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Mechanical Characterization of Aluminum Sandwich Structures with Woven-Ply Pineapple Leaf/Glass Fiber-Reinforced Hybrid Composite Core

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ABSTRACT

Fiber-metal laminates consisting of alternating metal and fiber-reinforced polymer layers have displayed remarkable performance in several engineering applications. This work aims to identify the feasibility of incorporating pineapple leaf fiber to partially supersede glass fiber in thermoplastic-based fiber-metal laminates. Fiber-metal laminates made of pineapple leaf/glass/polypropylene/aluminum were fabricated using the hot press molding technique. The tensile, flexural, Charpy impact and quasi-static indentation tests were performed. The findings indicated that the hybridization of glass with pineapple leaf fibers improved the mechanical properties of the laminates. The results are particularly promising in [G/P/G] laminates in which their tensile and flexural strengths are 38.98% and 20.19% higher than [P/P/P] laminates. In addition, the Charpy impact strengths of [G/P/G] laminates are also 236.66% and 175.68% greater than those of [P/P/P] laminates. In terms of indentation properties, the maximum indentation forces of [G/P/G] laminates are 16.71% and 13.76% higher than those of [P/P/P] laminates at indenter diameters of 12.7 and 20.0 mm, respectively. Interestingly, in-plane and out-of-plane properties of [G/P/G] laminates were comparable to [G/G/G] laminates. Thus, it is anticipated that the hybridization concept could escalate the utilization of natural fibers as a potential reinforcement for engineering applications.

摘要

由交替的金属层和纤维增强聚合物层组成的纤维-金属层压板在一些工程应用中显示出显著的性能. 这项工作旨在确定在热塑性纤维-金属层压板中加入菠萝叶纤维以部分取代玻璃纤维的可行性. 采用热压成型技术制备了由菠萝叶/玻璃/聚丙烯/铝制成的纤维-金属层压板. 进行了拉伸、弯曲、夏比冲击和准静态压痕试验. 研究结果表明, 玻璃与菠萝叶纤维的杂交改善了层压板的机械性能. 该结果在[G/P/G]层压板中尤其有前景, 其中其拉伸和弯曲强度分别比[P/P/P]层压板高38.98%和20.19%. 此外, [G/P/G]层压板的夏比冲击强度也比[P/P/P]层压板高236.66%和175.68%. 就压痕性能而言, 在压头直径为12.7 mm和20.0 mm时, [G/P/G]层压板的最大压痕力分别比[P/P/P]层压板高16.71%和13.76%. 有趣的是, [G/P/G]层压板的面内和面外性能与[G/G/G]层合板相当. 因此, 预计杂交概念可以提高天然纤维作为工程应用潜在增强材料的利用率.

KEYWORDS

Fiber-metal laminates; hybrid composites; pineapple leaf fiber; mechanical properties; quasi-static indentation; woven fabric

关键词

纤维金属层压板; 混杂复合材料; 菠萝叶纤维; 机械性能; 准静态压痕; 机织物

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Introduction

Fiber-metal laminates (FMLs) are advanced laminated structures comprising metal and fiber-reinforced polymers (FRPs) layers bonded by an adhesive agent. The conventional FMLs are mainly based on synthetic fibers which may result in environmental pollution and human health issues. On this note, natural fibers have become a viable option to replace synthetic fibers. Lightweight, biodegradable, non-toxicity, carbon dioxide neutral, high specific properties, low cost and excellent acoustic properties are the commonly known virtues of natural fibers. At this stage, the complete substitution of synthetic with natural fibers is not realistic, mainly because of the relatively low mechanical strength and the tendency of moisture uptake of natural fibers. Toward the balance in mechanical properties and eco-friendliness, the combination of synthetic and natural fibers in composites is considered an alternative way. Several research works have revealed a high potential of such materials in terms of mechanical properties (Ng, Yahya, and Muthukumar 2022; Sanjay and Yogesha 2018; Sharba et al. 2016; Velmurugan and Manikandan 2007). Since hybrid composites exhibit several favorable characteristics, it is expected that FMLs based on hybrid composites could inherit those benefits and can be employed to replace metal alloys in the automotive sector.

In an effort to reduce the cost and enhance the sustainability of the materials, post-harvest wastes are the prior choice to obtain renewable fibers. In this context, pineapple leaf fiber (PALF) has been attested to be a potential reinforcement for FRPs. PALF is extracted from the pineapple plant leaves, where the leaves are generally discarded as agro-waste, generating a huge amount of unutilized biomass. In addition, using PALF as reinforcement could develop value-added products, which matches well with the waste-to-wealth strategy. From the viewpoint of mechanical properties, PALF is one of the natural fibers exhibiting comparatively high mechanical properties because of its high cellulose content. Therefore, it is forecasted that the utilization of PALF could develop polymer composites with high economic value and mechanical properties while improving environmental friendliness.

A few experimental investigations have been conducted to determine the mechanical properties of FMLs based on natural fibers. Feng et al. (2021) explored the novel FMLs based on PALF fabric. They revealed that PALF-based FMLs encompassed higher absolute and specific mechanical properties than their composites and PALF fabric counterparts. Subramaniam et al. (2019) identified the tensile and indentation properties of FMLs with kenaf/glass fiber woven core after weight normalization. They concluded that the hybrid FMLs with high-strength glass fiber at the outermost layers of composites displayed the highest tensile and indentation properties. Similar results were found by Zareei, Geranmayeh, and Eslami-Farsani (2019), in which placing high-strength basalt fiber at the outer layers of composites provided the highest flexural and impact properties to the basalt/jute fiber-based FMLs. Abd El-Baky et al. (2022) identified the tensile and flexural properties of jute/glass-based composite-metal laminates. The findings showed that the partial replacement of jute with glass fibers improved the tensile and flexural properties. Mohammed et al. (2018) conducted mechanical characterization on the flax/kenaf/carbon fiber-based FMLs. They concluded that flax/carbon fiber-based FMLs had greater tensile and compressive strengths than other FMLs. Nonetheless, the flexural strength of flax/carbon fiber-based FMLs was weaker than that of kenaf/carbon fiber-based FMLs. Chandrasekar et al. (2019) explored the tensile properties of flax/sugar palm/carbon fiber-based FMLs. The greater tensile properties were noticed in flax/carbon FMLs when compared with sugar palm/carbon FMLs. However, the addition of flax in the sugar palm/carbon FMLs improved their tensile properties.

PALF has demonstrated excellent mechanical properties and is still considered agro-waste. Thus, the use of PALF as potential reinforcement is in line with the waste-to-wealth strategy. Several literature studies have been conducted to explore PALF-based hybrid composites (Kumar and Saha 2022; Najeeb et al. 2021; Ng, Yahya, and Muthukumar 2022). On the other hand, glass fiber is the most extensively employed synthetic fiber because of its high mechanical strength and low-cost characteristic. It is anticipated that combining glass and pineapple leaf fiber in FMLs can balance mechanical properties and environmental friendliness while improving the economic value of the materials. To date, the mechanical properties of FMLs with PALF/glass woven core still remain unexplored. Thus, this work aims at exploring the tensile, flexural, Charpy impact and quasi-static indentation properties of PALF/glass fiber-based FMLs with varying fiber layering sequences to identify the feasibility of encapsulating PALF in FMLs in the replacement of glass fiber-based FMLs.

