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https://doi.org/10.1177/0954406220914325

The Effect of Stacking Sequence of Basalt and Kevlar Fibers on the Charpy Impact Behavior of Hybrid Composites and Fiber Metal Laminates

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Abstract

In this study, the effect of the arrangement of Kevlar and basalt fibers as the reinforcements on the Charpy impact behavior of hybrid epoxy composites was investigated. Also, the effect of adding metal plates (aluminum 2024-T3 and stainless steel 316L) into the basalt/ Kevlar fibers reinforced epoxy composites to fabricate fiber metal laminates (FMLs) under Charpy impact loads was studied. The fabricated FMLs in this research consisted of three metal plates and two groups of composite layers placed between them and were fabricated by hand lay-up technique. Results indicated that the stacking sequence of fibers due to the hybridization effect caused the considerable improvement in the energy absorption value (99%) of hybrid composites, compared to specimens with one kind of fibers. Moreover, the effect of adding Al plates for the fabrication of FML was greater than adding steel plates. Considering the weight of composites, FMLs with Al and steel sheets, it was found that the average specific energy absorption value of Al-FMLs was about 2.5 times higher than those of steel-FMLs and composites.

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Keywords: Basalt fibers, Kevlar fibers, Fiber metal laminates, Hybridization effect, Charpy impact.

1. Introduction

Fiber-reinforced polymer composites are one of the widely used materials in different industries such as civil aircraft by both Boeing and Airbus. However, this type of composites has some disadvantages such as degradation at high temperatures and brittleness at low temperatures that limit their uses in industries as a perfect material [1, 2]. Fiber metal laminates (FMLs) are one of the advanced materials in the aviation industry. FMLs have impressive properties such as desired stiffness, and excellent fatigue and impact resistance [3]. Furthermore, the low density of these composites is a weight saving point compared to other materials. Moreover, because of their outstanding properties, these materials are suitable for the manufacturing of aircraft components. For instance, glass laminate aluminum reinforced epoxy (GLARE) is used in the upper fuselage skin of Airbus A380 has saved up to 794 kg of weight and in manufacturing lower wing skin panels of previous Fokker 27 aircraft and cargo door of Boeing C-17 [4]. Structural components should withstand static and dynamic loading, environmental conditions, and fracture threats during their lifetime. All these events can decrease the properties of materials. In this regard, because FMLs are suitable materials because they consist of composite layers and thin layers of metal [3, 5, 6].

In general, when two or more combined foreign materials are reinforced within a common host matrix, hybrid composites are fabricated. With the mixing of two or more materials, a hybridization effect is realized [7]. The hybridization effect of fibers due to some reasons such as residual stresses, changes in developing and propagation of damage, and dynamic stress concentrations can improve the impact resistance of composites [8]. In hybrid composites, the impact behavior greatly depends on the different design parameters. The thickness of the laminate and stacking sequence are two important parameters on the impact behavior of hybrid composites. It has been reported that the stacking sequence of fibers in polymer composite plays an important role in determining the impact behavior of hybrid composites. The position of each layer can change the impact energy and the energy absorption mechanisms of the hybrid composite [9].

Some fibers such as Kevlar, carbon, basalt, and glass are used as high-tech reinforcing materials in aviation, automobile and marine industry. Among all fibers, Kevlar fiber has the highest tensile strength-to-weight ratio. It is worth noting that the strength of Kevlar fiber is about 5 times higher than that of steel. Also, Kevlar fiber can absorb a lot of energy during the strike. Kevlar fiber used primarily in textile processing, plastic reinforcement, ropes, cables, and composites for marine sporting goods and aerospace applications [10]. Basalt fiber is a natural material from volcano lava that has a low price and good physicomechanical properties such as high tensile modulus, favorable thermal stability, and good adhesion to the resin. These natural fibers can be used in high temperature and chemical environment since they have high thermal and chemical stability. Basalt fibers are now being popular choices for material scientists for the replacement of steel [1].

Eslami-Farsani et al. [1] investigated the different laying of metal plates and basalt fiber reinforced epoxy composites under Charpy impact loads. Their results indicated that when FML was fabricated from steel sheets, it showed a higher energy absorption value than that of FMLs with

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aluminum sheets. On the other hand, it should be noted that if steel sheets are used for making FMLs, the weight of the fabricated structure will be increased dramatically.

Khalili et al. [3] fabricated FMLs with glass fiber reinforced polymer (GFRP) with the various laying of aluminum (Al) and steel (St) sheets and then they investigated the mechanical behavior of mentioned FMLs. They concluded that in tensile and flexural tests, the FML consisting of Al/GRP/Al/GRP/Al showed the best strength among others; while in the Charpy impact test, the highest energy absorption belongs to FML consisting of St/GRP/Al/GRP/St.

Ferrante et al. [11] fabricated FMLs consisting of basalt fabric epoxy prepreg and aluminum sheets and then compared the low-velocity impact behavior of FMLs with monolithic aluminum in several impact energy with two different indenters. Their results indicated that the impact behavior of basalt FMLs was slightly better than aluminum plates in impact loadings. This finding was related to the greater deformation capacity of basalt FMLs, in comparison with monolithic aluminum.

Bozkurt et al. [12,13] investigated the hybridization effects of fibers on the mechanical behavior of basalt/aramid fiber reinforced hybrid composites. For this purpose, they fabricated different configurations of laminates and then carried out the mechanical tests. Their findings indicated that the position of basalt layers had a major effect on the impact energy of hybrid composite. From their study, it can be deduced that replacing the aramid layers with basalt layers restricts the deformation of the aramid layer but, increases the impact energy of hybrid composite laminates through the delamination between basalt layers. Moreover, they found that the tensile, bending

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and Charpy impact behavior of neat basalt fibers/ epoxy was greater than that of the neat aramid fibers/epoxy laminate.

