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Research article

Improved mechanical properties of environmentally friendly jute fibre reinforced metal laminate sandwich composite through enhanced interface

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ABSTRACT

Natural plant based fibres are being increasingly used in sustainable fibre reinforced composite applications in order to meet the demand of using environmentally friendly materials for composites. Fibre metal laminates (FMLs) are used in aerospace, automobile, marine and civil engineering applications, due to their excellent mechanical behaviors compared to traditional metals and their alloys. This study describes a novel fabrication of jute fibre reinforced aluminum metal laminates, using different jute fibre architectures (plain and twill fabric structures), wherein jute fibres were used in the skins and aluminum in the core layers. Jute fibres and aluminum sheets were chemically treated to enhance the compatibility and interfacial bonding at fibre-metals-matrix interfaces. FMLs were manufactured by hot pressing technique, after the application of wet lay-up process for the resin impregnation and they were further tested under tensile, flexural and impact loading conditions. While comparing results, the twill architecture showed improved tensile and flexural properties compared to plain fabric based FMLs. Chemical treatments on twill jute fibres and metal sheets further exceptionally enhanced the flexural properties (151 MPa flexural strength and 21.3 GPa modulus and they were increased by 186.5 % and 722.7 % respectively compared to the untreated jute fibre counterparts) of the laminates due to a significant improvement in the adhesion between the jute fibre and aluminum sheet after alkali treatment applied. Therefore, with these enhanced properties, jute based FML laminates can be used as sustainable composite materials in many structural applications.

1. Introduction

In recent years, there has been a considerable interest in fibre-metal reinforced composite laminates (FMLs) due to their design flexibility, durability, chemical resistance, good fatigue performance, high impact resistance, good strength and stiffness at a low

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weight ratio. Currently, they are being used in automobile, aerospace, marine and civil engineering industries [1,2]. Fiber-metal reinforced composites are lightweight hybrid composite materials, fabricated by the hybridisation of thin layers of metals (aluminum, magnesium, titanium or some grades of steels) with the fibre reinforced composites in the ultimate composite structures [3]. Glass-laminated aluminum-reinforced epoxy (GLARE), aramid fiber-reinforced aluminum laminate (ARALL) and carbon fiber-reinforced aluminum laminate (CARALL) are the three most common types of traditional fiber-metal reinforced composites [4], used in different load-demanding applications.

Recently, natural plant fibre based textile reinforcements in structural composite applications are being attracted to replace glass or other synthetic fibre-based reinforcements because of their environmental benefits, cheaper prices and comparable specific properties [5–9]. Natural plant fibres such as flax, sisal, banana, hemp and jute have been used in FMLs to enhance the mechanical and environmental performances of FML composites. In FML design and fabrication, fibre architectures, fiber-matrix interfaces and the compatibility between fibres-matrix-metals are considered very important, as they significantly affect the mechanical performances of these hybrid laminates. Considering this, a detail investigation is needed before the optimisation of the fibre architecture in FMLs. Also, chemical treatments of fibres and metals can be applied to enhance their compatibility in FMLs, although they are challenging to implement. This investigation addresses these two challenging objectives to improve the mechanical performance of investigated FMLs.

In addition to above mentioned parameters, the selection of fibres also plays a pivotal rule in achieving the desired properties in FMLs in terms of cost, availability and flexibility. In this case, among many other reinforcing natural plant-based fibres, jute fibre has some unique attributes, such as availability of jute textile structures in different woven and knitted forms, relatively in cheaper price and good mechanical properties, which made this fibre as a right choice to be used as textile reinforcements in FMLs. Jute fibres may be able to substitute glass fibres due to their lower density, high specific strength and modulus [10], with high individual fibre length [5]. Additionally, jute is at least 50 % cheaper than flax and other natural fibres, and it is the second most produced natural fibre after cotton mostly in Bangladesh, India, and China [11–13]. Normally plain fabric structure (1/1) is extensively used in manufacturing natural plant fibre based composites for their easy and low cost dry fibre preforming process, although the mechanical properties of composites can be varied with different fabric structures. Arju and coworkers compared different jute fibre architecture (plain, twill, rib fabric structure) with polypropylene matrix to investigate their effects on tensile and bending properties of jute composites and found that twill structure showed better mechanical properties than the other architectures [14]. Similar study was conducted by Azim and his coworkers, they found that there is a large variation in the tensile, bending and impact performance of the composites based on their structures [15,16]. They depicted that twill derivatives particularly 3/1 twill structure performs well compared to plain structure with polyester matrix in jute composites. As fabric structure has a prominent effect in jute composites' mechanical performance, effects of jute fibre architectures were considered to investigate in this study for jute/aluminum based FMLs.

On the other hand, considering the fibre-matrix interface, previous studies suggest that FMLs cannot bear maximum amount of load due to their large variation in metal-fibre-matrix compatibility. Also, mechanical properties of natural fibre composites made are always affected with poor performance due to their inherent flaws such as hemicellulose, lignin and waxes etc. present in the fibre [2, 17–20]. Fibre-to-matrix compatibility and fibre quality can be improved by treating the natural fibres using traditional textile-based mercerization process, which are well explained in literature [21,22]. Another issue of FMLs was reported in the previous study, is that aluminum metal sheet generally offers smooth surface and therefore it cannot produce a strong bond with matrix and fibre. Again, metal sheets must be chemically treated before using in FMLs, so that a strong and uniform interface between the metal-fibre-matrix materials is ensured. Therefore, chemical modification of both fibre architectures and aluminum sheet was considered in the study for enhancing the interface bonding between the jute fiber and the aluminum metal [23–25]. While selecting core materials in the design of FML sandwich panels, previous study suggested that natural fibres can be prominent to be used in the core of the two metals sheet for manufacturing FMLs [26].

By considering the above descriptions, the main aim of this study was to investigate the manufacturing and mechanical properties of jute fibre/aluminum metal sheet FMLs. Two different fabric architectures (twill and plane), made of same linear density of jute yarns, were used to manufacture FMLs and understand their effects on mechanical properties of FMLs. Jute fabrics and aluminum sheets were chemically modified to improve the compatibility of jute fibre-metal sheet-epoxy matrix, leading to improve the mechanical performance of FMLs. A hot press (compression moulding) technique was used to manufacture FMLs, wherein, jute fibres were used in skin layers, while aluminum sheet was used in the core layer of FMLs. Tensile, flexural and impact properties of FMLs were investigated and compared to that the effects of fabric structures and chemical treatments on FMLs. To the best of authors' knowledge, the Fiber-Metal sandwich composites reinforced with different jute fiber architecture have not been yet reported in the existing literature. It is believed that the findings of this study will be helpful to design and manufacture jute fibre based-metal laminates as a special class of eco-friendly composite for various load-bearing applications in automotive, aerospace and marine sectors among others.

