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EXPERIMENTAL AND NUMERICAL STUDY ON MECHANICAL CHARACTERISTICS AND IMPACT STRENGTH OF FIBER-METAL COMPOSITE LAMINATES

Mohammad E. Golmakani [1], Tomasz Wiczenbach [2], Mohammad Malikan [2], Ebrahim Z. V. Karimi [1], Mina Masoumi [1] and Victor A. Eremeyev [2,3*]

[1] Department of Mechanical Engineering, Mashhad Branch, Islamic Azad University, 9187144123 Mashhad, Iran; m.e.golmakani@mshdiau.ac.ir (M.E.G.), e.z.v.karimi@mshdiau.ac.ir (E.Z.V.K.), mina-masoumi68@yahoo.com (MI.M.)

[2] Department of Mechanics of Materials and Structures, Gdansk University of Technology, 80-233 Gdansk, Poland; tomasz.wiczenbach@pg.edu.pl (T.W.), mohammad.malikan@pg.edu.pl (M.M.), victor.eremeev@pg.edu.pl (V.A.E.)

[3] Department of Civil and Environmental Engineering and Architecture, Università degli Studi di Cagliari, Via Marengo, 2, 09123 Cagliari, Italy, victor.eremeev@unica.it

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Abstract *In the present study, fiber-metal composite including aluminum sheets and glass fibers reinforcement, with a polyester matrix, were prepared by hand lay-up method. The effects of layer arrangement and quantity on composite's mechanical and physical properties were analyzed. What is more, two different densities of glass fibers were considered. For laminates preparation, ten different compositions were created. The mechanical properties concerning tensile modulus, strength, and impact strength were obtained following ASTM D3039 and ASTM D6110 standards. By performing the mentioned experiments, force-displacement and impact energy diagrams of various*

[*] Corresponding author; eremeyev.victor@gmail.com

fiber-metal multilayers were obtained. The obtained results show that the arrangement of the laminate layers impacts the Young's moduli and tensile strength. Furthermore, the impact test results of the laminated structure reinforced with glass fibers illustrate significant increases in the impact strength due to adding glass fibers compared to the control samples.

1. Introduction

Polymer-based composites have high strength, fatigue, heat, moisture, and chemical resistance [1, 2]. However, these composites usually have a low final working temperature, high thermal expansion coefficient, dimensional instability, sensitivity to radiation, and water absorption from the environment. These disadvantages cause harmful effects such as swelling, internal stresses, and temperature reduction [3]. Therefore, high efficiency and strength metal layers are used to diminish these undesirable properties along with composite layers [4, 5]. These materials are called fiber-metal laminates (fiber-metal multilayers or FML) [6-9]

One of today's advanced composites is glass laminate aluminum reinforced epoxy (GLARE). Several thin metal layers (commonly aluminum) shifted with glass-fiber layers, jointed together with a polymer matrix. These materials have become a suitable alternative for metal structures. Due to the widespread use of fiber-metal multilayers to manufacture mechanical components used in various industries, especially aerospace applications [10, 11]. FMLs have almost all the benefits of metallic and laminate material. They combine beneficial metal properties such as softness, damage, and impact resistance with the advantages of fiber composites such as high strength and certain rigidity, good corrosion resistance, and fatigue properties.