Behnia et al. [14] studied the influence of stacking sequence of fibers on the Charpy impact behavior of hybrid composites. After the fabrication of different hybrid composites and using various fibers, they concluded that when the number of basalt layers was greater than that of carbon ones, the basalt/carbon hybrid composites showed optimum behavior. Placing basalt fibers as the outer layers can also be considered as a subsidiary factor in enhancing the energy absorption capability of basalt/carbon hybrid composites.

Erkliğ et al. [15] studied the Charpy impact behavior of Kevlar/ S-glass epoxy hybrid composite laminates with different configurations. They found that the hybridization of S-glass fibers with Kevlar fibers improved the impact strength and absorbed energy of the overall hybrid structure. Moreover, when the hybrid specimens were impacted on the surface of the Kevlar side, they exhibited higher impact resistance, compared with the glass side impact.

Dorigato et al. [16] investigated the effect of stacking sequence and weight percent of carbon/basalt fibers on the flexural and impact behavior of polymer composites. They evidenced that the flexural modulus of the hybrid composites followed the rule of mixture, while positive deviations with important synergistic effects were detected for the ultimate properties. Furthermore, the introduction of basalt fibers in the carbon fiber laminates could promote an increase in the adsorbed impact energy, with an enhancement of the fracture propagation component.

Park et al. [9] investigated the effect of stacking sequence of fibers on the impact behavior of aramid and glass fiber hybrid composites. For this purpose, they fabricated one-layered, two-layered and three-layered types of these composites and carried out low-velocity impact tests. Their results showed that when the aramid layer was at the impacted surface, the laminate exhibited higher impact energy and delamination area. In another study, they found that when the aramid layer was at the impacted surface, the composite exhibited a higher impact energy [17].

Abdi et al. evaluated the influence of silanized $CaCO_3$ (S-$CaCO_3$) on the mechanical behavior of basalt fibers (BF)/epoxy composites. For this purpose, they added S-$CaCO_3$ nanoparticles with various weight contents (0, 1, 3 and 5 wt. %) with respect to the whole weight of the matrix including resin and curing agent and fabricated BF reinforced composites via hand lay-up technique. They demonstrated that with the dispersion of 3 wt. % S-$CaCO_3$, flexural strength, flexural modulus, tensile strength and tensile modulus enhanced by 28%, 35%, 20% and 30%, respectively [18].

Sarasini et al. [19] studied the low-velocity impact behavior of hybrid laminates reinforced with woven aramid and basalt fabrics that were manufactured by resin transfer molding. Results showed that hybrid laminates with intercalated configuration (alternating sequence of basalt and aramid fabrics) had a better impact energy absorption capability and enhanced damage tolerance, compared to the all-aramid laminates.

Based on the above-mentioned literatures, there are extremely limited researches on the Charpy impact behavior of hybrid composites and hybrid FMLs made of basalt and Kevlar fibers. To the best of author's knowledge, there is no comparative study on the polymer composite and FMLs

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with the same condition yet, in literature. So, the results can help to increase the use of polymer composite and FML structures for various applications. This study aims to investigate the effect of stacking sequence of basalt and Kevlar fibers on Charpy impact behavior of epoxy composite, aluminum FML and steel FML.

2. Materials and experimental procedure

2.1. Materials

To produce the hybrid composites and FMLs, woven basalt fibers (BAS 350.1270.A supplied by Basaltex NV, Belgium) and plain weave Kevlar 49 fibers (produced by fiber Glast Developments Corp., USA) were used. No sizing treatment was applied for used fibers in this study. The properties of basalt and Kevlar fabrics are given in table 1.

Table 1- Properties of Basalt and Kevlar fabrics (According to the company's data sheet).

Fibers type	Surface density (g/m^2)	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)
Basalt	350	2.7	2100	91	2.6
Kevlar 49	200	1.44	3600	124	2.4

For the fabrication of composites, the epoxy resin Epon 828 (produced by Shell chemical) with polyamine hardener (TETA)[1] as curing agent was used. The resin to hardener ratio was 1:10. Also,

[1] Triethylenetetraamine

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in order to fabricate FMLs, two kinds of metal plates (aluminum 2024-T3 and stainless steel 316L) were used; their properties are listed in table 2.

Table 2- The properties of aluminum 2024-T3 and stainless steel 316L.

Metal plate type	Ultimate tensile strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)	Thickness (mm)
Aluminum 2024-T3	469	73.1	2.78	0.5
Stainless steel 316L	515	193	7.99	0.5

In the fabrication of FMLs, the used Aluminum 2024-T3 plates were cut by water jet into 1 cm × 9 cm size. Then, the surface treatment with different steps [20] was applied on the aluminum sheets, to improve the adhesion between the layers. At first, the plates were degreased by acetone at room temperature. For preparing the Al surface, plates were immersed in the NaOH solution. To deoxidation of the surface, plates were immersed in the HNO_3 solution at room temperature. Then, plates were anodized by the chromic acid solution. Finally, to assure of cleaning, aluminum plates were cleaned by cotton soaked in acetone.

To fabricate FMLs, stainless steel 316L plates were used as another metal alloy. Similar to Al plates, the steel plates were cut by waterjet cutting into 1 cm × 9 cm. After cutting the plates, for chemical preparation of plates, some surface treatment steps [20] were carried out. At first, the plates were degreased by acetone at room temperature. Then, the plates were immersed in the NaOH solution for cleaning. After this step, the plates were immersed in a tank of distilled water and were rinsed by the same liquid. Then, the cleaned plates were immersed in the sulfuric acid.

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To start the reaction, the plates were pulled out from acid and were exposed to the air. For etching treatment, the plates were immersed in the same acid solution again and then, they were rinsed by distilled water. Finally, the plates were immersed in a passivation solution consisting of sulfuric acid and sodium dichromate and then they were washed and dried.