2. Experimental procedures

2.1. Materials

High quality jute yarns were produced using widely used Tossa jute long fibre, which are the species of Hibiscas Canavinas and they were purchased from the local jute yarn manufacturing industry (Akij Jute Mills) in Narsingdi, Bangladesh. The linear density of the yarns was 5/2 lb/spindle with double ply twisted yarn. To produce plain (1/1) and twill (3/1) jute woven fabric, a commercial power loom at Tangail, Bangladesh was used, all fabric properties are presented in Table 1. Aluminum sheets (Al 2024-T4) with a thickness of

0.5 mm, were collected from Altech Aluminum Industries Limited, Dhaka, Bangladesh. In order to modify the Aluminum sheet, commercial grade sodium hydroxide pellets, acetone, 98 wt% H2SO4 and K2Cr2O7 were collected from Modina Chemicals, Dhaka Bangladesh. To fabricate composite materials, Diglycidyl ether of Bisphenol A (AY-105) type epoxy resin and Hardener (HY-951) were supplied by Atul Ltd Gujrat, India. Aluminum and jute fabric were used as reinforcing materials where epoxy resin and hardener were used as matrix materials with a ratio of 10:1. The information of reinforcement and matrix materials are provided Table 2.

2.2. Methods

2.2.1. Fabric preparation

Both plain and twill jute woven fabrics were manufactured from the same count (5lb/spindle) of warp and weft yarns using a conventional power loom so that a high quality of jute woven fabric architectures can be maintained, which ensures the quality of the reinforcements for FML composites.

The common technique was used to prepare the weaver's beam, in which, jute yarns were wrapped into a beam from small packages of jute yarns, it helped to arrange the jute yarn warp parallelly and gave continuous length for weaving. The weaver's beam was set up at the back of the power loom and each warp yarn was passed through the heald eye of the reed under high tension, then they were fixed in a cloth roller, where the produced fabric was accumulated. Drafting and lifting plans were the basic requirement to get new woven fabric architectures, according to these, healds were raised up and down that gave the shuttle a travel space to run and lay-off the weft yarns across the warp yarns. A picking mechanism operated the shuttle with weft yarns to place them into warp yarns to create ultimate warp/weft yarns inter-locking structure in the produced fabric. In Fig. 1(a)-1(f), schematic diagrams of jute woven fabrics are given, plain (1/1) and twill derivative (3/1) weave architectures were carefully manufactured in the power loom.

2.2.2. Surface modification

Surface modification was necessary for the aluminum sheets in order to achieve the desired improvement in the interfacial bonding between the epoxy matrix, fibres and the aluminum sheets. Etching, as performed at the forest products laboratory (FPL), is one of the quickest and easiest approaches to surface modification. The alkaline treatment was carried out to bring about a reduction in the hydrophilicity of the jute fibers. According to earlier literature [27], an alkaline treatment was used to enhance the wettability of epoxy with jute fibers. Jute fibers were immersed in a 5 wt% NaOH solution for 2 h at a temperature of 25 °C to achieve this (Fig. 2(a) −2(b)). The excess solution was removed from these fibers by repeatedly washing them in deionized water. Following that, these fibers were dried in a vacuum oven for 24 h at 60 °C. Acetone was used to clean the aluminum sheets, and this helped eliminate greases as well as surface contaminations. The Eickner technique [28] was used to modify the aluminum sheets surface. In this technique, aluminum sheets were immersed in a 4 wt% NaOH solution for 10 min to remove the oils and greases, which had not been removed by acetone. Afterwards, the aluminum sheets were washed by the deionized water. The temperature of this solution was elevated to 60 °C by a hotplate. After that, 35 g of potassium dichromate was dissolved in 1 L of deionized water. Then, 350 g of sulphuric acid (98 wt%) and 1 litter of deionized water was progressively added to the diluted sulphuric acid solution. The aluminum sheets then immersed for 30 min in this solution (Fig. 2(c) −2(d)). Following that, the aluminum sheets was rinsed with water until the residual solution was removed. Fig. 2(a)-2(d) illustrate the jute fibres and aluminum sheets before and after the surface modifications.

2.2.3. Composite fabrication

Hot compression moulding technique was used to manufacture the FMLs. Clean and dry jute fibers and aluminum with and without chemical treatments were used with the epoxy resin to fabricate jute fiber composites.

Epoxy resin and hardener were used as a ratio of 10:1 by weight to fabricate these composite materials. For the manufacturing of FMLs. Woven jute fabrics and aluminum sheets were placed in a mould with a dimension of 200 mm (l) × 200 mm (w) and the resin was applied with a hand lay-up method, the lay-up was placed between the upper and lower metal plates of the compression moulding machine to apply a high pressure of 25 MPa for 90 min at 80 °C temperature (Fig. 3). After that, the sample was allowed to cure and consolidate at room temperature for 24 h. In the FMLs, jute fabrics were used as skin layers and aluminum sheet was used as the core layer. Following the manufacturing of FMLs, they were coded according to the type of woven fabric structures and nature of treatment used in the study (Table 3). For example- (a) untreated plain fabric and aluminum based FML is identified as PLUT, (b) untreated twill fabric and aluminum based FML as TWUT, (c) treated plain fabric and aluminum FML as PLTT and (d) treated twill fabric and aluminum FML as TWTT.

Table 1

Physical properties of fabric used in this study with[a] and without treatment.

Fabric type	EPI	PPI	Warp Crimp (%)	Weft Crimp (%)	GSM
Plain Weave (1/1)	21	16	15.62	13.94	490
Twill Weave (3/1)	21	19	9.12	10.1	638
Treated Plain Weave (1/1)	22	19	17.11	15.34	502
Treated Twill Weave (3/1)	26	22	16.25	21.74	658

[a] Due to the chemical treatment (alkali), shrinkage was occurred in the fabric and because of this, in treated fabric structures all fabric physical properties were changed compared to the untreated fabric structures.

Table 2
Physical properties of Aluminum, Epoxy resin and Jute Fiber (according to supplier information).