Bieniaś et al. [12] investigated the effect of energy optimization behavior and impact damage properties of aluminum carbon/epoxy fiber metal laminates and carbon fiber reinforced polymer. Charpy testing has been performed on the samples. The results show that carbon-fiber-reinforced metal composites show significantly better impact strength. Sadighi et al. [13] studied aluminum glass/epoxy fiber metal laminates samples made by the hand lay-up technique. The effect of the fiber's angle on their impact resistance was investigated. The Charpy test results show that a composite layer with a zero-degree fiber angle significantly improves the impact properties. On the other hand, the location of the layers is essential. Therefore, it could be concluded that the presence of aluminum layers improves the mechanical properties of the composite. Song et al. [14] considered the impact strength of aluminum and GFRP-layers. The results show characteristics of damage tolerance, fatigue, and excellent impact properties with relatively low density. Reyes and Cantwell [15] investigated the mechanical properties of glass-fiber-reinforced FMLs composed of aluminum and polypropylene. The tensile test results show that the increment of the aluminum and composite layers increases the mechanical properties significantly. It has been found that the tensile strength of the linear load rises linearly. As the volume fraction in the FML composite decreases, the Young's modulus decreases. Kotik et al. [16] investigated the shear fatigue of short beams from fiber-metal multilayers. Three layers of aluminum alloy and two pre-impregnated glass fibers have been used to prepare the samples. Quasi-static tests have been performed to investigate the fatigue behavior of fiber-metal multilayers in two main directions of materials. The Charpy test showed that the impact strength along the material is more significant than its transverse direction. Shamohammadi Maryan et al. [17] considered fatigue and tensile responses of laminated metal fibers-epoxy structures including aluminum and aramid fibers based on the experimental efforts. Vasudevan et al. [18] examined flexural and tensile responses of plastic-aluminum hybrid composites reinforced by glass fibers via vacuum resin transfer moulding method. Hu et al. [19] studied failure and flexural behavior of carbon fiber reinforced polymer/aluminum composites using numerical and experimental works. Zakeri et al. [20] numerically simulated the fiber metal laminates under impact loads and included aluminum and ultra-a high molecular weight polyethylene as fibers. Zhu et al. [21] probed the mechanical properties and characterization of fiber metal laminates based on the AA6061 fiber and various aluminum-surface pretreatments. Vo et al. [22] using various aluminum alloy modeled a fiber-metal laminate and investigated its behavior under low-impulse blast conditions. Khan et al. [23] modeled an aluminum/glass fiber laminate and explored its energy absorption and damage behavior. Sharma and Khan [24] inspected impact response of aluminum laminates reinforced by glass fiber subjected to projectiles impact loads and evaluated the effect of metal layer distribution on the model. Rajkumar et al. [25] modeled a fiber metal laminate reinforced aluminum fiber subjected to bending and tensile conditions. There have been so many other experimental or numerical works performed on the fiber metal laminates. However, as far as this paper is not a review one, we will skip considering them.

Plastics have little strength as the result of their low tensile modulus, but their utilization is extensive. The main profits of plastics are their usage in high humidity environments and their low density. Differently, glass fibers as reinforcement show a significant tensile strength and modulus. Therefore, their applications are pervasive, as proved in the mentioned articles. Composite designation from these materials provides a magnificent utilization in many engineering fields. Regrettably, as with all composite materials, their mechanical and physical properties differ according to the content of the particular materials. Moreover, advanced solutions to strengthen composite materials are obtained by adding metal sheets. The additional reinforcement impacts the mechanical and physical properties of the final product. This paper examines the impact and tensile test for fiber-metal composites with multilayer arrangement. A comparison of the results is made with the control sample, which has only aluminum layers as a reinforcement. As a result, the primary goal of this research is to investigate the mechanical and physical properties of FML consisting of different amounts of aluminum and GFRP layers. Furthermore, numerical analysis was done to validate the experimental outcomes. Moreover, the impact strength of FMLs containing different layers is shown. This investigation could impact the design of FML products, considering the improvement of physical and mechanical properties.

2. Materials

The materials used in the manufacture of fiber-metal composite samples in the reinforcing part include glass fibers and aluminum sheets. For the matrix, part polyester is considered.
Type E glass fibers in the form of woven fabrics have been used. Its specifications are given in Table 1. Each glass layer had a thickness of 0.2 and 0.4 mm and a mass of 200 and 400 g/m^2, respectively.

Table 1. Glass fiber's physical and mechanical properties

Young's moduli (GPa)	Shear modulus (GPa)	Density (kg/m^3)	Poisson's ratio
74	30	2600	0.25

The second reinforcement which was considered is aluminum sheets (Figure 1). The specifications of this material are presented in Table 2. Note that the pure aluminum sheet in the form of punched (Figure 1) with a thickness of 0.2 mm was also prepared for composite metal layers.

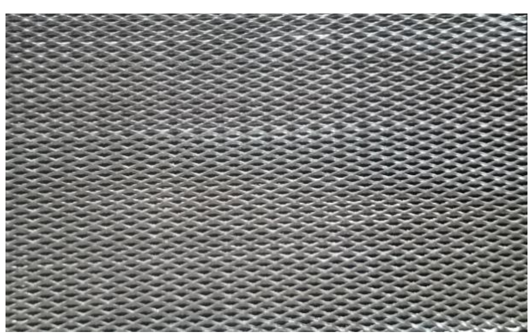


Fig. 1. Aluminum sheet.

Table 2. Aluminum physical and mechanical properties

Young's moduli (GPa)	Shear modulus (GPa)	Density (kg/m^3)	Poisson's ratio
72	100 - 190	2600	0.33

The characteristics of the polyester resin used in this research are given in Table 3.