Materials and methods

Materials

Plain woven-ply PALF having an areal weight of 315 g/m^2 was obtained from MechaSolve Engineering, Malaysia. Plain woven-ply glass fiber with an areal weight of 600 g/m^2 was procured from ZKK Sdn. Bhd, Malaysia. The homopolymer polypropylene (PP) pellets with a density of 0.91 g/cm^3 and melt flow rate of 1.2 g/min were purchased from Al Waha petrochemical company, Saudi Arabia. Aluminum 5052-H32 sheets of 0.5 mm thickness were provided by Novelis Inc., United States.

Preparation

The specimen preparation was divided into two steps: the fabrication of composite core and FMLs. The composite laminates were first fabricated using the hot press molding compression method. PALF was dried at a temperature of 80°C for 24 h to purge the excessive moisture content before the composite fabrication. The PP granules were compressed at a temperature of 175°C and 0.3 MPa to form films. The alternating PALF and glass fabric layers were then placed in a frame mold with a size of 250 mm × 250 mm × 3 mm. The PP films were inserted between each fiber layer to ensure excellent impregnation. The composite laminates were heat pressed at a temperature of 175°C and pressure of 3.5 MPa using a hydraulic hot press machine. The composite laminates were cooled to an ambient temperature at the same pressure to maintain the geometrical consistency. A total number of four layering sequences have been fixed in this research study. The non-hybrid PALF and glass fiber-based FMLs are represented by [P/P/P] and [G/G/G], respectively, where P indicates the PALF layer and G implies the glass fiber layer. When one middle PALF layer was substituted with a glass fiber layer in the composite core, the hybrid FMLs were referred to as [P/G/P]. When the outermost PALF layers were replaced with glass fiber layers in the composite core, the hybrid FMLs were denoted as [G/P/G]. The fiber weight and volume fractions of the composite core are summarized in Table 1. The density and void content of each composite laminate are recorded in Table 2.

The aluminum sheets were annealed at a temperature of 343°C for 3 h in a furnace, followed by cooling to room temperature. The aluminum surface was subjected to mechanical surface treatment using silicon carbide abrasive papers with 80 grit-size to ensure excellent interfacial adhesion between adjacent composite laminate and the metal substrates. Subsequently, the degreasing was done using ethanol to eliminate impurities on the aluminum surface. It was found that the mechanical surface treatment could significantly improve the metal-composite interfacial adhesion (Ng et al. 2019). FMLs were stacked in a 2/1 configuration where two aluminum skin layers were bonded with a single composite core. The PP adhesive films were inserted at the metal–composite interfaces for bonding purposes. The metal sheet/composite setup was subjected to hot compression at a temperature of 170°C and pressure of 1 MPa with the aid of a hydraulic hot press machine. Finally, FMLs were let to cool down to room temperature and visually inspected for defects. The PALF/glass fiber-reinforced metal laminates and each of their constituents are shown in Figure 1. The metal volume fraction (MVF) of FMLs was determined as FMLs are defined based on this property. MVF of FMLs can be calculated in accordance with Equation (1) (Vlot and Gunnink 2001).

$$MVF = \frac{\sum_1^n t_{metal}}{t_{laminate}} \tag{1}$$

where t_{metal} is the thickness of each metal sheet; n is the number of metal layers; $t_{laminate}$ is the total thickness of the FMLs.

Table 1. Fiber weight and volume fractions of the composite core.

Fiber layering sequence	Fiber weight fraction (%)	Fiber volume fraction (%)		
		PALF	Glass	Total
[P/P/P]	31.07 ± 2.65	21.09 ± 0.15	–	21.09 ± 0.15
[P/G/P]	36.08 ± 0.58	13.75 ± 0.27	7.86 ± 0.16	21.61 ± 0.43
[G/P/G]	42.56 ± 1.68	7.16 ± 0.37	16.35 ± 0.86	23.51 ± 1.23
[G/G/G]	47.08 ± 1.32	–	24.47 ± 0.98	24.47 ± 0.98

Table 2. Density and void content of the composite cores.

Fiber layering sequence	Theoretical density (g/cm^3)	Experimental density (g/cm^3)	Void content (%)
[P/P/P]	1.028	1.002	2.53
[P/G/P]	1.106	1.086	1.81
[G/P/G]	1.202	1.183	1.58
[G/G/G]	1.288	1.271	1.32

Experimental work

The tensile properties of FMLs were determined through the tensile test according to ASTM D3039. The tensile specimens with a dimension of 175 mm × 25 mm were loaded at a 2 mm/min cross-head displacement rate using the 25 kN Instron model 8872 servo-hydraulic universal testing machine (UTM). Extensometer was positioned on the middle section of the specimens to determine the strain values. The specimens with a dimension of 127 mm × 12.7 mm were also prepared for flexural tests. A 3-point bending test was conducted with a span-to-depth ratio of 16:1 in accordance with ASTM D790 using the same Instron machine at a 2 mm/min loading rate. A Charpy impact test was performed to determine the impact strength of FMLs with varying fiber layering sequences. The specimens with a dimension of 125 mm × 12.7 mm were subjected to Charpy impact in edgewise and flatwise orientations with reference to ASTM D6110 using Instron CEAST 9250 Drop Tower Impact. The impact orientations of FMLs in Charpy impact tests are shown in Figure 2. Finally, a quasi-static indentation test was carried out according to ASTM D6264 in an edge-supported configuration at a 1.27 mm/min speed using the Instron model 5585 UTM. The FMLs were cut into the dimension of 100 mm × 100 mm for indentation tests. All the tests were repeated five times for each fiber layering sequence. The morphological study of fractured tensile specimens was then performed using scanning electron microscope (SEM).

Results and discussion

Tensile properties

In this work, FMLs showed an average MVF of 0.27, irrespective of fiber layering sequences. The tensile and flexural properties of PALF/glass fiber-based FMLs are recorded in Table 3. The stress–strain curves of PALF/glass fiber-based FMLs with varying fiber layering sequences are shown in Figure 3. When examining the tensile strength of PALF/glass fiber-based FMLs, non-hybrid [G/G/G] FMLs exhibited the highest tensile strength of 87.57 MPa, which is 52.80% greater than [P/P/P] FMLs showing a least tensile strength of 57.31 MPa. Although PALF-based FMLs had a lower tensile strength than glass fiber-based FMLs, improvement was observed when high-strength glass fiber was encapsulated in hybrid PALF/glass fiber-based FMLs. From Table 3, it can be seen that when the middle PALF was replaced by a glass fiber layer in [P/G/P] FMLs, the tensile strength was improved by 13.49%. Further improvement was observed in [G/P/G] FMLs in which their tensile strength is 38.98% higher than [P/P/P] FMLs. It is worth mentioning that the tensile strength of [G/G/G] FMLs is only 9.94% higher than that of [G/P/G] FMLs, demonstrating the feasibility of replacing synthetic fiber-based FMLs with hybrid FMLs. When scrutinizing the tensile properties, as recorded in Table 3, it can be identified that the outermost fiber layers play a critical role in determining the tensile properties of