Material	Tensile Modulus GPa	Tensile Strength MPa	Density g/cm^3	Specific Modulus GPa/(g/cm^3)	Specific Strength GPa/(g/cm^3)
Aluminum 2024- T$_4$	73	410	2.7	27.0	152
Epoxy resin	23.15	70	1.15	2.73	60.8
Jute Fiber	28	290	1.48	18.9	195.9

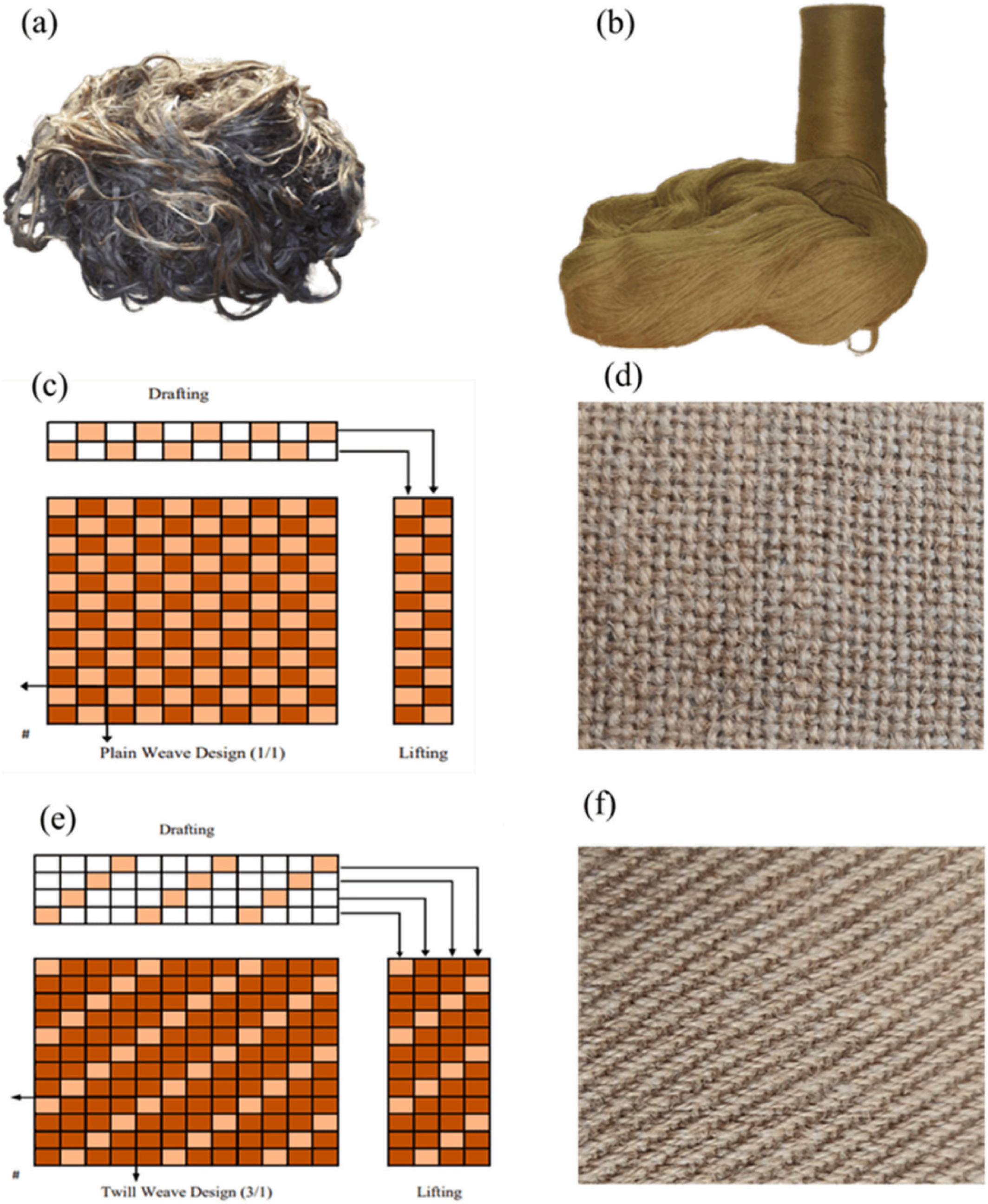

Fig. 1. Digital images of (a) raw jute fibres and (b) processed jute yarns from field retted jute fibres; (c) drafting and lifting plans of plain fabric structure (1/1); (d) digital image of manufactured plain jute fabric used in the study; (e) drafting and lifting plans of twill fabric structure (3/1); (f) digital image of manufactured twill jute fabric used in the study.

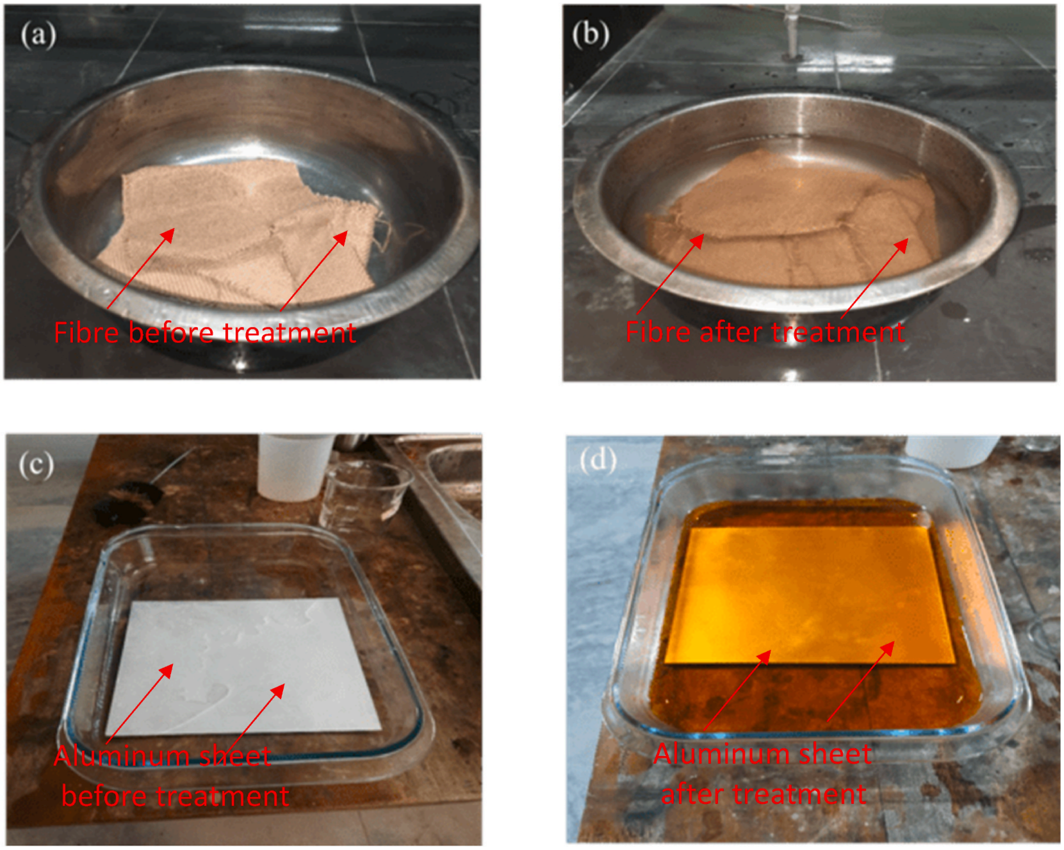

Fig. 2. Digital images of (a) jute fabric before treatment; (b) jute fabric after treatment; (c) aluminum sheet before treatment; (d) aluminum sheet during treatment.