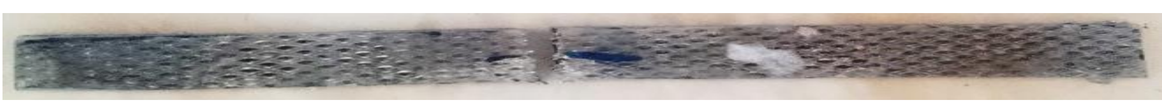
Table 3. Polyester physical and mechanical properties

Young's moduli (GPa)	Shear modulus (GPa)	Density (kg/m^3)	Poisson's ratio
0.8	0.28	1200	0.4

2.2. Fiber-Metal Laminate samples preparation

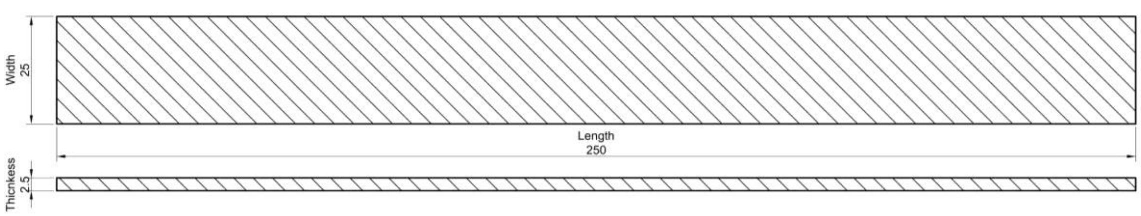
For laminates specimens' preparation, a hand lay-up manufacturing procedure was used. In this method, the release part was first sprayed on the surface of the mold to separate the fabricated laminate easily. Then, the coating gel was applied to the mold to make the piece's surface desirable in terms of quality and appearance. The glass fibers were placed in the mold and then poured with the polyester resin. The next layer consisted of the aluminum sheet impregnated with the matrix. Additional air particles were removed manually with the rollers. Layering and impregnation were continued till the desired sample was reached. The laminate specimens were cured on a glass table at ambient temperature for 24 hours. After that, the pieces were post-cured in an oven for 16 hours at 40°C. Finally, specimens were cooled at room temperature, washed, and flashed removed before testing. The samples were made as sheets. The milling machine (Aslanian Machine, Tehran, Iran) was used to prepare standardized models. According to ASTM D3039 and ASTM D6110 standards for the tensile and impact test, samples were cut to the desired standard dimensions, respectively. Figure 2a shows the specimen for the tensile test, and Figure 2b presents the impact test specimen. Furthermore, Figure 3a and Figure 3b illustrate the dimensions of samples for the tensile and impact test, respectively.

(a)



(b)

Fig. 2. Specimens for: (a) tensile; (b) impact test.



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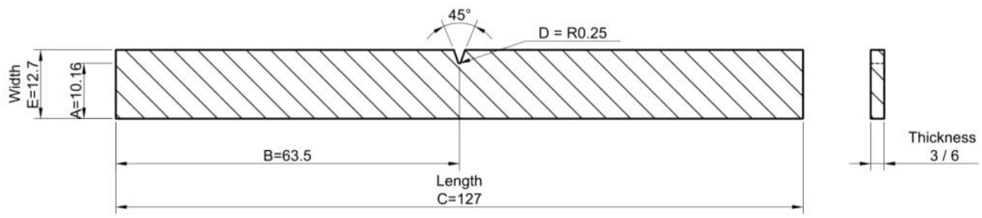


(b)

Fig. 3. Samples dimensions [mm] (a) tensile; (b) impact test.

Table 4 presents the arrangement of layers (AL – aluminum sheets, FI – glass fibers) and sample codes (TT – Tensile Test, IT – Impact Test) based on the fiber mass and arrangement. It should be noted that three control samples were made for testing, consisting of only aluminum sheets and polyester resin. Moreover, the number of layers has been selected randomly.