2.2. Fabrication of composites and FMLs

After preparing metal plates, all the composite and FML specimens were fabricated by hand lay-up technique and put into a fixture. The fixture was put under press machine with 5 bar pressure and was kept at room temperature for the next 24 h and then specimens were removed from the fixture. Each FML specimen consists of 3 plates of metal and 3 polymeric composite layers that were placed between metal plates, as shown in Figure 1. The hybrid composites were made by Basalt and Kevlar fibers reinforced epoxy.

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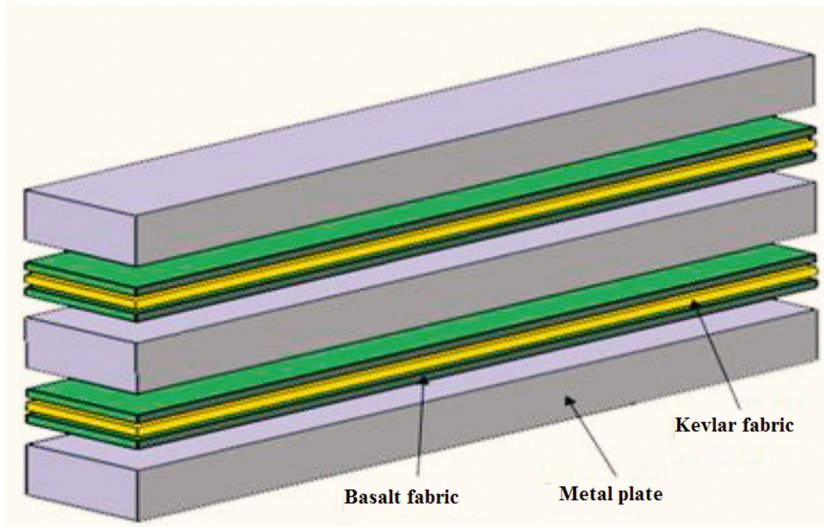

Figure 1- The schematic illustration of typical FML consists of three metal plates and two groups of composites placed between them.

These fibers were placed in different arrangements, as shown and coded in table 3. The code numbers of each specimen consist of two digits. The first digit shows the type of metal plates used in FML structure (1: none, 2: steel, and 3: aluminum) and the second one indicates the arrangement of used fibers for the fabrication of the composite. Also, the specimen's codes, sample thickness, and the content of composite components are given in table 4.

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Table 3- The type of specimens, their corresponding codes and fiber volume fractions.

Type of fiber arrangement*	Specimen code	Fiber volume fractions (%)
BBBBBB	11	55
BKBBKB	12	55
KBKKBK	13	55
KKKKKK	14	55
St/BBB/St/BBB/St	21	25
St/BKB/St/BKB/St	22	25
St/KBK/St/KBK/St	23	25
St/KKK/St/KKK/St	24	25
Al/BBB/Al/BBB/Al	31	25
Al/BKB/Al/BKB/Al	32	25
Al/KBK/Al/KBK/Al	33	25
Al/KKK/Al/KKK/Al	34	25

*B: Basalt fibers, K: Kevlar fibers, St: Steel, Al: Aluminum

Table 4- Information of polymer composite and FMLs.

Specimen's codes	Specimen's thickness (mm)	Content of composite components (wt.%)				
		Kevlar fibres	Basalt fibres	Epon 828	St sheet	Al sheet
11	1.75	-	79	21	-	-
12	1.72	26	55	19	-	-
13	1.72	56	26	18	-	-
14	1.70	83	-	17	-	-
21	3.22	-	23	14	63	-
22	3.20	7	17	13	63	-
23	3.18	15	10	12	63	-
24	3.15	25	-	12	63	-
31	3.25	-	23	14	-	63
32	3.20	7	18	12	-	63
33	3.20	15	10	12	-	63
34	3.17	26	-	11	-	63

2.3. Charpy impact test

During the Charpy impact test, the specimens were struck by SIT-200B SANTAM at room temperature. The used energy value for the Charpy impact tests was 200 J. So, the hammer was instrumented for this purpose and the used support span during these tests was 7 cm. Also, the Charpy impact test was conducted on a flatwise direction. According to the standard ISO 179-1, a pendulum with specified energy is released to strike the specimen and causes to break it. Three specimens of each category were tested and the average value was reported.

2.4. Microscopic characterization

To analyze the surface of aluminum and steel plates, scanning electron microscopy (SEM) Vega\\Tescan-LMU was used. Moreover, the damage assessment was also supported by an optical microscope of cross-sectioned specimens with the aim of gaining a better knowledge of the failure mechanisms of samples. Therefore, to analyze the fracture surface of specimens, the optical microscope Meiji techno - IM 7200 was used.

3. Result and discussion

3.1. Comparison the surface-treated aluminum and steel plates

Figure 2 shows the SEM images of the surface-treated steel and aluminum plates. As can be seen in this figure, the pits of surface-treated Al plate is more than that of surface-treated steel plate. Furthermore, the size of the pits on the surface of the Al plate is smaller and very deeper than that of the steel plate. Thereby, it can be predicted that the polymer penetration in the pits of aluminum plates can be done more easily than in the pits of steel plates. As a result, it can be deduced that the mechanical interlocking of the polymer with anodized Al plate is more than that of etched steel plate.