2.3. *Mechanical testing*

2.3.1. *Tensile test*

Tensile properties were investigated by carrying out tensile testing in accordance with the international standard ASTM D 638, utilizing the Shimadzu testing equipment AG-X series from Kyoto, Japan, as well as the Ni-9237 data collection card (National Instruments Corporation, Austin, TX, USA). The dimensions of the sample were 150 mm (l) x 25 mm (w) x 3 mm (t) and the cross-head speed applied for tensile test was 5 mm/min.

2.3.2. *Flexural test*

The international standard ASTM D790 was utilized for the flexural tests. Specimens were constructed from laminates that were manufactured and their dimensions were 127 mm (l) x 12.7 mm (w). The specimens were subjected to a 3-point bending force with a span-to-depth ratio of 32:1. The cross-head speed during flexural testing was 1.4 mm/min. Five specimens were tested for each sample types, and the average value is reported in this study.

2.3.3. *Impact test*

Based on the ASTM D256 standard, impact tests were carried out using a Charpy impact test machine with a 15 J hammer. The laminates were used to make the unnotched specimens with a dimension of 80 mm in length and 10 mm in width. A total of five specimens were tested and the average values of impact properties are reported in the study.

2.3.4. *Surface morphology observation*

Surface morphology of the fibres were observed using a Phenom Pro-G desktop Scanning Electron Microscope (SEM), Netherlands. All specimens were gold coated and images were taken at different magnifications.

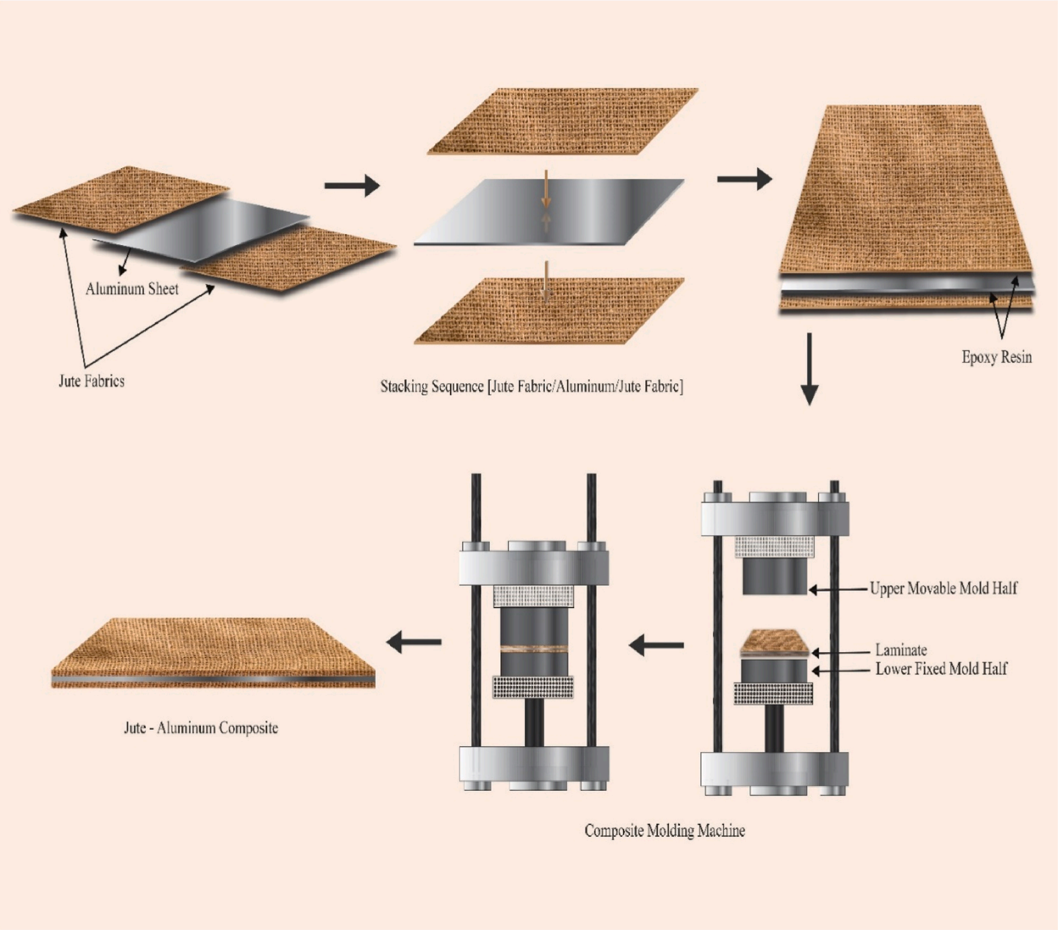

Fig. 3. Schematic diagram of manufacturing process of jute-aluminum/epoxy FML: placement of jute fibres as skin layers, stacking of constituents, impregnation of fibre and aluminum sheets, compression moulding of jute and aluminum sheet and fully cured jute fibre-aluminum/epoxy FMLs.

Table 3
Physical properties of jute fibre metal laminates.

Composite code	Fibre volume fraction (%)	Metal volume fraction (%)	Matrix volume fraction (%)	Theoretical density of FML (g/cm^3)	Experimental density (g/cm^3)	Void content (%)
PLUT	28.9	15.77	55.33	1.48	1.4566	1.58
PLTT	26.29	16.18	57.53	1.47	1.4576	1.20
TWUT	29.94	17.24	52.82	1.50	1.4646	3.5
TWTT	27.94	14.72	57.35	1.47	1.4599	1.15

3. Results and discussion

3.1. Physical properties of the laminates

Table 3 provides physical properties of developed jute/aluminum FMLs. Density, fibre volume fraction of laminates are the key indicators of changes in the physical structure with respect to the application of chemical treatments.