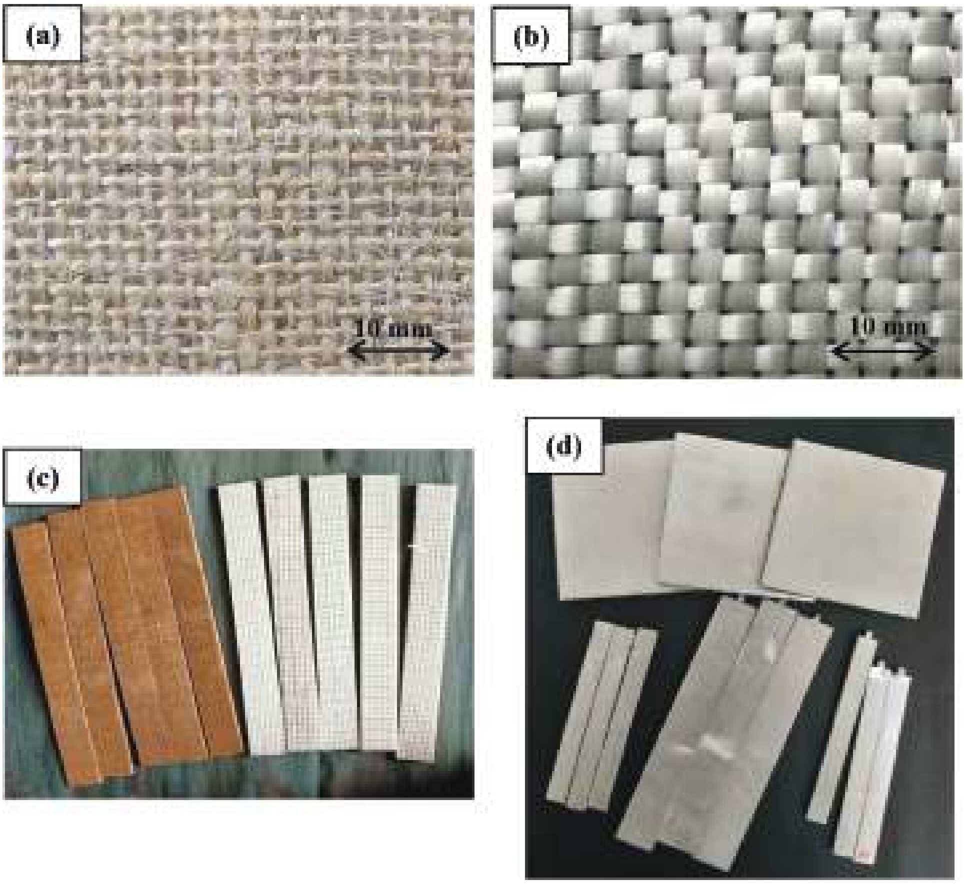

Figure 1. PALF/Glass fiber-reinforced metal laminates (a) PALF (b) glass fiber (c) PALF/glass fiber-reinforced composites (d) FML specimens.

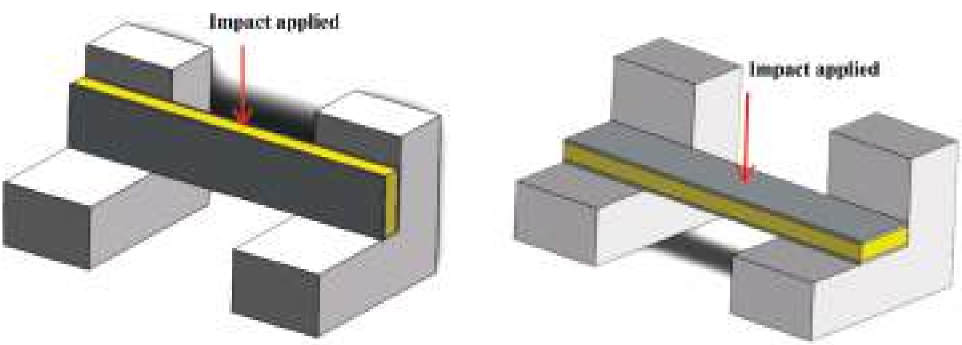

Figure 2. Impact orientations of FMLs in Charpy impact tests (a) edgewise (b) flatwise.

FMLs. Since [G/P/G] and [G/G/G] FMLs had the same outermost fiber layers in the composite laminates, their tensile properties are similar. Similarly, [P/P/P] FMLs had comparable tensile strength to [P/G/P] FMLs due to the same outermost fiber layers in the composite laminates. Previous literature studies revealed similar findings where placing high-strength fibers in the outermost layer endowed superior mechanical properties to the composite laminates and FMLs (Idicula, Joseph, and Thomas 2010; Subramaniam et al. 2019).

Table 3. Tensile and flexural properties of PALF/glass fiber-based FMLs.

	Tensile properties		Flexural properties	
Fiber layering sequences	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
[G/G/G]	87.57 ± 4.07	21.72 ± 0.25	176.50 ± 3.98	4.12 ± 0.23
[G/P/G]	79.65 ± 3.62	20.97 ± 1.60	143.22 ± 5.54	4.06 ± 0.57
[P/G/P]	65.04 ± 1.19	19.40 ± 1.06	130.19 ± 3.17	3.92 ± 0.46
[P/P/P]	57.31 ± 0.52	18.71 ± 0.74	119.16 ± 2.96	3.35 ± 0.31

When looking into the tensile modulus, [G/G/G] FMLs encompassed the highest tensile modulus of 21.72 GPa, which is 16.09% higher than [P/P/P] FMLs. Similar to their tensile strength, the partial incorporation of high-strength glass fiber enhanced the tensile modulus of the laminates. In accordance with Table 3, replacing one middle PALF layer with glass fabric in [P/G/P] FMLs improved the tensile modulus by 3.69%. When the outermost PALF layers in the composite laminates were superseded by glass fiber in [G/P/G] FMLs, the tensile modulus was further enhanced up to 12.08%. These findings revealed that adding a certain amount of glass fiber could undoubtedly increase the tensile properties of the laminates. Moreover, the [G/P/G] FMLs showed a comparable tensile modulus to [G/G/G] FMLs, which is only 3.45% lower than [G/G/G] FMLs, showing that the outermost fabric layers undoubtedly have a profound impact on the tensile modulus of the FMLs. Since the outermost layers are the main load-carrying constituents, placing high-strength fiber layers in the outermost positions of the composite core is more efficient in sustaining the external load, and thus displaying higher tensile properties.

Flexural properties

The 3-point bending test was carried out to determine the flexural properties of FMLs. Figure 4 displays the load–displacement curves of PALF/glass fiber-based FMLs under flexural loading. Overall, the flexural properties of the FMLs showed a similar trend to their tensile properties. From Table 3, it can be seen that [G/G/G] FMLs encompassed the highest flexural properties. Despite the lowest flexural properties of [P/P/P] FMLs, a positive hybrid effect was observed in hybrid FMLs. Compared with [P/P/P] FMLs, substituting the middle PALF layer with glass fiber in [P/G/P] FMLs resulted in an increment in flexural strength by 9.26%. The positive hybrid effect was more profound in [G/P/G] FMLs, in which their flexural strength was found to be 20.19% greater than [P/P/P] FMLs.

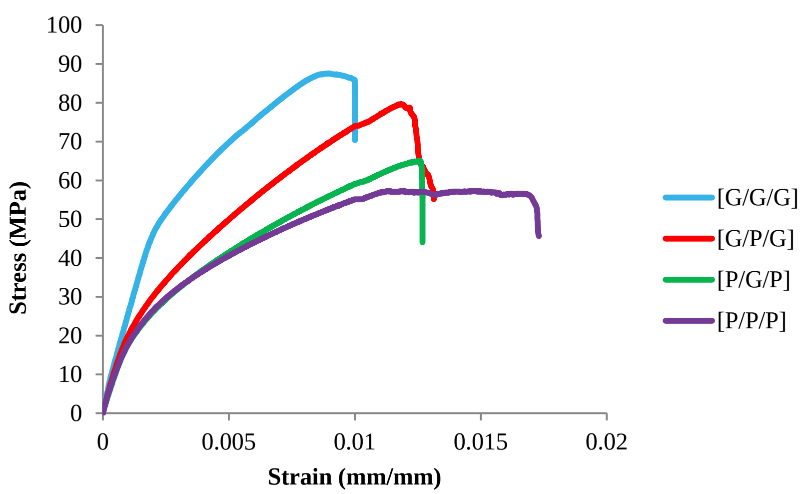

Figure 3. Stress–strain curves of PALF/glass fiber-based FMLs.