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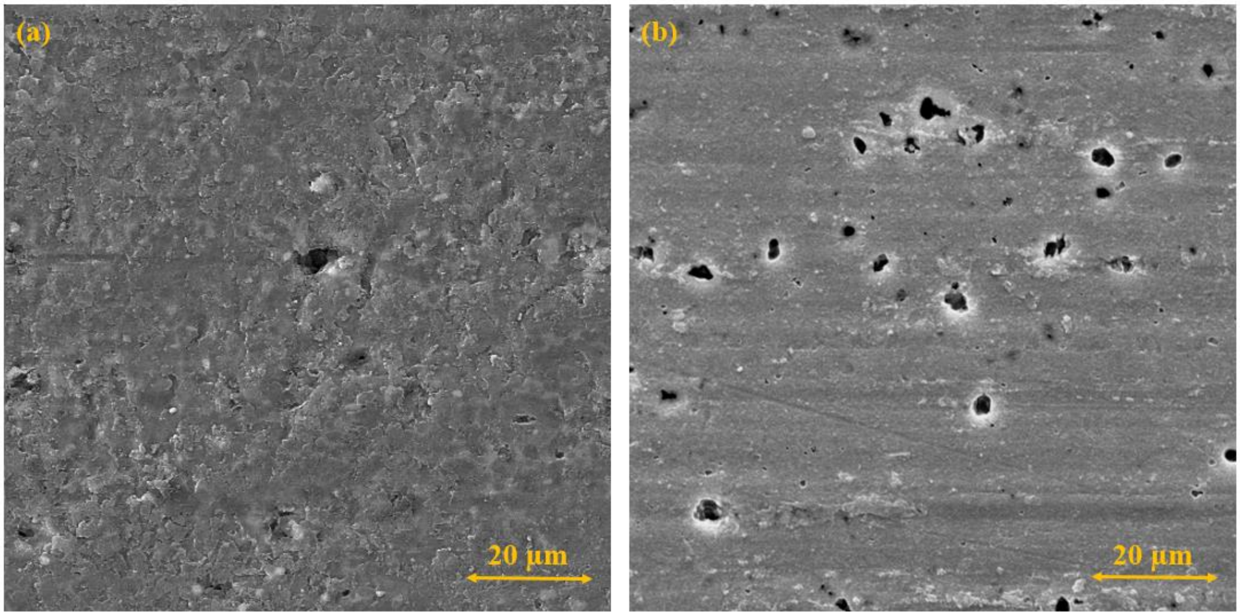

Figure 2- Treated surface of, (a) steel plate (etched), and (b) aluminum plate (anodized) imaged by SEM.

3.2. Charpy impact test

All the composite and FML specimens were tested under Charpy impact loading at room temperature and the experimental results are given in Table 5. According to table 5, the energy absorption value of composites has been increased by the hybridization of basalt and Kevlar fibers. The energy absorption of steel-FMLs has been increased by increasing the number of Kevlar fiber layers in them; while the energy absorption of Al-FMLs has been increased by increasing the number of basalt fiber layers in them.

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Table 5- Absorbed energy values of specimens during Charpy impact test.

Specimen code	Specimen weight (g)	Absorbed energy (kJ/m^2)	Specific energy absorption ($kJ/g.m^2$)	
			Value	Standard deviation
11	2.64	1.201	0.45	0.011
12	2.38	1.523	0.64	0.009
13	1.71	1.355	0.79	0.012
14	1.54	0.765	0.49	0.014
21	16.44	8.298	0.50	0.010
22	16.04	8.421	0.52	0.011
23	15.95	8.839	0.55	0.008
24	15.42	11.455	0.74	0.016
31	7.08	10.185	1.44	0.013
32	6.47	9.912	1.53	0.018
33	6.19	9.034	1.46	0.015
34	5.55	7.503	1.35	0.009

The effect of fiber arrangement on the absorbed energy of composites is shown in Figure 3. Charpy impact test results indicate that the composite specimens with hybrid fibers show higher absorbed energy than that of other types of composites with basalt or Kevlar fibers (neat). It is clear that using both Kevlar and basalt fibers for the fabrication of composites has resulted in the improvement of the absorbed energy value. So, the energy absorption values of specimens 12 and 13 with two types of fibers (respectively 1.523 and 1.355 kJ/m^2) are higher than those of specimens 11 and 14 fabricated by one type of basalt or Kevlar fiber (respectively 1.201 and 0.765 kJ/m^2). When two types of fibers are used for the fabrication of composites, the hybridization effect appears. As can be seen in Figure 3, specimen 12 has the highest absorbed energy among all samples (specimen 12 is about 99% greater than specimen 14). Therefore, the effect of hybridization in composite fabricating can be observed. This effect is one of the effective ways to

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increase the impact resistance and energy absorption capability of composites using high-strength fibers such as carbon and Kevlar fibers. On the other hand, the cost of composites can be reduced using more economic fibers like glass and basalt fibers [15]. Figure 3 presents the absorbed energy values of composites as a function of the fiber arrangement. It can be noted that the neat basalt laminate (specimen 11) show higher energy absorption (56.9%), in comparison with neat Kevlar laminate (specimen 14). The similar results were also reported by Bozkurt et al. [12].

Figure 4 shows the fracture surfaces of the polymer composite interlayers in the 14 and 11 specimens after the Charpy impact test. As shown in Fig. 4-a, for the specimen 14, the delamination at the polymer matrix/fibers interface indicate weak adhesion at the polymer matrix/fibers interface, causing the weak failure in the polymer composite interlayers. These observations indicate that the load transfer from the matrix to the fibers was almost insignificant. On the other hand, for the specimen 11 (Fig. 4-b), surfaces of the fibers are not smooth, indicating the good wettability and the attachment of matrix to the fibers. So, in spite of the better mechanical properties of Kevlar fibers compared to basalt fibers, the strong adhesion at the interface in polymer composite including basalt fibers led to considerable load transfer from matrix to the fibers. Also, it can be concluded that the wettability of basalt fiber by epoxy resin is more than the wettability of Kevlar fiber by it [21, 22].

In the case of hybrid and non-hybrid composites, it can be mentioned that the high wettability of basalt fibers in presence of epoxy and high inherent mechanical behavior of Kevlar fiber are two key factors in increasing the impact properties of hybrid composites, compared to non-hybrid composites.