Density of the laminates was calculated using Archimedes principle and details of the test can be found in previous study reported in the literature [29,30]. This study focuses on both the structural changes of jute fibres and chemical treatments on both fibres and metals to study the compatibility of them while reinforced with epoxy matrix. Fibre volume fractions showed a range of 26–30 %. It was noticeable that chemical treatment of jute fibres and aluminum sheet have overall great impact in the volume fraction of fibres and aluminum, respectively. Alkali treatment removes polysaccharides (large percentage of hemicellulose) from the interfibrillar region of the fibres and a small percentage of lignins from the intercell of the jute fibres. In Fig. 4(a)-4(b), alkali treated and non-treated fibre surface SEM images were shown, wherein the impurities are clearly seen as removed by the alkali treatment. Similarly, in Eickner technique, aluminum sheets were treated with alkali, potassium dichromate and sulphuric acid which ultimately helped in removing the impurities and frictional effect on the surface of aluminum sheet. Thus, the combination of both the fibre and aluminum treatment resulted in changes in the constituents of the laminates as well as density of the laminates (Table 3).

3.2. Mechanical properties

In this study, mechanical properties of the developed composites were evaluated by comparing their tensile, flexural and impact properties. Effect of fibre architecture and chemical treatment of fibres and metals and their effect on FMLs mechanical properties are compared and discussed in the following section.

3.2.1. Tensile properties

Measurements were taken to determine the tensile strength and modulus of treated and untreated plain and twill woven fabric reinforced metal hybrid laminated composites. Both the treated and untreated woven fabric architectures had a great influence on the tensile properties of fiber metal laminates (FMLs). The fiber architecture of a composite material is believed to be a fundamental aspect that impacts both the tensile strength of composite materials including FMLs. Fabrics that are woven are produced by interlacing threads in warp and weft directions. The stress–strain and force-displacement curves of plain and twill woven FMLs are depicted in Fig. 5(a)-5(d). The curve illustrates the influence of different fiber architectures and chemical treatments on the tensile properties of plain and twill woven FMLs.

From the tensile test fractured images shown in Fig. 6(a)-6(d), it was remarkably noticed that upon tensile test FMLs were delaminated for all of the fabric structure and chemical treatments used. In the case of PLUT FML (Fig. 6a), the delamination of fabric layer and aluminum was occurred more readily than the PLTT FML (Fig. 6b). In PLTT FML, fabric layer is strongly adhered with aluminum layer due to the chemical treatment. A strong mechanical interlocking was visible between treated fabric and treated aluminum (see Fig. 6b). Same phenomenon was observed for TWUT (Fig. 6c) and TWTT FMLs (Fig. 6d) too. This behaviour of FMLs can be justified based on the previous study. According to Ref. [31] the delamination size is increased with the increase of time and applied stress during the test though growth rate of delamination remains same.

When the applied stresses went beyond the ultimate limit of the bonding between the layers, they started to delaminate, and the delamination areas were expanded, which caused the stiffness to decrease. The process continued until the panels were collapsed, which was easily identifiable by surface take-off [32]. Initial delamination was occurred by a number of factors, including improper material preparation and uneven surfaces, which were identified and removed with the chemical treatments. Another reason is, the lacking of a strong interfacial adhesion between the face layers jute fabric and alumina core materials. Initial delamination also influenced by the fiber architecture. A weak bonding between the fiber, metal and matrix increased the delamination. The bonding is increased among them by the chemical treatment of fiber and metal [33].

While comparing tensile properties it was observed that PLUT exhibited a tensile strength and modulus of 51.85 MPa and 4.44 GPa respectively, whereas PLTT Composites showed these properties as 62.41 MPa and 4.21 GPa respectively. On the other hand, TWUT showed a tensile strength and modulus of 68.89 MPa and 4.29 GPa, respectively, while, for TWTT tensile strength and modulus values were calculated as 59.56 MPa and 4.17 GPa, respectively. In comparison of different fiber architecture, untreated twill woven FMLs (TWUT) demonstrated a higher tensile strength, than untreated plain woven FMLs composites (PLUT). For chemically treated FML composites, twill woven FMLs (TWTT) showed lower tensile strength than plain woven FMLs composites (PLTT). It was established that the waviness of the yarns may reduce the mechanical properties of the composite materials [34]. After chemical treatment of jute fabrics, twill woven fabric increases the crimp percentage compared to plain woven fabric. That's why, treated twill woven FML

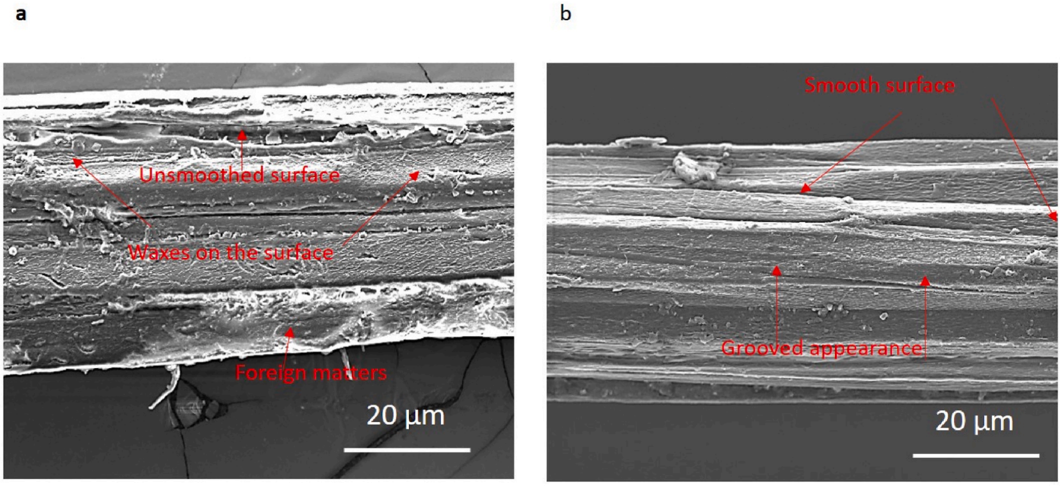

Fig. 4. Chemically (alkali) (a) non-treated and (b) treated surfaces of jute fibre used in the study.