Table 4. Stack sequence of layers and code of investigated samples

Specimen	Stack sequence of plies	Number of reinforcement layers	Sample code	Sample thickness (mm)
1	[AL/FI/AL/FI/AL/FI][1]	6	L200-6-1-TT	2.5
2	[AL/FI/AL/FI/AL/FI][2]	6	L400-6-2-TT	2.5
3	[2AL/FI/AL/2FI][1]	6	L200-6-3-TT	2.5
4	[2AL/FI/AL/2FI][2]	6	L400-6-4-TT	2.5
5	[3AL]	3	C-3-TT	2.5
6	[AL/FI/AL/FI/AL/FI][1]	6	L200-6-1-IT	3
7	[AL/FI/AL/FI/AL/FI][2]	6	L400-6-2-IT	3
8	[2AL/FI/AL/2FI][1]	6	L200-6-3-IT	3
9	[2AL/FI/AL/2FI][2]	6	L400-6-4-IT	3
10	[3AL]	3	C-3-IT	3
11	[AL/FI/AL/FI/AL/FI/AL/FI/AL/FI/AL/FI][1]	12	L200-12-1-IT	6
12	[AL/FI/AL/FI/AL/FI/AL/FI/AL/FI/AL/FI][2]	12	L400-12-2-IT	6
13	[3AL/FI/2AL/2FI/AL/3FI][1]	12	L200-12-3-IT	6

14	[3AL/FI/2AL/2FI/AL/3FI][2]	12	L400-12-4-IT	6
15	[6AL]	6	C-6-IT	6

[1] 200 g/m^2 glass fibers [2] 400 g/m^2 glass fibers

2.3. Mechanical testing

For tensile and impact investigations, ASTM D3039 and ASTM D6110 standards were applied, respectively. The specimen's mechanical evaluations were done on the experimental machine Instron 1186 (Norwood, MA, USA) at 20±1°C ambient temperature. Charpy tests were executed on the Zwick Model 5102 (Zwick GmbH & Co. KG, Ulm, Germany) with a room temperature of 20±1°C. Tensile examinations were done with an initial load cell force of 500N. The constant level of 2 mm/min crosshead speed was studied. All performed mechanical investigations of each sample composition were done at least five times. Force-displacement curves were obtained from the mechanical tests. To achieve tensile strength and modulus, the calculations were performed. From computations, mean values were considered as outcomes. Furthermore, by performing the Charpy test, the impact strength was calculated. Impact testing was performed on the ten different sample compositions.

2.4. Numerical Analysis

2.4.1. Tensile test

The laminate sample was done utilizing the dimensions and shape presented in the ASTM D3039 standard. All examined numerical examinations were performed in Abaqus software version 6.14.1 (Dassault Systemes, ABAQUS Inc., Waltham, MA, USA). In this research, the simulation of the uniaxial tensile test was performed to determine the failure longitudinal displacement value of fiber-metal. The specimen type was considered deformable.

The material section defined the two properties, density and elasticity, for the specimens. In order to define the properties of the material in the elastic region, the material was considered isotropic, and Young's modulus and Poisson's ratio were entered according to Table 5. Then plastic mechanical behavior was considered. Stress-strain curves are essential in material mechanics and especially in simulations. These curves are generally obtained through tensile tests, which are limited by the phenomenon of narrowing. In order to solve this problem, engineering stress-strain curves are converted to real stress-strain curves using very simple relations Eq. 1-3. The values of the strain and stress gained from the tensile test were converted to real stress and strain values using the following formula Eq. 1-3.

$$\sigma_T = \sigma_N(1 + \varepsilon_N), \tag{1}$$

$$\varepsilon_T = \ln(1 + \varepsilon_N), \tag{2}$$

$$\varepsilon_P = \varepsilon_T - \frac{\sigma_T}{E}, \tag{3}$$

where σ_T is the real stress, ε_T is the real strain, ε_N is the engineering strain (from the tensile test) and ε_p is the plastic strain.

Table 5. Material properties for each sample

Specimen	Sample code	σ_y (MPa)	σ_{num} (MPa)	ε_p (-)	E (MPa)	v (-)
1	L200-6-1-TT	1.14	63.82	3.80	1548.46	0.33
2	L400-6-2-TT	1.15	62.65	4.15	1875.10	0.33
3	L200-6-3-TT	1.76	67.88	3.74	996.90	0.33
4	L400-6-4-TT	1.78	59.59	4.17	1163.17	0.33
5	C-3-TT	1.64	4.76	0.58	753.20	0.33

The boundary conditions of one edge of the sample at the machine's fixed-grip were considered motionless. The opposite side could be in motion in a neutral axis direction. After performing the sensitivity analysis, mesh size was considered as 1 mm. At last, the specimen was aligned with the hexagonal elements regularly and uniformly. Then, the numerical analysis was done with Abaqus software.

Fig. 4 presents the meshed sample for the numerical tensile examination.