A similar trend was noticed in the flexural modulus of FMLs, where the flexural modulus of hybrid FMLs lay between the non-hybrid [P/P/P] and [G/G/G] FMLs. Flexural properties of composite laminates were also found to be governed by the outermost fabric layers, as the top and bottom layers are subjected to tensile and compression forces. Hence, the outermost fiber layers in the composite laminates undoubtedly have a prominent effect on flexural properties. When observing the load–displacement curves, as shown in Figure 4, it can be observed that the flexural behaviors of [G/P/G] and [G/G/G] FMLs are identical, whereas the [P/G/P] and [P/P/P] FMLs showed very similar flexural behavior. This phenomenon could be attributed to the same type of fiber layers in the outermost positions of the composite cores. Overall, the results attested that increasing the amount of glass fiber improved the resistance of FMLs against flexural loads and deformation. These results reflect those of Zareei, Geranmayeh, and Eslami-Farsani (2019) who also found that basalt/jute fiber-based FMLs had the highest flexural and impact properties when placing the high-strength fiber as the outermost layers of composites in FMLs.

Impact properties

The Charpy impact test aims to identify the impact energy absorption of PALF/glass fiber-based FMLs. Compared with metallic alloys, the energy-absorbing mechanism of FMLs is more sophisticated as it involves fiber breakage, fiber pull-out and delamination. However, the energy-absorbing mechanism of FMLs is typically essential for higher energy absorption into the material. Moreover, the impact behavior of FMLs also consists of the plastic deformation of the metallic skin layers, leading to improved energy absorption. In addition to the global plastic deformation, FMLs have been shown to have less internal damage than composites, which further enhances the impact resistance of the materials (Ferrante et al. 2016).

Figure 5 shows the impact strength of PALF/glass fiber-based FMLs in flatwise and edgewise impact orientations. It can be clearly seen that the hybridization of glass fiber with PALF significantly enhanced the impact strength of FMLs, irrespective of the impact orientations. This is most probably due to the higher impact resistance of glass fiber. In the flatwise orientation, [P/G/P] FMLs exhibited an impact strength of 102.24 kJ/m^2, which is 146.60% higher than [P/P/P] FMLs. By incorporating two glass fibers in the outermost layers of composite laminates in [G/P/G] FMLs, the impact strength was drastically improved by 236.66%. Overall, [G/G/G] FMLs displayed the highest impact strength of 146 kJ/m^2. However, it can be observed that the impact strength of [G/G/G] FMLs is only 4.60% higher

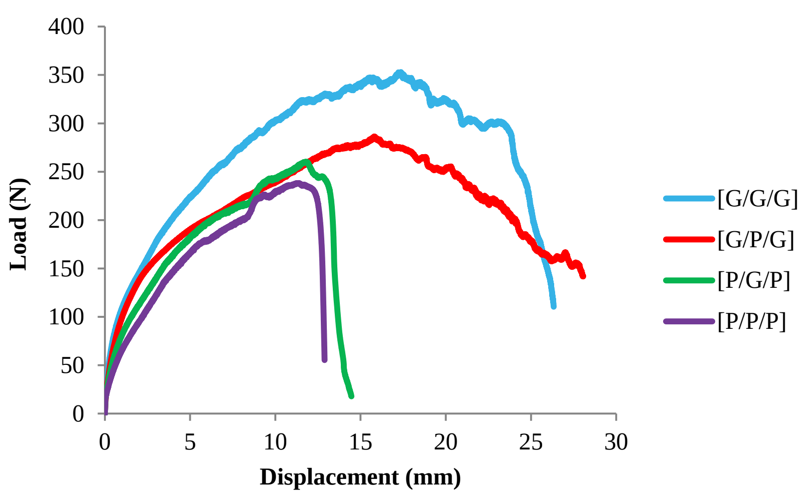

Figure 4. Load–displacement curves of PALF/glass fiber-based FMLs.

than that of [G/P/G] FMLs. A similar observation was noticed in the impact strength of FMLs in edgewise orientation. The [G/G/G] FMLs displayed the highest impact strength of 202.22 kJ/m^2, whereas the [P/P/P] FMLs exhibited the lowest impact strength of 68.08 kJ/m^2. The hybrid [G/P/G] and [P/G/P] FMLs showed impact strengths of 187.68 kJ/m^2 and 122.72 kJ/m^2, respectively, which are in between those non-hybrid FMLs. In addition, it was found that the impact strength of [G/G/G] FMLs is merely 7.75% higher than that of [G/P/G] FMLs. These results are consistent with the findings reported by Najeeb et al. (2021). They concluded that the hybrid composites with glass fiber located in the outermost layers had comparable impact properties to non-hybrid glass fiber-reinforced composites. Similar to the flexural properties, the findings indicate that the fiber layering sequences profoundly influence the impact strength of the hybrid FMLs. In addition to the aluminum skin layers of FMLs, the outermost fiber layers in the composite core play a vital role in absorbing the impact energy. In other words, FMLs with the same outermost fiber layers in the composite core have similar behaviors when subjected to out-of-plane loadings. Moreover, it has been identified that fiber pull-out dissipates more energy than fiber fracture (John and Anandjiwala 2009). Since glass fiber has a very smooth surface, fiber pull-out was more significant than PALF, which was verified in the morphological analysis in the subsequent section. This also explains the higher impact strength of glass fiber-based FMLs than that of PALF-based FMLs. When comparing the impact strength of PALF/glass fiber-based FMLs in different impact orientations, it was found that the impact strength in edgewise orientation was superior to flatwise orientation regardless of fiber layering sequences. This is most probably due to the larger width of the specimens in edgewise orientation when compared with the flatwise orientation. Hence, a higher amount of energy is required to penetrate the specimens in edgewise orientation.

Indentation properties

Many engineering applications using composite materials always involve localized impact loading which is referred to as indentation. The damage resulting from quasi-static indentation loading is one of the critical concerns as it might tremendously undermine the residual strength of the composite materials during their service life. The damage mechanism of quasi-static indentation is actually identical to low-velocity impact (Taghizadeh et al. 2019). Therefore, it is worthwhile to identify the quasi-static indentation behaviors of the FMLs. This work determines the indentation properties in terms of maximum force and energy absorption of PALF/glass fiber-based FMLs. The energy

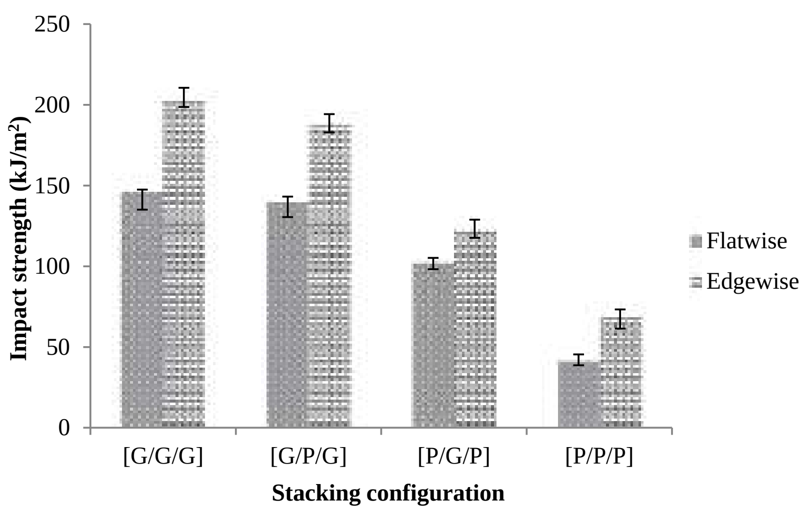

Figure 5. Impact strength of PALF/glass fiber-based FMLs.

absorption of the FMLs was obtained by determining the area under the force–displacement curves. Table 4 summarizes the indentation properties of PALF/glass fiber-based FMLs with two different indenter sizes.