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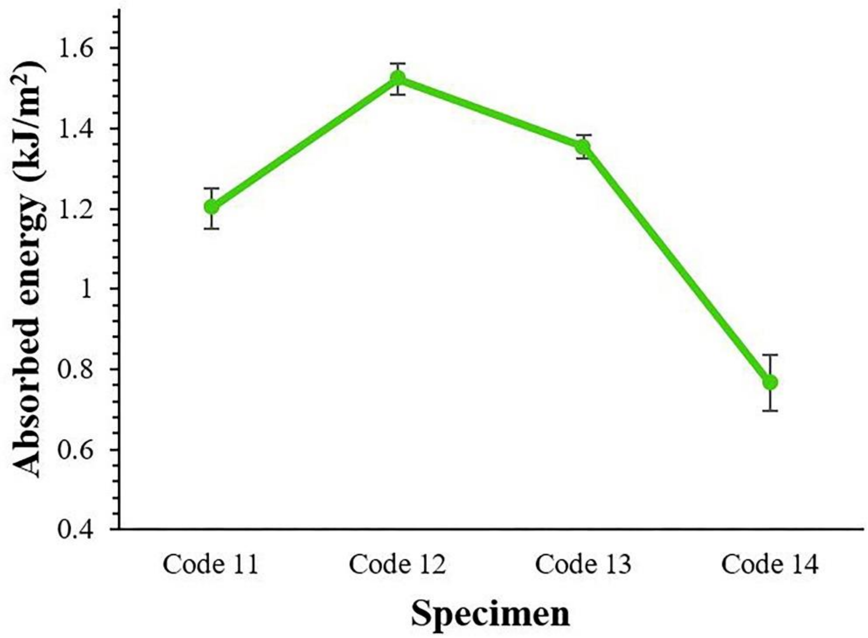

Figure 3- Absorbed energy of composites as a function of fiber's arrangement.

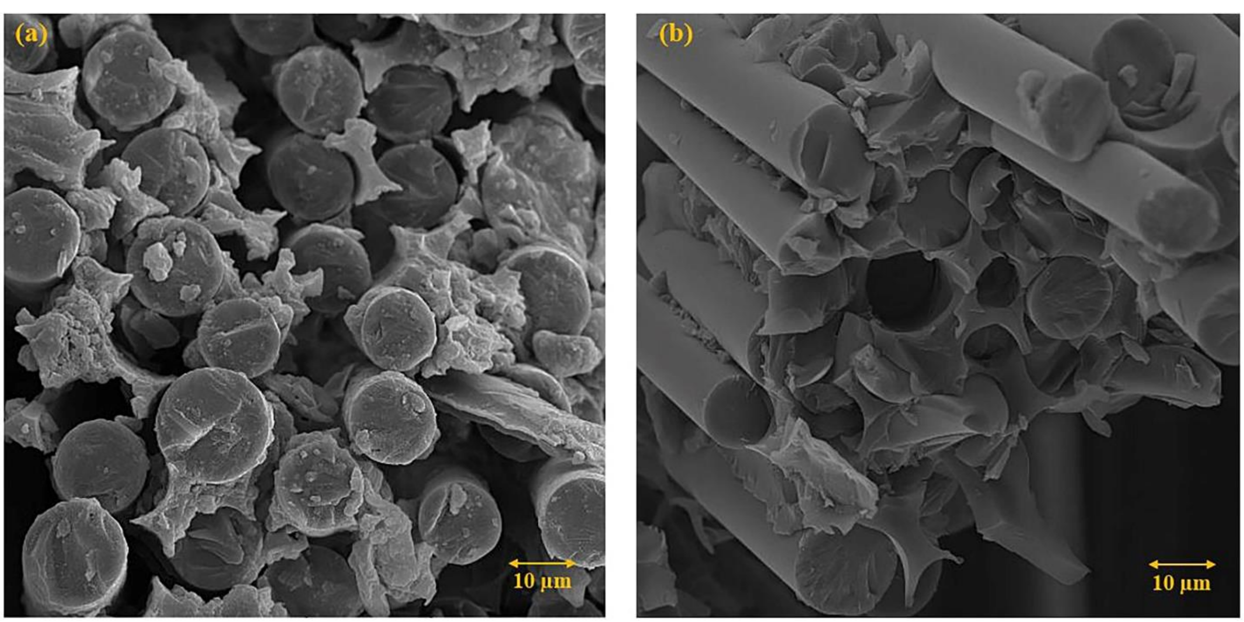

Figure 4- Fracture surfaces of polymer composite containing, (a) neat Kevlar fibers, and (b) neat basalt fibers.

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The absorbed energy of fabricated FMLs by steel plates as a function of fiber arrangement is depicted in Figure 5. From this figure, it can be deduced that fabricated specimen by Kevlar layers (specimen 24) has the highest energy absorption among other configurations of steel-FMLs. As can be seen in Figure 5, the absorbed energy of specimen 24 that consists of Kevlar fibers (11.455 kJ/m^2) is about 38% higher than that of specimen 21 that consists of basalt fibers (8.298 kJ/m^2). It should be noted that there are two mechanisms in the final results of the impact behavior of hybrid FMLs including adhesion between the metal plate and polymer composite, and fiber properties. In this case, the inherently high mechanical properties of Kevlar fiber is the dominant mechanism in the attainment of final impact behavior and leads to be the highest energy absorption of specimen 24. It is obvious that by increasing the number of Kevlar fiber layers in the steel-FML, the absorbed energy is increased, progressively. The hybrid steel-FMLs (specimens 22 and 23) show energy absorption values between two steel FMLs (specimens 21 and 24). So that, the absorbed energy of specimen 24 is about 36% higher than that of specimen 22 (8.421 kJ/m^2) and about 29% higher than that of specimen 23 (8.839 kJ/m^2).

