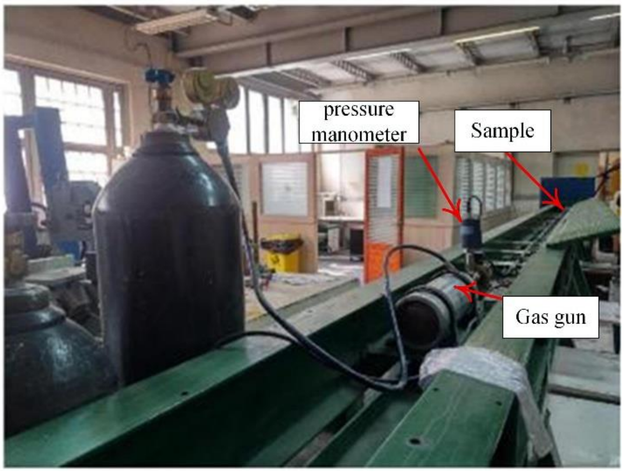


Fig. 6. Gas gun setup

3. Results and Discussion

The fabricated samples, including both aluminum sheets and FML (Fiber Metal Laminate) specimens, were subjected to ballistic impact tests using flat-nose and spherical-nose projectiles. The post-impact damage patterns of the tested samples are shown in Figure 7.

a b c

Fig. 7. Post-impact samples: (a) FML impacted by flat-nose projectile, (b) FML impacted by spherical-nose projectile, (c) aluminum sheet after impact.

The ballistic limit velocity (V_b) is considered the most significant outcome of ballistic impact testing. It represents the velocity at which the projectile completely penetrates the target without passing through it. By using different combinations of initial (V_i) and residual velocities (V_r) for both projectile types, the ballistic limit and penetration energy were determined. In the fiber–metal laminates, the presence of the aluminum layer, together with the high tensile strength and strain-to-failure of the 3D glass fibers, contributed to the laminate's ability to effectively absorb impact energy. Moreover, the PVC powder within the glass fiber layers enhanced the interfacial bonding and overall structural strength, improving the resistance of the laminate against high-velocity impacts. The results for impact velocity and absorbed energy are summarized in Table 2.

Table 2. Results of ballistic impact tests

Test Type and Sample	Input Speed (m/s)	Output Speed (m/s)	Elastic Limit (m/s)	Absorbed Energy (J)
composite with flat-nose bullet	116	116 (with deviation)	116	62.5
composite with flat-nose bullet	155	102	116.7	63.3
composite with spherical-nose projectile	116	– (Not exited)	116	62.5
composite with spherical-nose projectile	155	109	110.1	56.3
aluminum with flat-nose bullet	116	111	223.6	5.2
aluminum with spherical-nose projectile	116	103	53.3	13.2

Due to minor deviations and projectile misalignments during testing, the dataset was reduced to four FML samples and two aluminum samples, each tested with both projectile types. At an impact velocity of 116 m/s, neither flat-nose nor spherical-nose projectiles completely perforated the FML specimens; however, they fully penetrated the aluminum sheets, with residual velocities of 103 m/s and 111 m/s, respectively. The calculated absorbed energy indicated that the impact strength of FML specimens was significantly higher than that of pure aluminum sheets. As shown in Figure 8, the ballistic limit velocity for flat-nose projectiles was lower than that of spherical-nose ones in the aluminum sheets, while the opposite trend was observed for the FML samples, where flat-nose projectiles exhibited higher ballistic limits. Overall, the ballistic limit of the FML was approximately 70% higher than that of the aluminum sheet, and the energy absorption was about 52% greater. The ballistic limit of the composite sheets was up to twice that of the aluminum sheet.Compared with conventional aluminum sheets, the enhanced ballistic performance of the FMLs can be attributed to synergistic energy absorption mechanisms including fiber fracture, matrix cracking, and metal plastic deformation.