From Table 4, it can be found that the non-hybrid [G/G/G] FMLs had superior indentation properties. Conversely, the lowest indentation properties were noticed in non-hybrid [P/P/P] FMLs. Nevertheless, the indentation properties of hybrid FMLs were improved when middle PALF was partially replaced with glass fiber. The [P/G/P] FMLs displayed maximum indentation force and energy absorption of 4178.92 N and 34.65 J, respectively, demonstrating increments up to 9.29% and 3.74% in comparison with [P/P/P] FMLs. Further enhancements up to 16.71% and 8.68% were obtained when the glass fiber was located at the outermost layers of composite laminates, as demonstrated in [G/P/G] FMLs. On further looking into the indentation properties of PALF/glass FMLs with an indenter size of 20.0 mm, a similar trend was observed where the [G/G/G] FMLs still demonstrated their superior maximum indentation force and energy absorption of 7034.16 N and 73.47 J, respectively. The lowest maximum indentation force and energy absorption of 5968.50 N and 62.22 J were still obtained in [P/P/P] FMLs. The indentation properties of hybrid [P/G/P] and [G/P/G] were intermediate to non-hybrid FMLs. Overall, the hybridization of PALF and glass has undeniably improved the indentation properties of FMLs. Specifically, the indentation properties of composite laminates are related to the stiffness of the outermost fabric layers. Therefore, placing high-stiffness fabrics at highly stressed locations could enhance the out-of-plane properties (Ying et al. 2017).

Figure 6 shows the indentation force–displacement curves of PALF/glass fiber-based FMLs at indenter diameters of 12.7 and 20.0 mm, respectively. The force–displacement curves of FMLs have shown an identical behavior regardless of fiber layering sequences and indenter diameters. The indentation force increased along with the increase in displacement until reaching the peak indentation force. In general, the indentation force–displacement curve can be characterized by the initial damages, including delamination, matrix cracking, and indented surface. The initial damages are followed by fiber breakage and fracture, causing a drastic drop from the peak indentation force. Finally, FMLs were utterly penetrated by the indenter, inducing the frictional force between the indenter and the fractured surface. When scrutinizing the indentation properties of FMLs with different indenter diameters, it was revealed that the indentation properties of FMLs with 20.0 mm indenter diameter were greater than FMLs with 12.7 mm indenter diameter, irrespective of fiber layering sequences. This phenomenon can be explained by the larger contact area between the indenter and the specimens, leading to more global deformation, allowing the materials to have high indentation resistance and energy absorption.

Morphological analysis

The morphological behaviors of FMLs with different fiber layering sequences were studied via SEM. Figure 7 displays the SEM micrographs of PALF/glass fiber-based FMLs after being subjected to tensile loading. Obviously, the metal-composite delamination, fiber pull-out and fiber breakage were the main fracture mechanisms of PALF/glass fiber-based FMLs. The metal-composite delamination is attributed to the shear deformation at the interfacial regions of FMLs when subjected to tensile loading (Huang et al. 2015). Delamination is beneficial to

Table 4. Indentation properties of PALF/glass fiber-based FMLs.

	12.7 mm indenter		20.0 mm indenter	
Fiber layering sequences	Maximum indentation force (N)	Energy absorption (J)	Maximum indentation force (N)	Energy absorption (J)
[G/G/G]	4680.43 ± 238.92	41.97 ± 4.01	7034.16 ± 300.47	73.47 ± 4.89
[G/P/G]	4462.63 ± 281.65	36.30 ± 3.28	6789.75 ± 595.64	70.41 ± 6.48
[P/G/P]	4178.92 ± 64.79	34.65 ± 3.22	6350.87 ± 172.05	63.29 ± 7.04
[P/P/P]	3823.68 ± 248.41	33.40 ± 3.56	5968.50 ± 213.01	62.22 ± 1.38

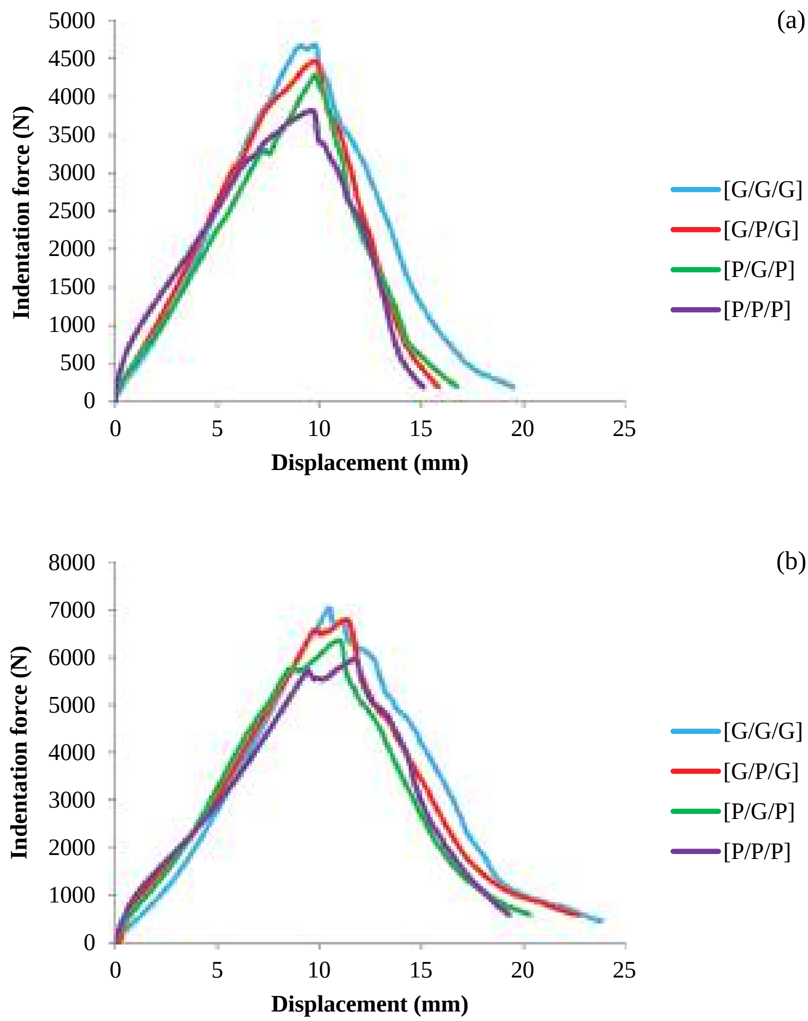

Figure 6. Indentation force–displacement curves of PALF/glass fiber-based FMLs at indenter diameter of (a) 12.7 mm (b) 20.0 mm.

impact properties as it could dissipate approximately 15% to 70% of the total impact energy, indirectly enhancing energy absorption (Ruan, Kariem, and Crouch 2017). Furthermore, the fiber pull-out can be observed in both PALF and glass fibers at the fractured surfaces. However, fiber pull-out is more apparent for glass fiber, which might be due to the poor adhesion between glass fiber and the polymer matrix. Wu et al. (2010) revealed that a rough fiber surface provides better interfacial bonding with polymer matrix. In this context, glass fiber encompasses a smooth surface compared to PALF, hence resulting in a more severe fiber pull-out. In addition to the excellent impact strength of glass fiber, the apparent fiber pull-out of glass fiber could be one of the reasons that further enhance the energy absorption of glass fiber-based FMLs as fiber pull-out allows the materials to dissipate more energy than fiber fracture. This correlates well with the remarkable impact strength of [G/P/G] and [G/G/G] FMLs, as shown in Figure 5.