The absorbed energy values of all configuration of tested steel-FMLs are greater than those of composites with the same configuration of fibers (Figures 3 and 5). In the case of steel-FMLs, it can be said that although these types of FMLs present a high impact behavior, their impact resistance is lesser than expected values, due to their high overall density. From the comparison between the weight of specimens and their energy absorption values, it can be concluded that the average weight of steel-FMLs is 7.74 times more than the average weight of hybrid composites;

while the average absorbed energy of steel FMLs is only 7.64 times greater than that of hybrid composites. Thereby, it can be noted that by considering the weight of specimens, the performance of steel plates is not proper for improving the impact behavior of composites.

In the case of hybrid FML, the adhesion between the metal and composite layers plays an important role in the energy absorption value [7, 12, 15]. According to the results of many researchers, when composite layers properly adhere to the metal layer, the delamination between metal and composite layers will not occur after the collision phenomenon and this FML shows a favorable energy absorption under impact loads [23, 24]. However, in the case of steel-FMLs, due to the weak adhesion between the metal and epoxy resin, the absorbed energy is lesser than expected values. By comparison between Figures 3 and 5, it can be concluded the FMLs with 6 layers of Kevlar fibers (specimen 24) shows a significant enhancement in the energy absorption (11.455 kJ/m^2) and its value is almost 15 times greater than that of composite with 6 layers of Kevlar fibers (specimen 14).

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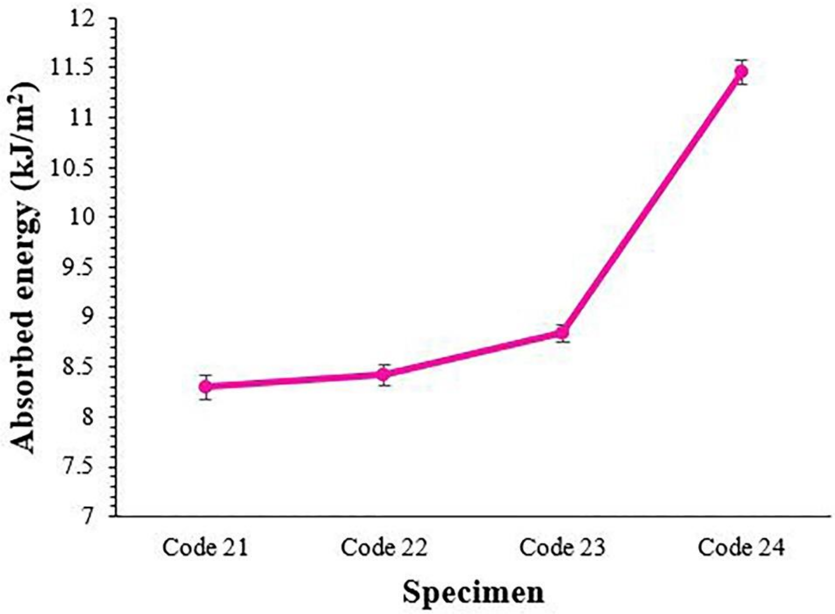

Figure 5- Absorbed energy of FMLs fabricated by steel plates as a function of fiber's arrangement.

The effect of fiber arrangement on the absorbed energy value of fabricated FMLs by aluminum plates is shown in Figure 6. According to this figure, the fabricated specimen by basalt fibers (specimen 31) has the highest energy absorption among other configurations of Al-FMLs. The absorbed energy of specimen 31 that consists of basalt fibers is 10.185 kJ/m^2; while this value in the specimen 34 that consists of Kevlar fibers is 7.503 kJ/m^2. Thus, the energy absorption of specimen 31 is 35% higher than that of specimen 34. In this case, the high wettability of basalt fiber by epoxy results in the strong adhesion between the metal plate and polymer composite. This phenomenon is the dominant mechanism in the attainment of final impact behavior and is the main reason for the highest energy absorption of specimen 31. It can be seen that by increasing the number of basalt fiber layers in Al-FML, the absorbed energy has been progressively increased. The hybrid Al-FMLs (specimens 32 and 33) show energy absorption values between two

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aluminum FMLs (specimens 31 and 34). So that, the absorbed energy of specimen 31 is about 3% higher than that of specimen 32 (9.912 kJ/m^2) and 13% higher than that of specimen 33 (9.034 kJ/m^2).

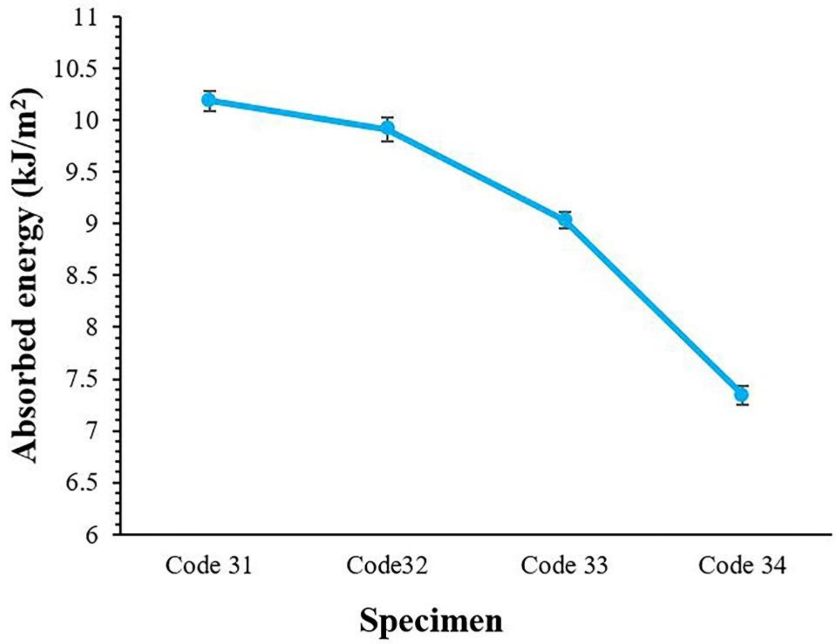

Figure 6- Absorbed energy of FMLs fabricated by aluminum plates as a function of fiber's arrangement.