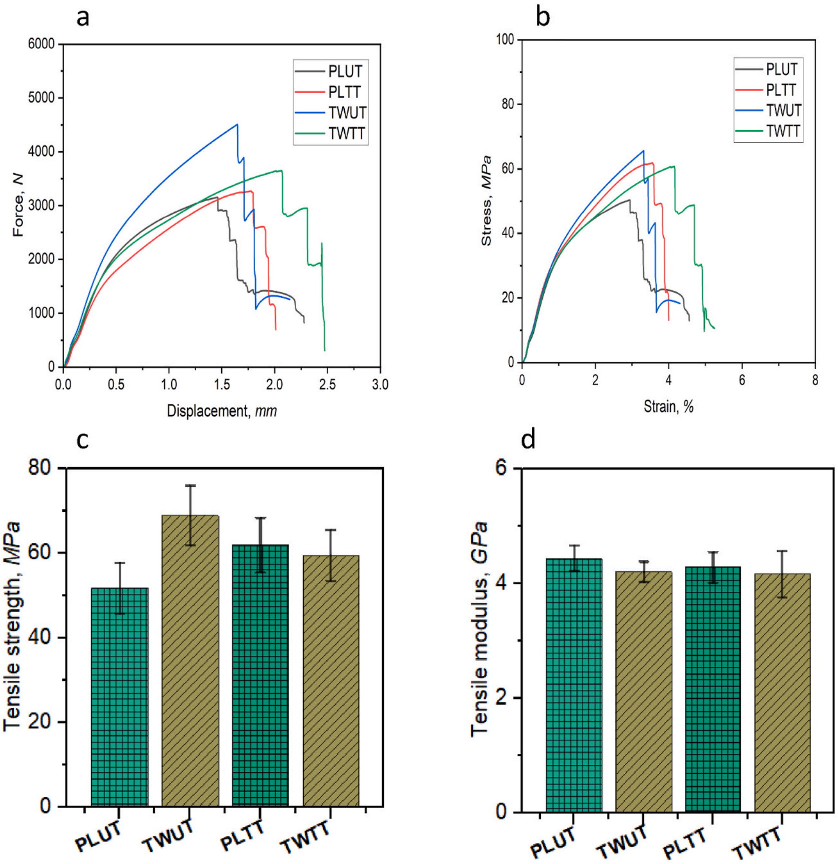

Fig. 5. Comparison of different jute fibre architecture aluminum sandwich epoxy composites with and without treatment: (a) tensile force-displacement curves, (b) tensile stress-strain curves; (c) tensile strength and (d) tensile modulus values.

composites (TWTT) showed lower tensile strength than treated plain woven FMLs Composites (PLTT). Both the waviness and the yarn crimp unquestionably have an effect on the mechanical strength of composite materials and FMLs. But for untreated composites, due to the maximal interlacing of yarns in both the warp and weft directions, plain woven fabric had a greater amount of waviness which ultimately reduced the tensile properties (PLUT) compared to their untreated twill FMLs (TWUT).

Hence, PLUT demonstrated poorer tensile characteristics compared to TWUT. PLTT FMLs showed a higher tensile strength compared to PLUT FMLs. This could be due to the action of alkali treatment. Although after the treatment, crimp percentage of plain-woven fabric was slightly increased, this was not significantly enough to affect the mechanical properties of PLTT FMLs. Therefore, the observed increment in the mechanical properties of PLTT were related to the actions of alkali treatment on jute fibres. This observation was totally opposite for the twill fabric, since treated twill fabric created a very high crimp percentage leading to a mechanical properties reduction in TWTT compared to TWUT composites. Previously, it was demonstrated that high crimp levels accelerate damage development in composite materials, resulting in a lower tensile characteristic [35]. This supports our tensile test findings for the developed plain and twill jute fabric metal laminates.

3.2.2. Flexural properties

A three-point bending load was applied to both plain and twill woven FMLs composites with and without chemical treatments, in order to evaluate the flexural strength and modulus of the developed FML composite materials before reaching the fracture point.

The flexural strength and modulus values reflect the capacity of a material to endure a combination of compression and tensile forces applied in a bending load and deformation.

The force-displacement and stress–strain curves of plain and twill woven FMLs are depicted in Fig. 7(a)-7(b) respectively. The curve illustrates the influence of different fiber architectures and chemical treatments on the flexural properties of plain and twill woven FMLs. The fiber-based metal laminate structures followed four steps to reach the failure in the bending test, these were the elastic stage, plastic stage, fracture of fiber layers and delamination stage [36] By the comparison of chemical treatment influences for the same type of fabric structure, treated plain fiber-based metal composites (PLTT) showed the greater bending properties than untreated plain fiber-based metal composites (PLUT). A similar observation was also found for treated twill woven fabric laminates (TWTT) over non-treated twill woven fabric composites (TWUT). PLUT composites showed a flexural strength and modulus of 61.42 MPa and 4.20 GPa, whereas, PLTT showed these values as 110.77 MPa and 19.56 GPa respectively (see Fig. 7(c)-7(d)).