Figure 8 visualizes the fractured surfaces of PALF/glass fiber-based FMLs after quasi-static indentation tests with indenter sizes of 12.7 and 20 mm. From Figure 8, the fracture behaviors of each of the FMLs are similar to each other irrespective of the indenter size. The damaged area is the only difference between the fractured surfaces of FMLs with different indenter sizes. The

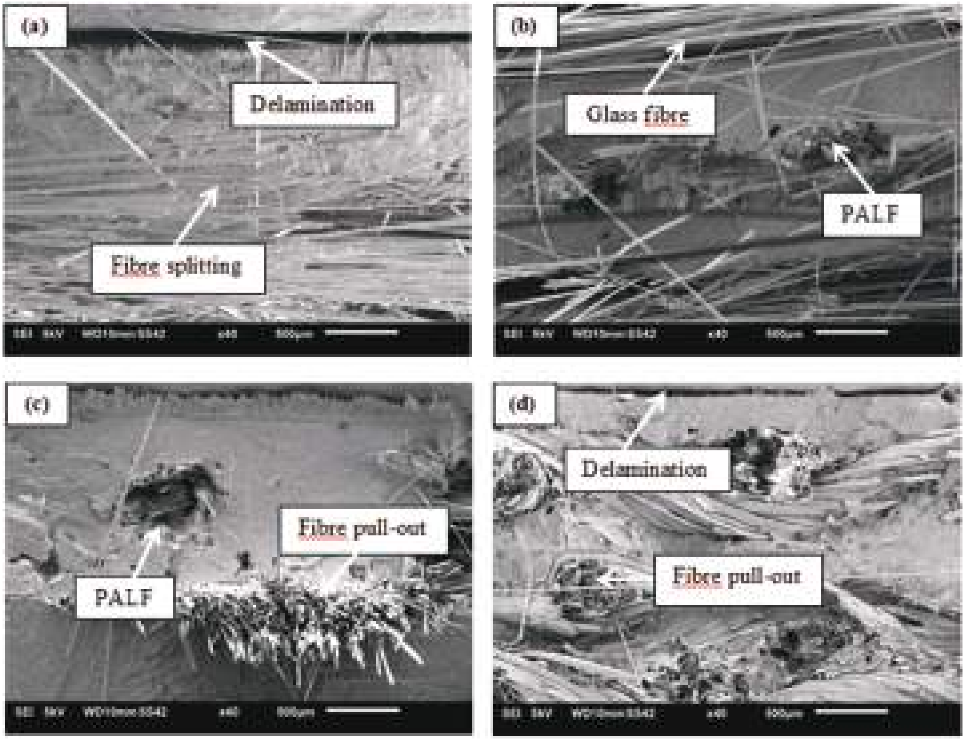

Figure 7. SEM micrographs of PALF/glass fiber-based FMLs (a) [G/G/G] (b) [G/P/G] (c) [P/G/P] (d) [P/P/P].

damages induced by the indenter size of 20.0 mm are significantly larger than the small indenter. This implies that the aluminum layers at either the tension or compressive sides were subjected to more deformation with increased indenter size. This will be considered advantageous to the energy absorption of FMLs as metals absorb energy through plastic deformation (Verma et al. 2021). The fracture modes of the PALF/glass fiber-based FMLs involve petaling, plugging, intra-ply delamination, fiber pull-out and metal-composite delamination. The petaling cracks are mainly ascribed to the crack initiation and propagation from the center point of the rear surface of FMLs during the indentation process. At the same time, the indentation process also pushes the center point of the front surface of FMLs through the thickness, resulting in the formation of plugging failure. When comparing the damage level of the front and rear surfaces of FMLs, the damage at the rear surfaces was more severe than the front surfaces regardless of the indenter size. This is probably because of the aluminum tearing effect at the rear surface, leading to more deformation than the front surface. From the fracture surfaces of the FMLs, intra-ply delamination was also observed in PALF and glass fabrics due to poor fiber wettability. The PALF and glass fabrics consisted of fiber tows or filaments that had been mechanically interlocked in the warp and weft directions. The loosening of the fiber yarns happened once the indenter penetrated the FMLs, and broke each fiber yarn at the center point. The loosening and poor wettability of each fiber yarn lead to intra-ply delamination and fiber splitting.

Conclusion

The mechanical properties in terms of tensile, flexural, Charpy impact and quasi-static indentation properties of PALF/glass fiber-reinforced aluminum laminates with different fiber layering sequences