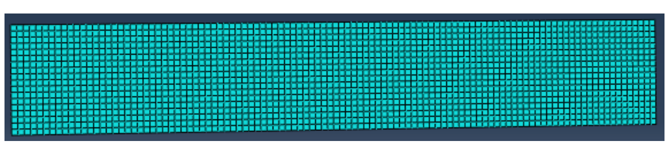


Fig. 4. The meshed specimen for numerical analysis.

2.5.2. Impact test

The impact test sample was designed according to the ASTM D6110 standard in three dimensions and the extrusion method. Therefore, the sample was considered deformable. Figure 5 shows the designed sample. In order to design the pendulum, the discrete rigid property was used to create rigid objects. Considering this property for the pendulum, no deformation occurs when colliding with the specimen. Therefore, the pendulum is designed in accordance with the device's pendulum. Then mechanical properties were considered as maximum stress, density, elastic and plastic, which were defined according to Table 6 for each sample. The type of pendulum contact with the sample surface was defined with the surface-to-surface interaction. Then, using the rigid body constraint, the pendulum was considered rigid, and its movement was limited to the movement of a point. Also, the pressure-interference relationship of the hard contact type was considered. The boundary conditions for the sample were defined so that the lower part of the sample was considered as fixed, as it is in the device. The pendulum speed was considered 2.5 mm/s, in accordance with the impact test standard. The structure mesh type and shape were set to hexagonal and size of 1 mm. To obtain the size of the meshes, a sensitivity diagram was examined.

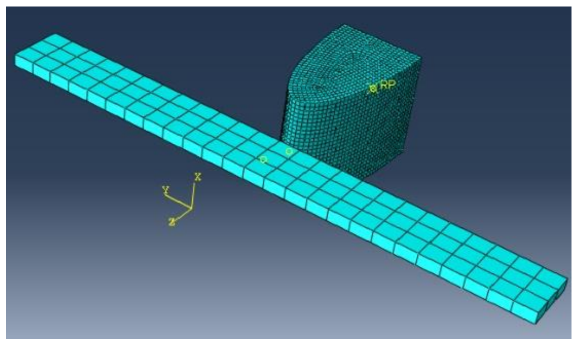


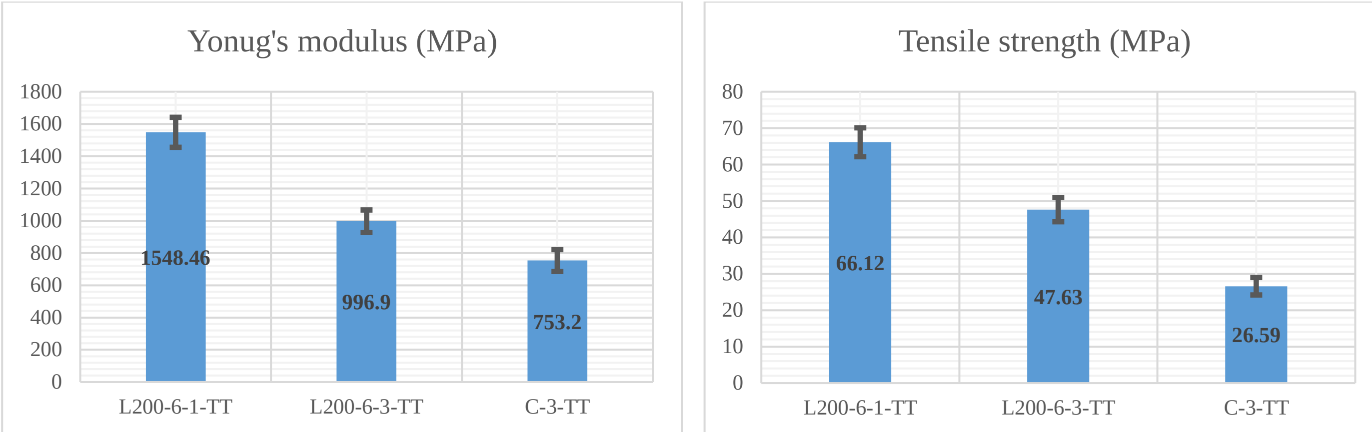
Fig. 5. Model of the sample for the numerical impact test.