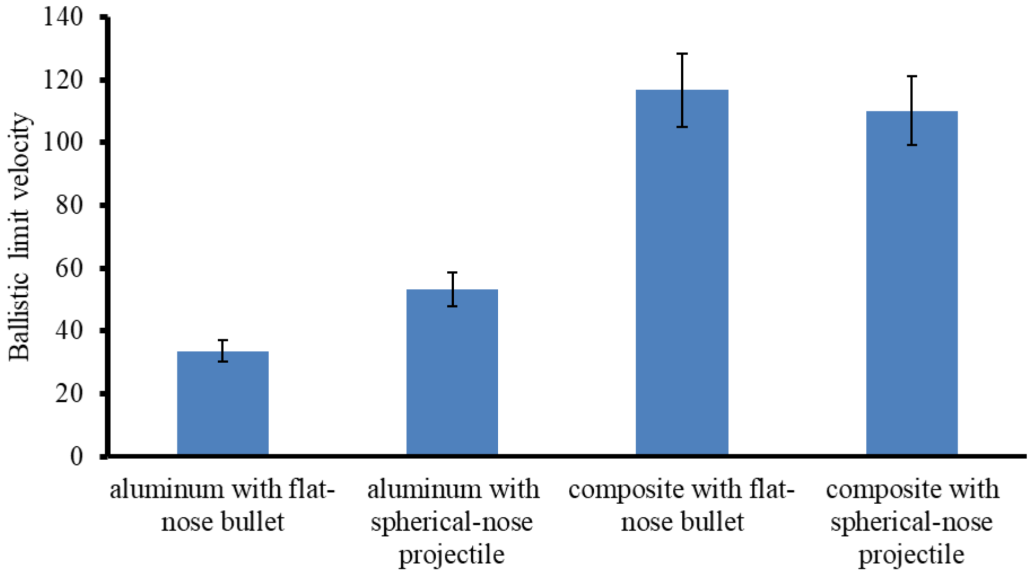


Fig. 8. Ballistic limit velocity of FML and aluminum samples (error bars indicate standard deviation)

The penetration and deformation mechanisms for both projectile types were further analyzed through observation of the impact craters and deformation patterns. Based on the experiments, the failure mechanism of FMLs under ballistic impact can be divided into three distinct stages:

1. Projectile penetration into the front composite layer: This stage begins when the projectile first contacts the front composite layer. Part of the impact energy is dissipated through fiber fracture and matrix cracking in the PVC layer.

2. Penetration through the aluminum layer: The aluminum sheet initially undergoes buckling and localized plastic deformation. With further stress increase, deformation progresses rapidly until tensile rupture occurs.

3. Penetration into the rear composite layer: After passing through the aluminum layer, the projectile strikes the back composite layer. The primary energy absorption mechanisms at this stage include delamination, fiber breakage, and matrix cracking.

The velocity–time histories for flat-nose and spherical-nose projectiles with an initial velocity of 155 m/s are shown in Figure 9. For the flat-nose projectile, the velocity sharply decreased after impact, and a crack initiated at the contact edge after approximately 0.1 ms. As the crack propagated, the slope of velocity reduction decreased, and by 0.27 ms, the laminate was completely perforated. For the spherical projectile, the velocity decreased more gradually, with total perforation occurring at about 0.36 ms, indicating a more uniform deformation process.