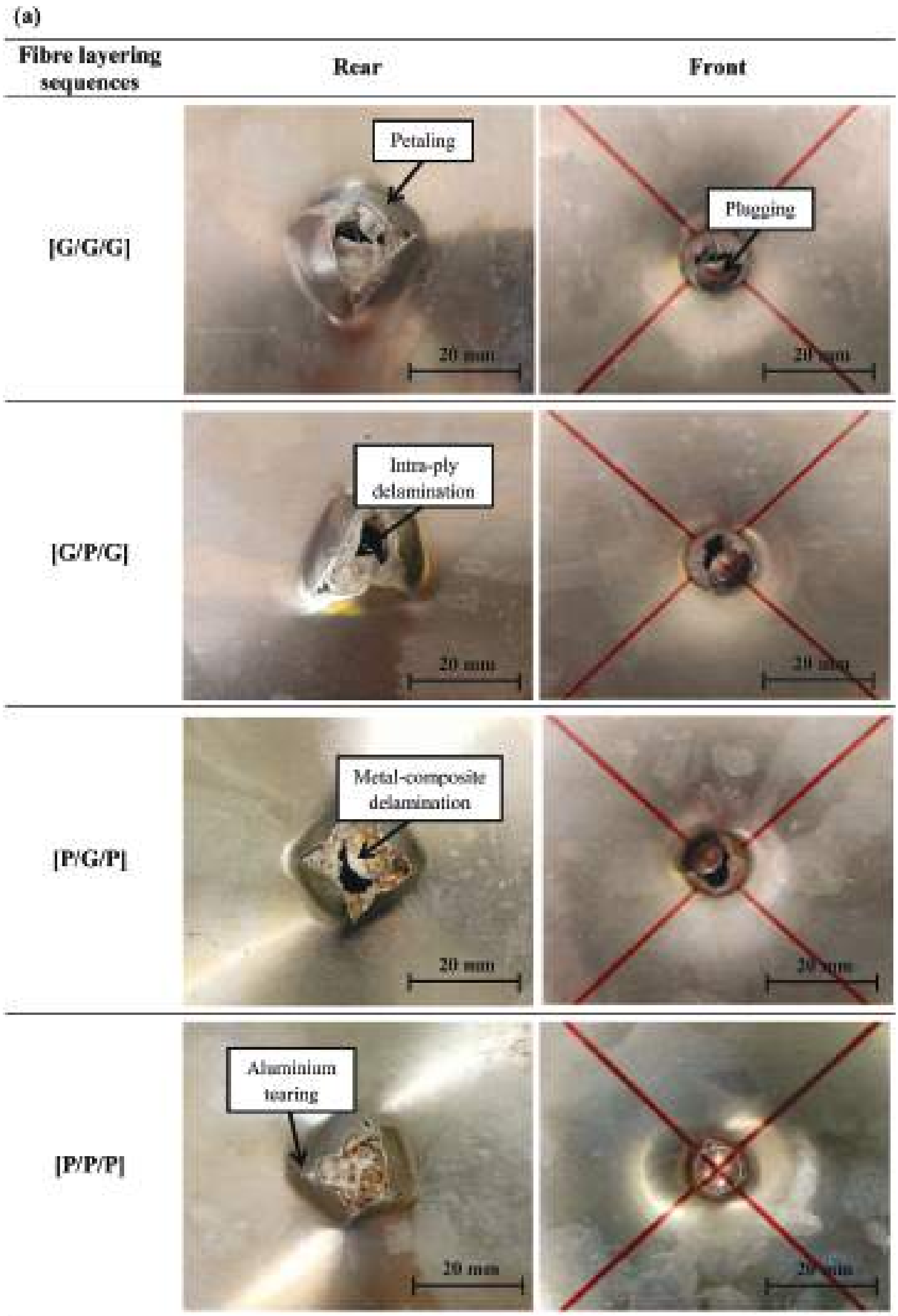

Figure 8. Optical images of PALF/glass fiber-based FMLs after indentation tests with different indenter sizes. (a) 12.7 mm, (b) 20.0 mm.

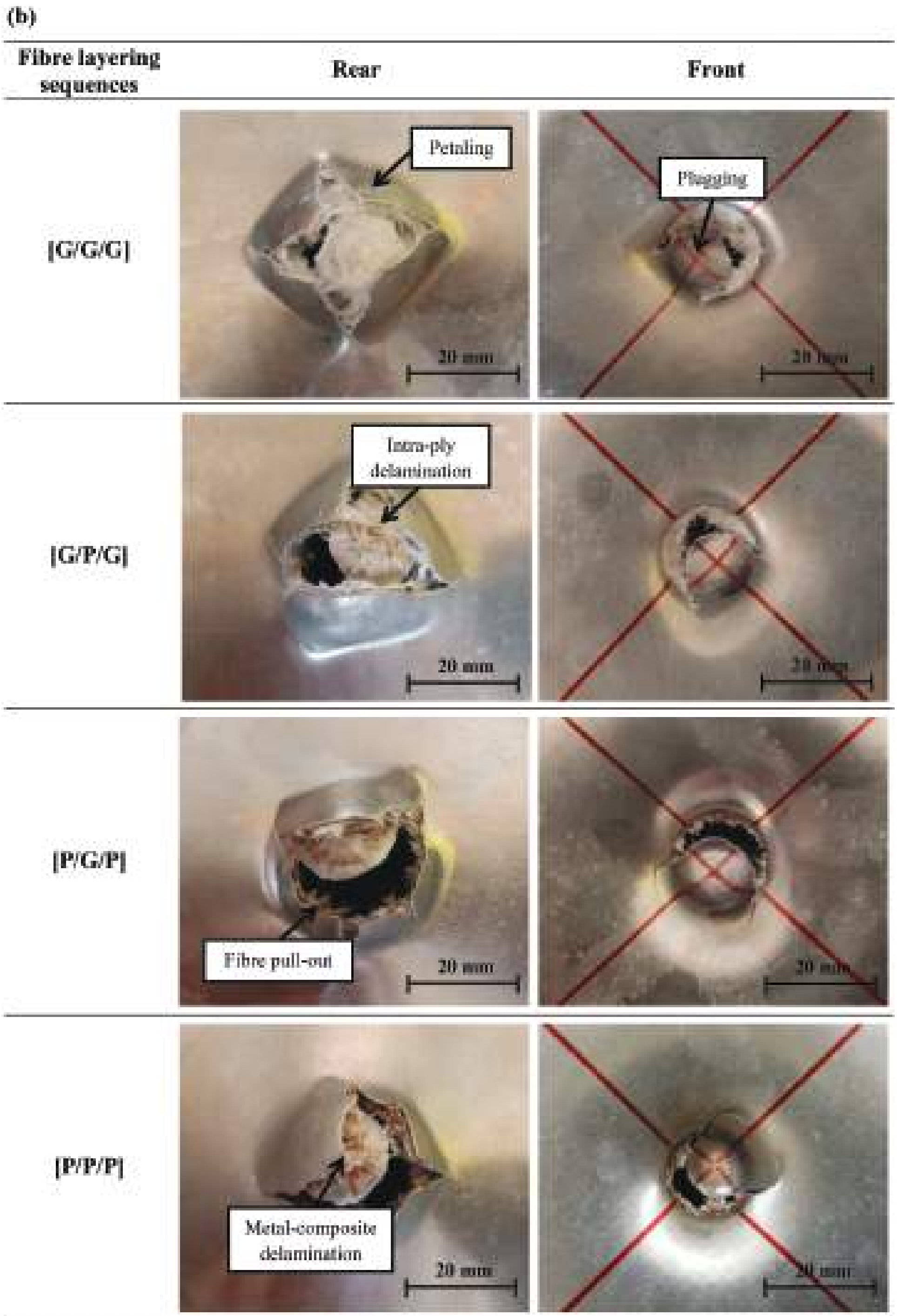

Figure 8. (continued).

were identified in this research work. The following conclusions were drawn from the experimental investigation:

(1) The findings revealed that the partial substitution of PALF with glass fiber improved their mechanical performance. The tensile and flexural strengths of [P/G/P] FMLs are 13.49% and 9.26%, respectively, greater than those of [P/P/P] FMLs. Furthermore, when comparing the [P/P/P] to [G/P/G] FMLs, the tensile and flexural strengths were further enhanced by 38.98% and 20.19%, respectively. Overall, non-hybrid [G/G/G] FMLs displayed the highest tensile and flexural properties.
(2) In terms of Charpy impact properties, the energy absorption of PALF-based FML is apparently enhanced with the presence of glass fiber in the FMLs, irrespective of the impact orientations. However, the placement of glass fiber in the outermost layers of composites was found to be more appropriate as the outermost fiber layers of composite laminates were the primary constituent for the energy-absorbing capacity of the entire structures.
(3) The results corroborated that the quasi-static indentation properties of PALF/glass fiber-based FMLs highly relied on the fiber type and layering sequence. When observing the indentation performance of [G/P/G] FMLs, their maximum indentation forces are 16.71% and 13.76%, respectively, higher than [P/P/P] FMLs in the case of 12.7 and 20.0 mm indenter diameters. In terms of indenter size, the indentation properties of FMLs with an indenter diameter of 20.0 mm outperformed those FMLs with an indenter diameter of 12.7 mm, mainly due to more extensive global deformation and the contact area between the indenter and the FMLs, requiring higher stress and energy to penetrate the specimens.
(4) Hybridization provides an alternative way to attain a balance between mechanical performance and environmental friendliness. According to the findings, [G/P/G] FMLs exhibited comparable mechanical properties to the [G/G/G] FMLs. Thus, it is expected that using PALF as reinforcement could increase the socioeconomic value of the materials while having acceptable mechanical performance. Moreover, by properly designing the hybrid FMLs in a judicious way, the mechanical properties of such materials could be comparable to those of synthetic fiber-based FMLs. Due to the several promising attributes of hybrid FMLs, it is expected that these hybrid FMLs can be used as a substitute for metal alloys in the automotive sector.