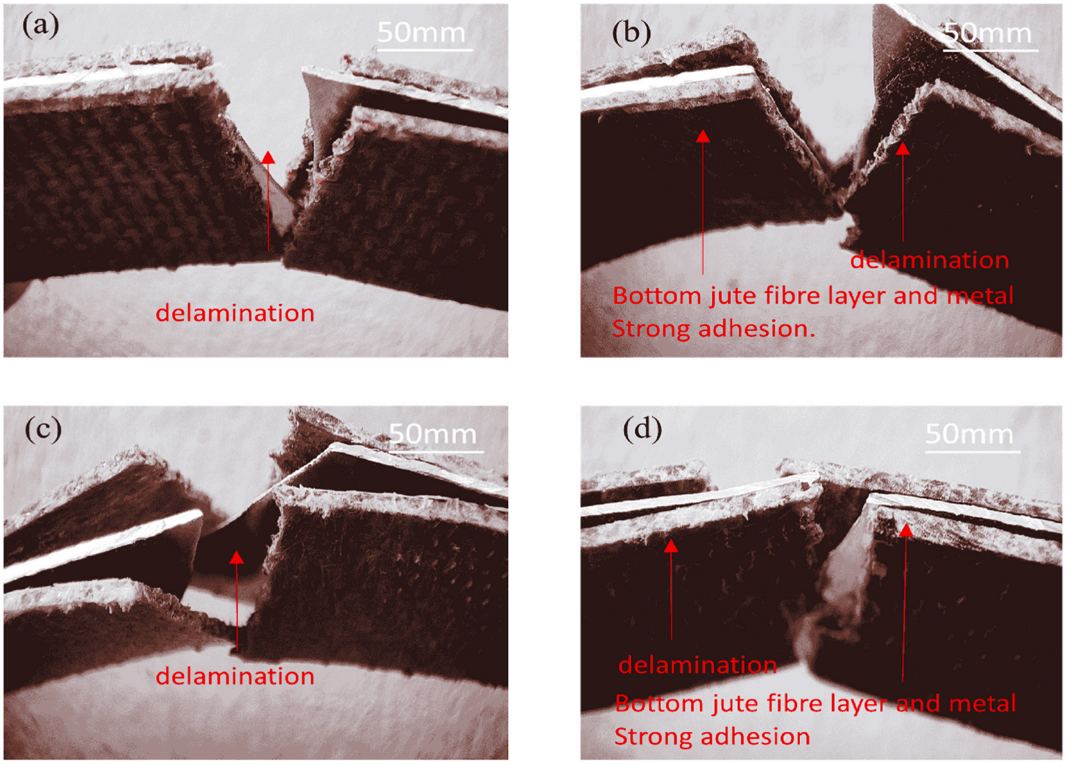

Fig. 6. Side view of tensile test fractured specimens of (a) PLUT, (b) PLTT, (c) TWUT and (d) TWTT jute fibre FML composites.

Similarly, TWTT laminates exhibited significantly higher flexural strength and modulus of 52.70 MPa and 2.61 GPa compared to the values of 150.93 MPa and 21.39 GPa for flexural strength and modulus respectively in TWUT laminates (see Fig. 7(c)-7(d)). As mentioned above, all of these FML composites showed four stages of bending failure mechanism, but through these failure stages, treated fabric composites for both woven fabric structures (PLTT and TWTT) showed less deformation and higher energy absorption capacity, which results in the ultimate higher strength and modulus values compared to their untreated counterparts (Fig. 8(a)-8(d)). The observation is related to the developed strong chemical bonding between the aluminum sheet and fibers due to the surface modification of the aluminum sheet and jute fibers through the application chemical treatments in this work. Chemical treatment of fiber and metal which played an important role to increase the bending properties by transferring the load from fiber and aluminum sheet to the composites structure.

While comparing the flexural properties of FMLs with different fiber architectures, it was found that the chemically treated composites, twill woven FMLs composites (TWTT) had superior flexural properties to those of the plain woven FMLs composites (PWTT). The similar trend was also seen for the chemically untreated composites, wherein, twill structure composites (TWUT) demonstrated a slightly higher flexural properties compared to plain structure FMLs (PLUT). In treated woven structures, the interface between fibres and metals of twill structure could be stronger than that of plan fabric structure which absorbed more loads and increased the properties ultimately.

3.2.3. Impact properties

The impact properties of the materials provide an indicator of the energy-absorbing capability of the material during an impact event. Charpy impact loading was applied to plain and twill woven FMLs composites with different fiber architectures in order to measure the impact strength. The impact strengths of plain and twill woven FML composites are depicted in Fig. 9. There are three basic types of failure such as complete, partial and non-present are common in fiber-based metal composites under a Charpy impact test. A matrix failure is indicated by the existence of a crack in the matrix phase parallel to the fibers; delamination of the laminate layers due to interlaminar stresses; fiber failure, including fibre breaking and fibre buckling; and complete penetration of the laminate [37]. Due to the bridging effect over a fracture, which restricts crack propagation, FMLs are known to possess stronger impact resistance than metal alloys and composite materials [38].

The impact mechanism of FMLs is more complex than that of metal alloys and composite materials because their energy dissipation involves elastic-plastic deformation, delamination, fiber pull-out and fiber fracture. The delamination of FMLs is very advantageous for energy dissipation. The delamination is predicated to dissipate between 15 and 70 % of the impact energy [39]. Due to the ductility of metal alloys, FMLs are able to absorb a great deal of impact energy via elastic-plastic deformation [40].

Impact properties of FMLs made from plain and twill architecture showed different properties than the tensile and flexural

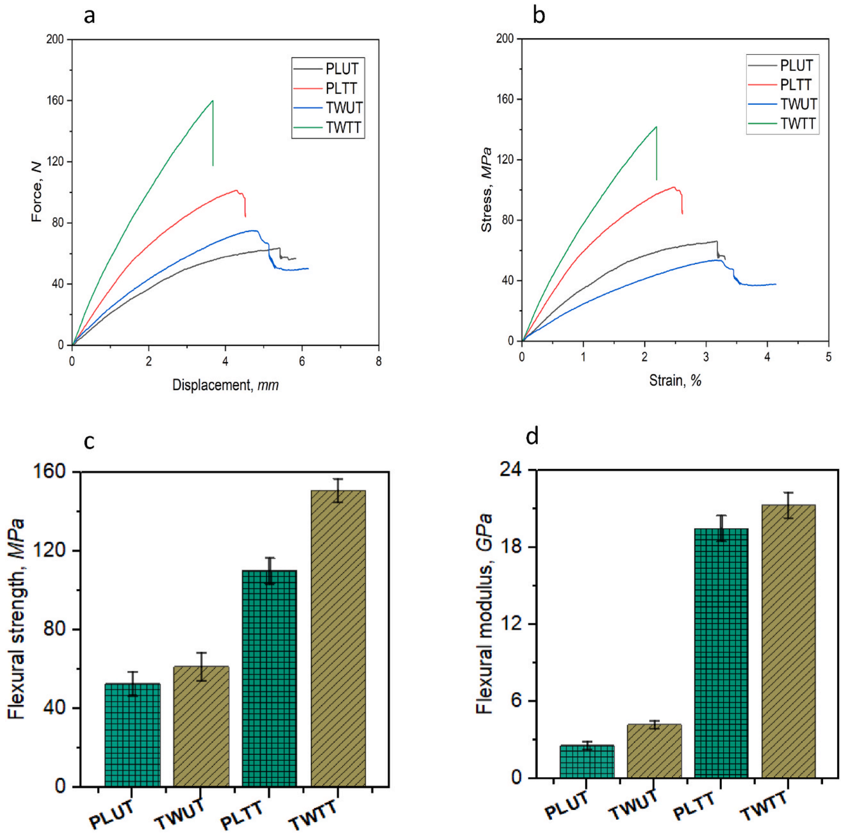

Fig. 7. Flexural properties jute fibre architecture aluminum sandwich epoxy composites with and without treatment: (a) comparison on the force-displacement curves; (b) comparison on the stress-strain curves; (c) comparison on tensile strengths; (d) comparison on tensile modulus values.