3. Results

3.1. Experimental analysis

3.1.1. Tensile test

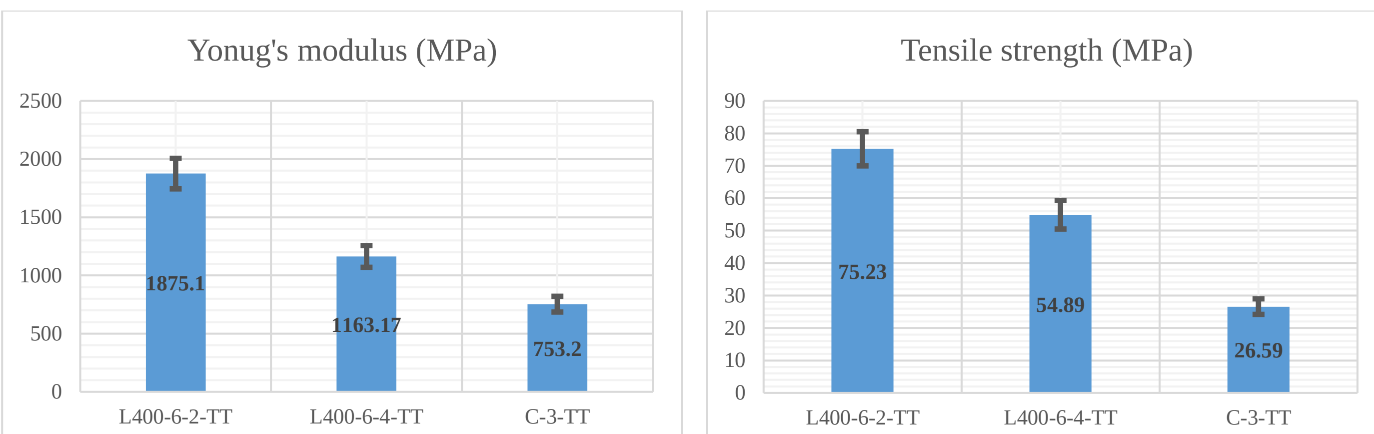
Figures 6a and 6b exhibit the results gained for FML containing 200 g/m^2 glass fibers and a control sample. Young's modulus and tensile strength of laboratory tests are presented. Additionally, the standard deviation is presented with the black lines. As it can be observed, the glass fibers addition significantly increases Young's modulus. In addition, the multilayer composite L200-6-1-TT sample has a higher tensile strength than the other two compositions.



(a) (b)

Fig. 6. Tensile (a) modulus; (b) strength for FML containing 200 g/m^2 glass fibers.

The samples studied in this part consist of 400 g/m^2 glass fibers and aluminum sheets compared with the control sample. In Figure 7a, the tensile modulus results are presented. The outcomes show that Young's modulus of the multilayer composite sample is higher than other samples. In Figure 7b, the tensile strength of the specimens is compared and examined. According to the diagram, for the L400-6-4-TT sample, a 50% increase in tensile strength can be observed compared to the aluminum sheet-reinforced sample. What is more, the control sample compared to the aluminum-reinforced L400-6-2-TT sample increases about three times.



(a) (b)

Fig. 7. Tensile (a) modulus; (b) strength for FML containing 400 g/m^2 glass fibers.

Table 6 presents the tested specimens' experimental values of tensile modulus and strength.

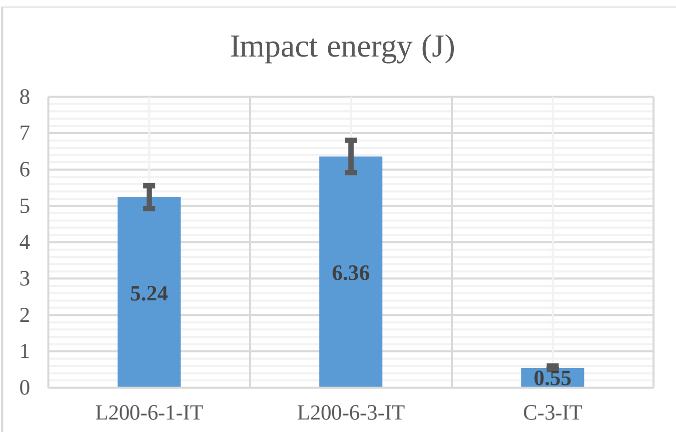
Table 6. Results of Young's modulus and tensile strength.