Highlights

- Non-hybrid and hybrid fiber-metal laminates (FMLs) based on woven glass and PALF fabrics were prepared.
- Tensile, flexural, Charpy impact and quasi-static indentation properties of non-hybrid and hybrid PALF/glass fiber-reinforced FMLs with varying fiber layering sequences were measured.
- The findings revealed the positive hybrid effect in which the partial incorporation of glass fiber in FMLs had led to the improvement in the mechanical properties.
- On average, hybrid FMLs with glass fiber as the outermost layers in the composite core exhibited comparable mechanical properties to the non-hybrid glass fiber-based FMLs.
- It is anticipated the hybridization of pineapple leaf and glass fibers in FMLs could lead to a balance in mechanical properties, environmental friendliness and economic value.

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References

Abd El-Baky, M. A., A. E. Alshorbagy, A. M. Alsaeedy, and M. Megahed. 2022. Fabrication of cost effective fiber metal laminates based on jute and glass fabrics for enhanced mechanical properties. *Journal of Natural Fibers* 19 (1):303–18. doi:10.1080/15440478.2020.1739594.

Chandrasekar, M., M. R. Ishak, S. M. Sapuan, Z. Leman, M. Jawaid, and R. M. Shahroze. 2019. Fabrication of fibre metal laminate with flax and sugar palm fibre based epoxy composite and evaluation of their fatigue properties. *Journal of Polymer Materials* 35 (4):461–71. doi:10.32381/jpm.2018.35.04.5.

Feng, N. L., S. Dhar Malingam, N. Mohd Ishak, and K. Subramaniam. 2021. Novel sandwich structure of composite-metal laminates based on cellulosic woven pineapple leaf fibre. *Journal of Sandwich Structures and Materials* 23 (7):3450–65. doi:10.1177/1099636220931479.

Ferrante, L., F. Sarasini, J. Tirillò, L. Lampani, T. Valente, and P. Gaudenzi. 2016. Low velocity impact response of basalt-aluminium fibre metal laminates. *Materials & Design* 98:98–107. doi:10.1016/j.matdes.2016.03.002.

Huang, Y., J. Liu, X. Huang, J. Zhang, and G. Yue. 2015. Delamination and fatigue crack growth behavior in fiber metal laminates (glare) under single overloads. *International Journal of Fatigue* 78:53–60. doi:10.1016/j.ijfatigue.2015.04.002.

Idicula, M., K. Joseph, and S. Thomas. 2010. Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. *Journal of Reinforced Plastics and Composites* 29 (1):12–29. doi:10.1177/0731684408095033.

John, M. J., and R. D. Anandjiwala. 2009. Chemical modification of flax reinforced polypropylene composites. *Composites: Part A, Applied Science and Manufacturing* 40 (4):442–48. doi:10.1016/j.compositesa.2009.01.007.

Kumar, S., and A. Saha. 2022. Effects of stacking sequence of pineapple leaf-flax reinforced hybrid composite laminates on mechanical characterization and moisture resistant properties. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 236 (3):1733–50. doi:10.1177/09544062211023105.

Mohammed, I., A. R. Abu Talib, M. T. Hameed Sultan, M. Jawaid, A. H. Ariffin, and S. Saadon. 2018. Mechanical properties of fibre-metal laminates made of natural/synthetic fibre composites. *BioResources* 13 (1):2022–34. doi:10.15376/biores.13.1.2022-2034.

Najeeb, M. I., M. T. H. Sultan, A. U. Md Shah, S. M. M. Amir, S. N. A. Safri, M. Jawaid, and M. R. Shari. 2021. Low-velocity impact analysis of pineapple leaf fiber (palf) hybrid composites. *Polymers* 13 (18):3194. doi:10.3390/polym13183194.

Ng, L. F., D. Sivakumar, X. J. Woo, S. Kathiravan, and I. Siva. 2019. The effects of bonding temperature and surface roughness on the shear strength of bonded aluminium laminates using polypropylene based adhesive. *Journal of Advanced Manufacturing Technology* 13 (2):113–27.

Ng, L. F., M. Y. Yahya, and C. Muthukumar. 2022. Mechanical characterization and water absorption behaviors of pineapple leaf/glass fiber-reinforced polypropylene hybrid composites. *Polymer Composites* 43 (1):203–14. doi:10.1002/pc.26367.

Ruan, D., M. A. Kariem, and I. G. Crouch. 2017. High strain rate and specialised testing. In *The science of armour materials*, ed. I. G. Crouch, 581–637. Woodhead Publishing. doi: 10.1016/b978-0-08-100704-4.00010-4.

Sanjay, M. R., and B. Yogesha. 2018. Studies on hybridization effect of jute/Kenaf/E-glass woven fabric epoxy composites for potential applications: Effect of laminate stacking sequences. *Journal of Industrial Textiles* 47 (7):1830–48. doi:10.1177/1528083717710713.

Sharba, M. J., Z. Leman, M. T. H. Sultan, M. R. Ishak, and M. A. Azmah Hanim. 2016. Effects of kenaf fiber orientation on mechanical properties and fatigue life of glass/kenaf hybrid composites. *BioResources* 11 (1):1448–65. doi:10.15376/biores.11.1.2665-2683.

Subramaniam, K., S. Dhar Malingam, N. L. Feng, and O. Bapokutty. 2019. The effects of stacking configuration on the response of tensile and quasi-static penetration to woven kenaf/glass hybrid composite metal laminate. *Polymer Composites* 40 (2):568–77. doi:10.1002/pc.24691.

Taghizadeh, S. A., G. Liaghat, A. Niknejad, and E. Pedram. 2019. Experimental study on quasi-static penetration process of cylindrical indenters with different nose shapes into the hybrid composite panels. *Journal of Composite Materials* 53 (1):107–23. doi:10.1177/0021998318780490.

Velmurugan, R., and V. Manikandan. 2007. Mechanical properties of palmyra/glass fiber hybrid composites. *Composites: Part A, Applied Science and Manufacturing* 38 (10):2216–26. doi:10.1016/j.compositesa.2007.06.006.

Verma, L., J. J. Andrew, S. M. Sivakumar, G. Balaganesan, S. Vedantam, and H. N. Dhakal. 2021. Evaluation of quasi-static indentation response of superelastic shape memory alloy embedded GFRP laminates using AE monitoring. *Polymer testing* 93:106942. doi:10.1016/j.polymertesting.2020.106942.

Vlot, A., and W. Gunnink. 2001. *Fibre Metal Laminates: An Introduction*. *The Netherlands*: Kluwer Academic Publishers. Netherlands Kluwer Acad.

Wu, Z., X. Wang, K. Iwashita, T. Sasaki, and Y. Hamaguchi. 2010. Tensile fatigue behaviour of FRP and hybrid FRP sheets. *Composites Part B: Engineering* 41 (5):396–402. doi:10.1016/j.compositesb.2010.02.001.

Ying, S., T. Mengyun, R. Zhijun, S. Baohui, and C. Li. 2017. An experimental investigation on the low-velocity impact response of carbon-aramid/epoxy hybrid composite laminates. *Journal of Reinforced Plastics and Composites* 36 (6):422–34. doi:10.1177/0731684416680893.

Zareei, N., A. Geranmayeh, and R. Eslami-Farsani. 2019. The effect of different configurations on the bending and impact properties of the laminated composites of aluminum-hybrid basalt and jute fibers-epoxy. *Fibers and Polymers* 20:1054–60. doi:10.1007/s12221-019-1148-2.