According to table 2, the density of stainless steel 316 L (7.99 g/cm^3) is about 2.87 times higher than that of aluminum 2024 T3 (2.78 g/cm^3). As can be seen in Figure 2, the results indicate that by considering the difference between the density of aluminum and steel plates, the fabricated FMLs by aluminum plates illustrate the most desirable absorbed energy with respect to FMLs with steel plates and composites with the same fibers. This can be attributed to the excellent adhesion between Al plates and epoxy resin due to numerous and deep pits on the surface of aluminum. According to table 5, the average energy absorption and the average weight of Al FMLs are 9.158 kJ/m^2 and 6.32 g, respectively. On the other hand, the average energy absorption and the average

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weight of steel FMLs are 9.253 kJ/m^2 and 15.96 g, respectively. Accordingly, it can be concluded that the average energy absorption to the weight ratio of Al-FMLs (1.45 kJ/g.m^2) is 2.5 times more than those of steel-FMLs (0.58 kJ/g.m^2) and basalt/ Kevlar fibers hybrid composite (0.59 kJ/g.m^2).

Figure 7 shows the fractured samples after applying the Charpy impact test in order to comparison of damage patterns in samples. It can be shown in Figure 7-a, neat composites (specimens 11 and 14) have a brittle fracturing. While in other tested composites (specimens 12 and 13), due to appearing the hybridization effect, the type of fractures have changed and samples have absorbed more energy during fracture. In Al FMLs (Figure 7-b) due to better adhesion of basalt fibers to Al sheets (specimen 31), fracture process has been delayed and this strong adhesion prevents the fracture of Al sheets; On the other hand, partly weak adhesion between Kevlar fibers and aluminum sheets couldn't tolerate high energy strike and specimen 34 has absorbed less energy during fracture.

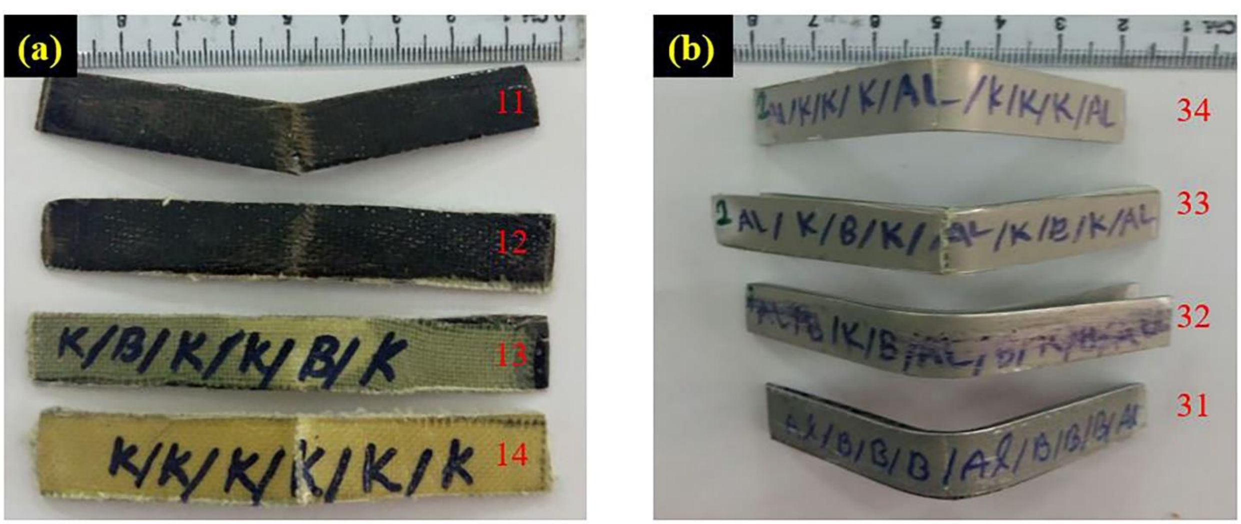

Figure 7- The fracture surface of (a) polymer composites, (b) Al FMLs.

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To study the failure mechanism of specimens, optical microscopy images were used. Figure 8 corresponds to Al and steel-FML specimens with the highest and lowest absorbed energy after Charpy impact tests. Figures 8a and 8b show the fracture surface of Al-FMLs. As can be seen in Figure 8a, there is a strong adhesion between the Al layer and basalt fibers. It is clear that the strong adhesion between the Al layer and basalt fibers has remained even after Charpy impact loading. However, in the case of Kevlar FML (Figure 8b), after the failure of external layer, the polymeric composite existing in FML has been crushed and then failed. Figures 8c and 8d show the fracture surface of steel FMLs. It is obvious that after struck, a delamination phenomenon has occurred in the FML with basalt fibers (Figure 8c). Finally, in the case of steel-FML and Kevlar fibers (Figure 8d), it can be noted that due to the weak adhesion between layers, the delamination between steel plate and adjacent Kevlar fibers layer has occurred, before the failure of polymeric composite layers. The above-mentioned description has also marked on the photographs by arrows (Figure 8).