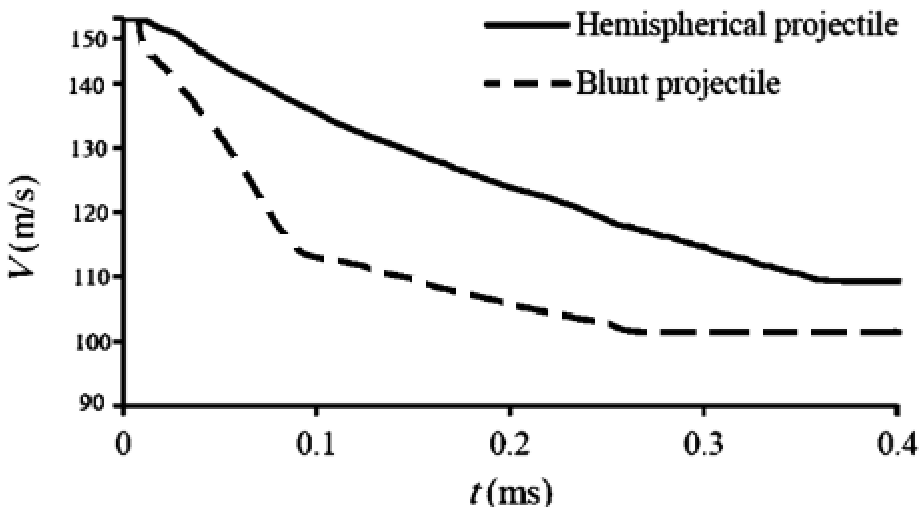
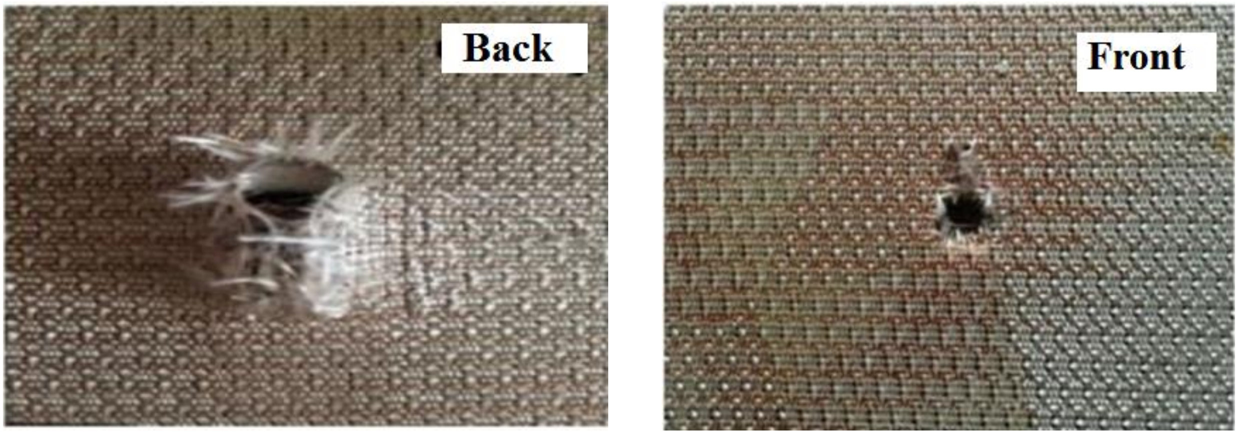
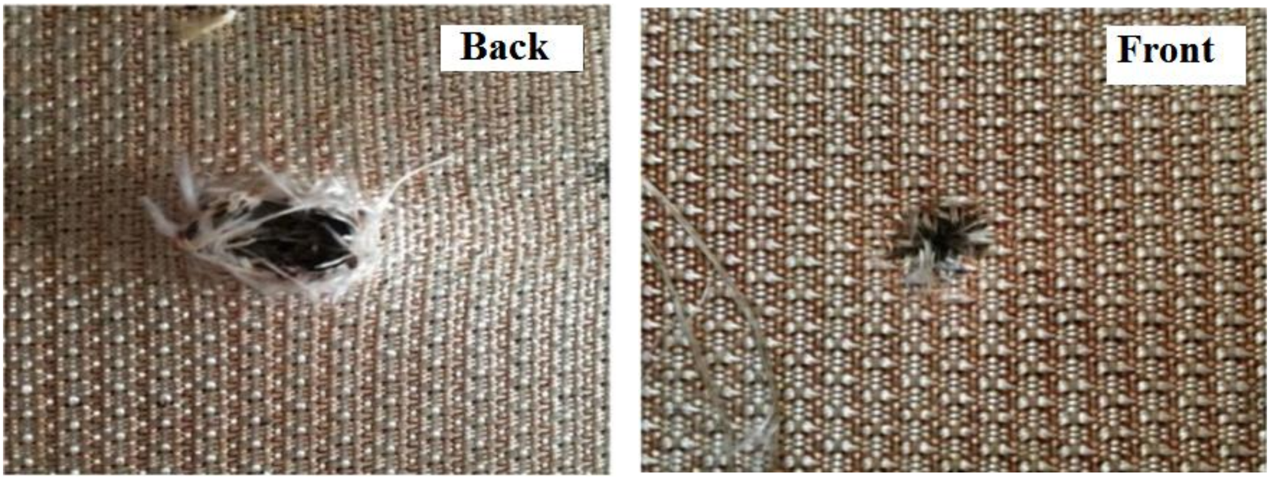


Fig. 9. Projectile velocity–time curves during impact with FML samples

The deformation patterns of the samples after impact are shown in Figure 10. It can be seen that the rear surface experienced greater damage than the front surface, including fiber stretching, matrix cracking, and interlayer delamination.