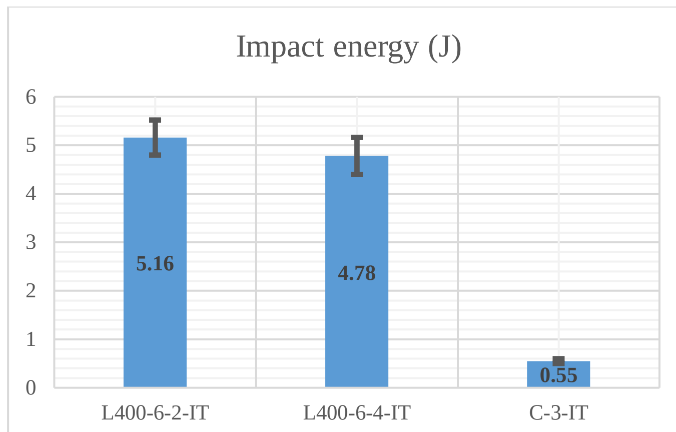
Specimen	Sample code	Young's Moduli (MPa)	Tensile strength (MPa)

1	L200-6-1-TT	1548.46	66.12
2	L400-6-2-TT	1875.10	75.23
3	L200-6-3-TT	996.90	47.63
4	L400-6-4-TT	1163.17	54.89
5	C-3-TT	753.20	26.59

3.1.2. Impact test

Figures 8a and 8b present the effect of glass fiber mass and stack sequence of plies on impact energy. The highest impact energy was obtained for the L200-6-3-IT specimen, consisting of the 200 g/m^2 glass fibers. Conversely, the lowest impact energy was obtained for the L400-6-4-IT sample.

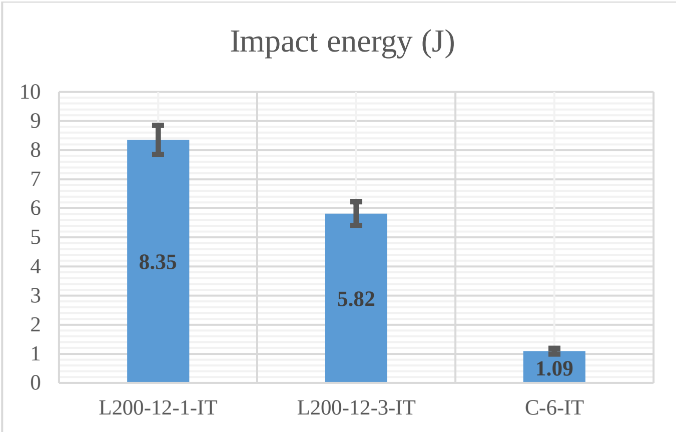




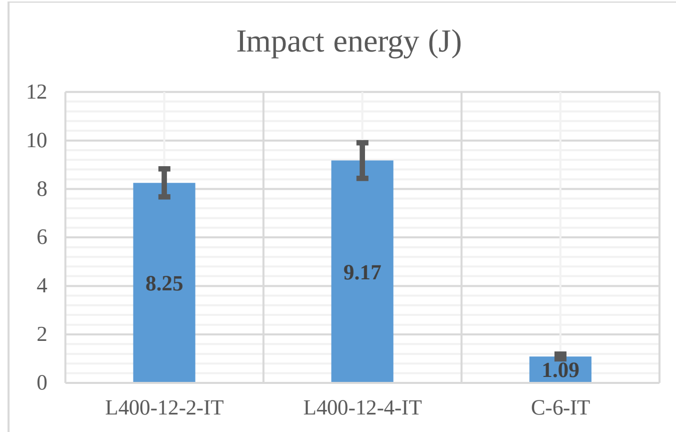
(a) (b)

Fig. 8. Impact energy for laminate (six layers) containing (a) 200 g/m^2; (b) 400 g/m^2 glass fibers.

Figures 9a and 9b show the effect of glass fiber mass and stack sequence of plies on impact energy. The highest impact energy was obtained for the L400-12-4-IT sample, consisting of the 400 g/m^2 glass fibers. Conversely, the lowest impact energy was obtained for the L200-12-3-IT specimen.



(a)



(b)

Fig. 9. Impact energy for laminate (twelve layers) containing (a) 200 g/m^2; (b) 400 g/m^2 glass fibers.

Table 7 presents the experimental values of impact energy and strength for the tested FML samples. The addition of glass fibers significantly improves the impact strength of tested laminate structures. Stack sequence is crucial for the results of the impact energy. However, the number of layers does not give a better effect.

Table 7. Impact energy and strength of tested FML compositions.