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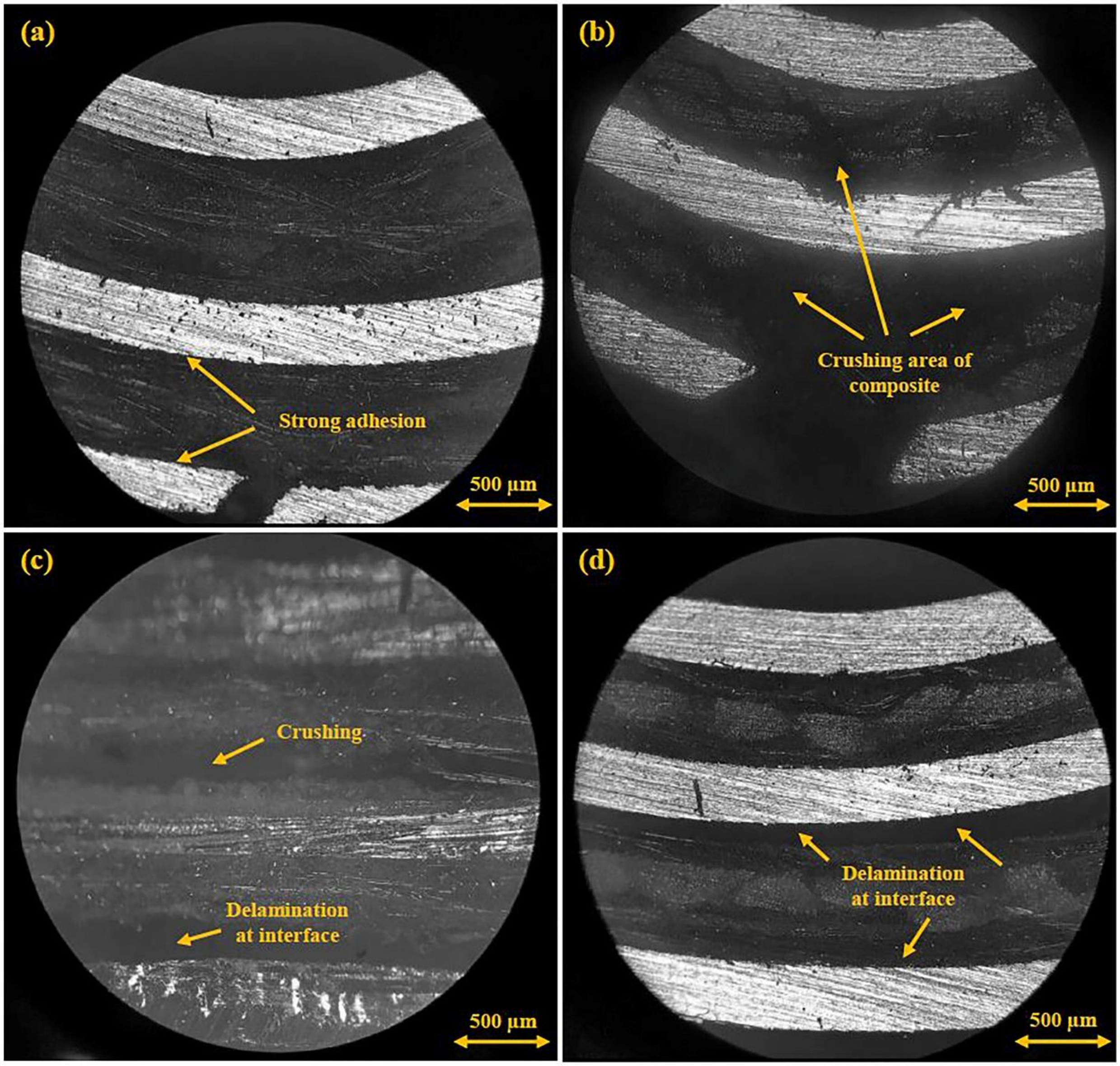

Figure 8- Fracture surface of, (a) Al/BBB/Al/BBB/Al, (b) Al/KKK/Al/KKK/Al, (c) St/BBB/St/BBB/St, and (d) St/KKK/St/KKK/St after Charpy impact tests.

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4- Conclusion

In this study, a comparison between basalt/ Kevlar fibers reinforced epoxy hybrid composites and basalt/ Kevlar fibers FMLs with steel and aluminum plates under Charpy impact load was carried out. By comparing the experimental results of this work, the following conclusions can be noted:

a- When both basalt and Kevlar fibers were used for the fabrication of composites, the hybridization effect appeared and hybrid composites had better impact behavior than neat composites. Results indicated that the composites with the configuration of BKBBKB and KBKKBK had absorbed energy respectively 26% and 12% higher than those of specimens containing basalt fibers and respectively 99% and 77% higher than those of specimens containing Kevlar fibers. This is due to the high delamination resistance and fiber pull-out of both fabricated specimens by basalt and Kevlar fibers.

b- Inherently, the energy absorption of Kevlar fibers was higher than that of basalt fibers. Results indicated that the energy absorption of steel-FMLs was improved by increasing the number of Kevlar fibers layer. So, the absorbed energy of specimen containing Kevlar fibers and steel plates was about 38% higher than that of specimen containing basalt fibers and steel plates. According to the results, among all samples, the steel-FML with 6 layers of Kevlar fibers had the highest absorbed energy (11.455 kJ/m^2) and its value was 15 times greater than that of the composite specimen with 6 layers of Kevlar fibers (0.765 kJ/m^2). Achieved results from Charpy impact tests demonstrated that by considering the high weight of these types of FMLs, the average absorbed energy to average weight ratio of steel-FMLs (0.58 $kJ/g.m^2$) was lower than that of composites (0.59 $kJ/g.m^2$).

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c- The fabricated FMLs by aluminum plates illustrated the most desirable absorbed energy compared to FMLs with steel plates and composites with the same fibers. This behavior was related to excellent adhesion between Al plates and epoxy resin. By increasing the number of basalt fiber layers in this type of FMLs, the absorbed energy was increased progressively. So, the energy absorption of specimen containing basalt fibers and aluminum plates was about 39% higher than that of specimen containing Kevlar fibers and aluminum plates. Generally, according to the Al and steel weights, it can be said that the average energy absorption to the average weight ratio of aluminum FMLs (1.45 $kJ/g.m^2$) was about 2.5 times higher than that of steel FMLs (0.58 $kJ/g.m^2$).

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