FML – Flat-Head Bullet – Speed 155 m/s



FML – Spherical Bullet – Speed 155 m/s

Fig. 10. Front and rear views of FML samples after ballistic limit testing

4. Conclusions

In this research, fiber metal laminate (FML) sheets consisting of aluminum and 3D glass fiber fabric filled with PVC powder were successfully fabricated using the hot-press method. Ballistic impact tests were conducted to evaluate their energy absorption and penetration resistance. The main findings are summarized as follows:

1. At an impact velocity of 116 m/s, the projectiles fully penetrated the aluminum sheet but failed to exit the FML specimens. At higher velocities of 155 m/s, both flat-nose and spherical-nose projectiles perforated the FML, with exit velocities of 116 m/s and 110 m/s, respectively.
2. For aluminum sheets, the ballistic limit of flat-nose projectiles was lower than that of spherical-nose ones, whereas for the FML samples, the trend was reversed. The ballistic limit and absorbed energy of FMLs were approximately 70% and 52% higher, respectively, than those of aluminum sheets.
3. FML specimens exhibited higher resistance to flat-nose projectiles compared with spherical ones, indicating better performance under high strain-rate loading with sharp-edged projectiles. Overall, the results demonstrate that PVC-filled 3D glass fiber–reinforced aluminum FMLs possess superior energy absorption and impact resistance, making them promising candidates for lightweight protective structures in aerospace and defense applications.

References

[1]. K. K. Chawla, Composite materials: science and engineering. 1st edition, NewYork: Springer Verlag, 1987.

[2]. Mazumdar, Sanjay. Composites manufacturing: materials, product, and process engineering. CrC press, 2001.

[3]. Kaw, Autar K. Mechanics of composite materials. CRC press, 2005.

[4]. W. Hufenbach, R. Böhm, M. Thieme, A. Winkler, E. Mäder, J. Rausch, M. Schade, Polypropylene/glass fibre 3D-textile reinforced composites for automotive applications, Materials and Design, 32, 1468–1476, 2011.

[5]. W. Wu, L. Xie, B. Jiang, G. Ziegmann, Simultaneous binding and toughening concept for textile reinforced pCBT composites: Manufacturing and flexural properties, Composite Structures, 105, 279–287, 2013.

[6]. H.F. Hwang, K.J. Hwang, Stamp forming of locally heated thermoplastic composites, Composites: Part A, 33, 669-676, 2002.
[7]. Langdon, G. S., G. N. Nurick, D. Karagiozova, and W. J. Cantwell. "Fiber–Metal Laminate Panels Subjected to Blast Loading." In Dynamic failure of materials and structures, pp. 269-296. Springer, Boston, MA, 2009.
[8]. Qin, Ren-Yan, and H. P. Schreiber. "Adhesion at partially restructured polymer surfaces." Colloids and Surfaces A: Physicochemical and Engineering Aspects 156, no. 1-3 (1999): 85-93.
[9]. Yamaguchi, T., T. Okabe, and Shigeki Yashiro. "Fatigue simulation for titanium/CFRP hybrid laminates using cohesive elements." Composites Science and Technology 69, no. 11-12 (2009): 1968-1973.
[10]. Khan, S. U., R. C. Alderliesten, C. D. Rans, and R. Benedictus. "Application of a modified Wheeler model to predict fatigue crack growth in Fibre Metal Laminates under variable amplitude loading." Engineering Fracture Mechanics 77, no. 9 (2010): 1400-1416.
[11]. Alderliesten, R. C. "Designing for damage tolerance in aerospace: A hybrid material technology." Materials & Design 66 (2015): 421-428.
[12]. Pora, J., and J. Hinrichsen. "Material and technology developments for the Airbus A380." In Proceedings of the 22nd International SAMPE Europe Conference of the society for the Advancement of Materials and Process Engineering, Paris. 2001.
[13]. Vlot, Ad, and Jan Willem Gunnink, eds. Fibre metal laminates: an introduction. Springer Science & Business Media, 2011.
[14]. Lin, C. T., and P. W. Kao. "Effect of fiber bridging on the fatigue crack propagation in carbon fiber-reinforced aluminum laminates." Materials Science and Engineering: A 190, no. 1-2 (1995): 65-73.
[15]. Long, A., and M. J. Clifford. "Composite forming mecanisms and material characterisation." Composites forming technologies (2007): 1-21.
[16]. Khan, M. Aurangzeb, Tarek Mabrouki, Emmanuelle Vidal-Sallé, and Philippe Boisse. "Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark." Journal of materials processing technology 210, no. 2 (2010): 378-388.
[17]. Reyes, German, and Sangeeta Gupta. "Manufacturing and mechanical properties of thermoplastic hybrid laminates based on DP500 steel." Composites Part A: Applied Science and Manufacturing 40, no. 2 (2009): 176-183.
[18]. Reyes, G., and H. Kang. "Mechanical behavior of lightweight thermoplastic fiber–metal laminates." Journal of materials processing technology 186, no. 1-3 (2007): 284-290.
[19]. Zal, Vahid, Hassan Moslemi Naeini, Ahmad Reza Bahramian, and Hadi Abdollahi. "Evaluation of the effect of aluminum surface treatment on mechanical and dynamic properties of PVC/aluminum/fiber glass fiber metal laminates." Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 231, no. 6 (2017): 1197-1205.
[20]. Reyes, G., W. J. Cantwell, M. J. Cruz, and A. F. A. Velasco. "The impact properties of novel thermoplastic-based fibre-metal laminates." In Proceedings of the VI International Conference on Composites and Materials, Morelia, Mich., Mexico, vol. 155. 2003.
[21]. Hu, Y. B., H. G. Li, L. Cai, J. P. Zhu, L. Pan, J. Xu, and J. Tao. "Preparation and properties of Fibre–Metal Laminates based on carbon fibre reinforced PMR polyimide." Composites Part B: Engineering 69 (2015): 587-591.
[22]. Reyes, G., and W. J. Cantwell. "Interfacial fracture in fibre-metal laminates based on glass fibre reinforced polypropylene." Advanced Composites Letters 7, no. 4 (1998): 096369359800700401.
[23]. Mosse, Luke, Paul Compston, Wesley J. Cantwell, Michael Cardew-Hall, and Shankar Kalyanasundaram. "Stamp forming of polypropylene based fibre–metal laminates: the effect of process variables on formability." Journal of Materials Processing Technology 172, no. 2 (2006): 163-168.
[24]. Mosse, Luke, Paul Compston, Wesley J. Cantwell, Michael Cardew-Hall, and Shankar Kalyanasundaram. "The development of a finite element model for simulating the stamp forming of fibre–metal laminates." Composite Structures 75, no. 1-4 (2006): 298-304.
[25]. Gresham, Joel, W. Cantwell, M. J. Cardew-Hall, Paul Compston, and Shankar Kalyanasundaram. "Drawing behaviour of metal–composite sandwich structures." Composite Structures 75, no. 1-4 (2006): 305-312.
[26]. Sexton, Anthony, Wesley Cantwell, and Shankar Kalyanasundaram. "Stretch forming studies on a fibre metal laminate based on a self-reinforcing polypropylene composite." Composite Structures 94, no. 2 (2012): 431-437.
[27]. Kalyanasundaram, Shankar, S. DharMalingam, Sudharshan Venkatesan, and Anthony Sexton. "Effect of process parameters during forming of self reinforced–PP based Fiber Metal Laminate." Composite Structures 97 (2013): 332-337.