Specimen	Sample code	Impact energy (J)	Impact strength (kJ/m^2)
6	L200-6-1-IT	5.24	164.78
7	L400-6-2-IT	5.16	162.26
8	L200-6-3-IT	6.36	200.00
9	L400-6-4-IT	4.78	150.31
10	C-3-IT	0.55	17.30
11	L200-12-1-IT	8.35	131.29
12	L400-12-2-IT	8.25	129.72
13	L200-12-3-IT	5.82	91.51
14	L400-12-4-IT	9.17	144.18
15	C-6-IT	1.09	17.14

3.2. Numerical analysis

3.2.1. Tensile test

Table 8 present the comparison of the samples' experimental (u_{exp}) and numerical (u_{num}) longitudinal displacement. Additionally, the approximation error is calculated. The results present significant convergence.

Table 8. Comparison of experimental and numerical longitudinal displacement

Specimen	Sample code	F_{exp} (N)	u_{exp} [mm]	u_{num} [mm]	Error (%)
1	L200-6-1-TT	6670.21	5.07	4.58	9.66
2	L400-6-2-TT	7300.26	7.05	6.44	8.65
3	L200-6-3-TT	6360.56	4.94	4.45	9.92
4	L400-6-4-TT	6000.42	6.50	5.92	8.92
5	C-3-TT	318.12	1.08	1.02	5.56

3.2.2. Impact test

Table 9 presents the comparison of the samples' experimental and numerical impact energy. What is more, the approximation error is determined. As it can be observed, the obtained results show that the performed analysis has high convergence.

Table 9. Comparison of experimental and numerical impact energy

Specimen	Sample code	Experimental impact energy (J)	Numerical impact energy (J)	Error (%)
6	L200-6-1-IT	5.24	4.72	9.92
7	L400-6-2-IT	5.16	4.81	6.78
8	L200-6-3-IT	6.36	5.75	9.59
9	L400-6-4-IT	4.78	4.62	3.35
10	C-3-IT	0.55	0.51	7.27

4. Conclusions

In fiber-metal laminates, metal layers are used alongside composite layers, which improve the mechanical properties and significantly improve the impact performance due to their optimal mechanical properties. Fiber-metal composite specimens with a polymer matrix and their tensile strength, modulus, and impact resistance have been studied. Furthermore, the difference between the mass of the fibers and the stack sequence of the layers has been investigated. Thus, two types of arrangement in multilayers form have been checked in the construction of composites. Control samples with three and six layers of the aluminum sheet have been used to compare obtained results. According to the obtained results and their analysis, the following can be stated as the results of this research:

- For the fiber-metal composite samples consisting of six layers with 200 g/m^2 and 400 g/m^2 glass fibers (L200-6-1-TT and L400-6-2-TT), the results show that the Young modulus is bigger for an alternating sequence of layer than for the L200-6-3-TT L400-6-4-TT samples, respectively. What is more, for all mentioned samples, better results of Young's modulus were obtained than the control sample, in which three layers of the aluminum sheet as reinforcement were used.
- The results show that the impact energy in the 6-layer sample L200-6-3-IT consisting of 200 g/m^2 glass fibers is higher than in the alternating layers sequence L200-6-1-IT. Additionally, the L200-6-3-IT showed 12 times better resistance than the control sample. The resistance has also increased with the increase of glass fibers to the composite as a second reinforcement.
- According to the results of the impact test, it can be observed an increase in impact energy in the 12-layer 200 g/m^2 and 400 g/m^2 glass fibers. Also, these samples are up to 7 times more resistant than the control sample.
- According to the impact energy diagram for the 400 g/m^2 6-layer sample, the impact resistance in the L200-6-2-IT sample is slightly higher than the L200-6-4-IT sample. These fiber-metal samples are up to 10 times more resistant than the control sample.
- For the impact energy of the 12-layer 400 g/m^2 sample, a significant increase in the impact resistance in the L400-12-4-IT sample can be observed compared to L400-12-2-IT. What is more, compared to the control sample, it has shown nine times better resistance. Thus, the highest impact resistance is observed in 12 layers of 400 g/m2 glass fiber sample.
- Performed numerical analysis shows good convergence with the experimental results.
- FML comparison of the tensile mechanical properties with control samples shows that the addition of glass fibers crucially improves the tensile modulus and strength.
- The stack sequence of plies determines the results of final mechanical properties. Therefore, the better ones were obtained for the samples with alternating layers ([AL/FI/AL/FI/AL/FI]).

- The addition of glass fibers significantly improves the impact strength of tested laminate structures compared to control samples.

It is essential to note that further analysis is impossible at this stage due to closing the funds and being inaccessible to equipment.

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