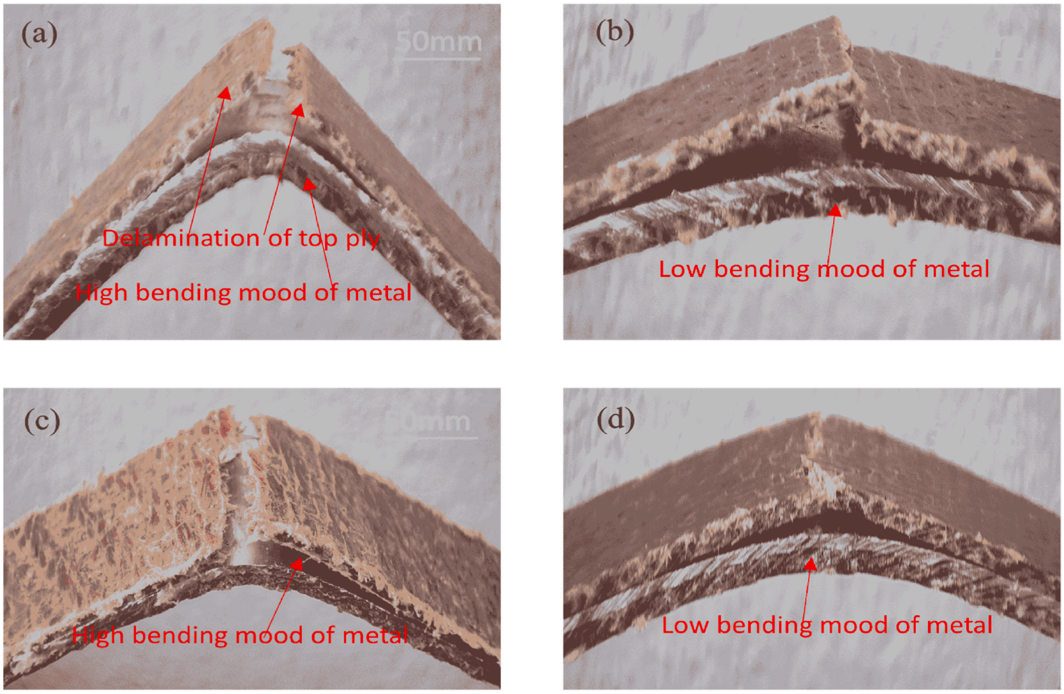

Fig. 8. Side view of the flexural test fractured specimens of (a) PLUT; (b) PLTT; (c) TWUT; (d) TWTT FML composites.

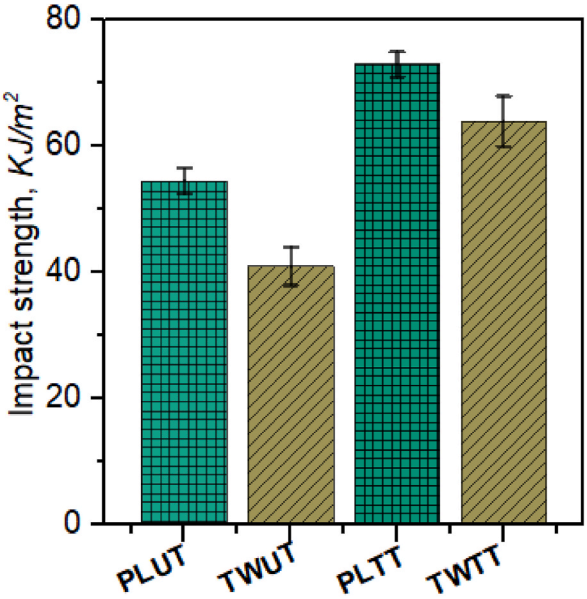

Fig. 9. (a) Comparison on the impact strength of different jute fibre architecture aluminum sandwich epoxy composites with and without treatment.

properties. In the previous section, tensile and flexural properties were achieved to be maximum for twill architecture but in the case of impact strength plain architecture with treatment showed highest values. For instance,

The impact strength of untreated plain and twill woven were 54.5 kJ/m^2 and 41.04 kJ/m^2, respectively, whereas impact strength of treated plain and twill woven are 72.93 kJ/m^2 and 63.78 kJ/m^2, respectively. Moreover, a positive effect of chemical treatment on jute and aluminum were reflected in the FMLs. As plain architectures have interlacement warp and weft yarns and they produce larger percentages of crimp in the fabric (see Table 1) ultimately absorbed more energy than the twill fabric structure. In addition, alkali treatment also increases the crimp percentage slightly than the untreated fabric also contributed in more impact strength.

4. Conclusions

This study focused on the development of two jute fibre architectures using similar linear density of yarns and the effect of chemical treatment of these fibre architectures towards the design and development of aluminum core jute-aluminum/epoxy FMLs. To improve the fibre-matrix interfacial quality and the compatibility of aluminum and fibre with epoxy matrices, aluminum sheet was also chemically treated to manufacture FMLs. Considering the physical and mechanical tested results of FMLs, the key conclusions are highlighted as follows:

1. Tensile strength and Young's modulus of the FMLs were highest for twill structured chemically untreated jute fibre FMLs. The improvement in properties is related to the lower amount of crimp formation in the twill structure. Therefore, this structure reduces the entrapped air between the yarn in the fabric which actually increases the impregnation of the resin and thus increases the load-bearing ability of FMLs.
2. Most significant enhancements were observed for the flexural properties of FMLs using different jute fibre architectures. The mean flexural strength and modulus for TWTT FMLs were recorded 151 MPa and 21.3 GPa, revealing the improvement of 186.5 % and 722.7 % than that of TWUT, respectively. Chemical treatments of fibres and aluminum worked synergistically to create strong bonding with epoxy matrix and enhanced mechanical interlocking of rough aluminum surface and epoxy matrix too.
3. Delamination in the tensile and bending tested specimens were observed for almost all samples. Though chemically treated FMLs showed a better interfacial adhesion than the untreated ones.

The primary observation of the study confirmed that utilization of suitable jute fibre architecture in developing FMLs (jute fibre in the skin) can be a promising alternative in structural composite applications. Further enhancement of the interface using different chemicals can be carried out as a future study for jute fibre dominant Jute-aluminum/epoxy FMLs to reduce delamination and fibre failures.

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Data availability statement

Data related to this investigation have not been included in a public repository. However, they can be made available on request to the corresponding author(s) of this paper.

CRediT authorship contribution statement

Emdadul Haq: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Abu Saifullah:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Ahasan Habib:** Methodology, Formal analysis. **Abu Yousuf Mohammad Anwarul Azim:** Methodology, Formal analysis. **Shah Alimuzzaman:** Formal analysis, Data curation. **Hom N. Dhakal:** Writing – review & editing, Formal analysis. **Forkan Sarker:** Writing – review & editing, Supervision, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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