[28]. DharMalingam, Sivakumar, Paul Compston, and Shankar Kalyanasundaram. "Process variables optimisation of Polypropylene based fibre-metal laminates forming using finite element analysis." In Key Engineering Materials, vol. 410, pp. 263-269. Trans Tech Publications, 2009.
[29]. Wollmann, Tino, Marlon Hahn, Sebastian Wiedemann, Andreas Zeiser, Joern Jaschinski, Niels Modler, Nooman Ben Khalifa, Frank Meissen, and Christian Paul. "Thermoplastic fibre metal laminates: Stiffness properties and forming behaviour by means of deep drawing." Archives of Civil and Mechanical Engineering 18, no. 2 (2018): 442-450.
[30]. Hahn, Marlon, Christian Weddeling, Nooman Ben Khalifa, and Arash Shabaninejad. "Springback Behavior of Carbon-Fiber-Reinforced Plastic Laminates With Metal Cover Layers in V-Die Bending." In ASME 2016 11th International Manufacturing Science and Engineering Conference, pp. V001T02A060-V001T02A060. American Society of Mechanical Engineers, 2016.
[31]. Rajabi, Ali, Mehran Kadkhodayan, Mohsen Manoochehri, and Reza Farjadfar. "Deep-drawing of thermoplastic metal-composite structures: Experimental investigations, statistical analyses and finite element modeling." Journal of Materials Processing Technology 215 (2015): 159-170.
[32]. S. Y. Park, W. J. Choi, H. S. Choi, H. Kwon, S. H. Kim, Recent trends in surface treatment technologies for airframe adhesive bonding processing: a review (1995–2008), The journal of adhesion, 86, 192–221, 2010.
[33] ASM Handbook, *Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, ASM International, Materials Park, OH, USA, 1990.
[34] Mark, J. E., *Polymer Data Handbook*, Oxford University Press, New York, USA, 1999.