Woven Natural Fiber-Reinforced PLA Polymers 3D Printed through a Laminated Object Manufacturing Process

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ABSTRACT

A novel additive manufacturing process utilizing the laminated object manufacturing (LOM) technology with woven natural fiber-reinforced biopolymer is investigated in this paper. Traditional synthetic composite materials are products from nonrenewable crude oil with limited end-of-life options, and therefore not environmentally friendly. The continuous woven natural fiber is used to significantly strengthen the mechanical properties of biocomposites and PLA biopolymer as the matrix made the material completely biodegradable. This is one of the promising replacements for synthetic composites in applications such as automotive panels, constructive materials, and sports and musical instruments. A LOM 3D printer prototype has been designed and built by the team using a laser beam in cutting the woven natural fiber reinforcement and molten PLA powder to bind layers together. Tensile and flexural properties of the LOM 3D printed biocomposites were measured using ASTM test standards and then compared with corresponding values measured from pure PLA specimens 3D printed through FDM. Improved mechanical properties from LOM 3D-printed biocomposites were identified by the team. SEM imaging was performed to identify the polymer infusing and fiber-matrix binding situations. This research took advantage of both the material and process's benefits and combine them into one sustainable practice.

Keywords: Laminated object manufacturing (LOM), woven natural fiber, PLA, mechanical properties

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1. INTRODUCTION

3D printing or additive manufacturing is the construction of a three-dimensional object directly from a CAD model or a digital 3D model. All of these technologies work by adding layers of material to an existing part or substrate. Laminated-object manufacturing (LOM) produces a solid physical model by stacking layers of sheet stock that are each cut to an outline corresponding to the cross-sectional shape of a CAD model that has been sliced into layers. The cut layers are sequentially stacked and bonded on top of the previous one to build the part. Excess material in each layer remains in place to support the whole part during the building process. Traditional feedstock materials in LOM include paper, cardboard, and plastic in sheet stock form, with a thickness from 0.05 to 0.50 mm (0.002 to 0.020 in) [1]. However, these feedstocks come with limited mechanical properties, and therefore their engineering applications are limited.

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Various polymer and polymer-based composite materials are attracting researchers' attention in the implementation of additive manufacturing. Pilipovic et al. [2] studied PVC parts made through the LOM procedure using a commercial SD 300 Pro LOM 3D printer. Tensile and flexural properties were measured using specimens 3D printed in different directions (x, y, and z). They found polymer sheets are much better feedstock materials compared to paper to be used in LOM as they provide significantly improved mechanical properties and thus expand the application of such technology. Kumar et al. [3] presented the LOM manufacturing of flexural test samples using ABS and thermoplastic polyurethane (TPU) polymers. The two polymer single layers were first FDM printed using two polymer filaments, and then LOM printed to form two types of sandwich specimens (ABS-TPU-ABS (ATA) and TPU-ABS-TPU (TAT)). They found that ATA-based samples held greater flexural strength than TAT LOM samples, while the flexural strength of TAT composites improved significantly from approximately 6.8 MPa to 13 MPa (~92% increase). The authors provided some recommended applications of both types of sandwich-structured composites at the end of their paper. Chang et al. [4] reported using continuous carbon fiber-reinforced thermoplastic composites (CF/PA6 prepregs) in a LOM 3D printing process, in which a laser beam was used in cutting the prepreg plies, and an ultrasonic roller was used for cut ply consolidation. 3D-printed composite parts were then measured for their tensile properties, with their unidirectional tensile strength reaching 1760.2 MPa and tensile modulus of 105.7 GPa, both of which are superior in performance. In summary, LOM-manufactured polymers and composites show great potential as load-carrying structure parts in many industries.

Synthetic fibers provide excellent mechanical properties and allow for versatile design possibilities, in the meantime, environmental and economic concerns are stimulating research in the design and production of innovative materials for the transportation, sports goods, and musical instrument industries. New materials in which a product is based on natural renewable resources, preventing further stresses on the environment are of particular interest [5]. Among these materials, natural fiber-reinforced polymers are gaining more interest as a substitute for glass fiber-reinforced polymer composites because of their many benefits such as low cost, biodegradability, low-carbon footprint, acceptable mechanical properties, and society's focus on environmental issues and sustainability [6].

Jute fibers are easily available in fabric and fiber forms with good mechanical and thermal properties compared to other natural fibers. These fibers are extracted from the ribbon of the stem and are the most promising reinforcement material due to their high content of cellulose (61-72%), hemicellulose (14-20.4%), lignin (12-13%), and pectin (0.2%) [7]. Polylactic acid (PLA, $(C_3H_4O_2)_n$ [8]) is used as the biopolymer as it can be made at a reasonable cost using renewable resources. It is classified as an aliphatic polyester due to the ester bonds that connect the monomer units which can degrade naturally in situ through a hydrolysis mechanism: water molecules break the ester bonds that constitute the polymer backbone, therefore making it a green matrix polymer material [9]. When it comes to plastic filament for 3D printing, PLA is the most popular choice. The qualities that make it the best material for this job include its low melting point, high strength, minimal thermal expansion, good layer adhesion, and great heat resistance when annealed [10]. Without annealing, PLA is the least heat-resistant of the major 3D printing polymers [10]. The melting temperature of PLA is between 170 and 180 °C [11]. In this paper, the sheet feedstock for a custom-designed LOM 3D printing process was made using woven jute fabrics and PLA polymer. Mechanical properties of 3D-printed biocomposite objects are measured and then analyzed.

2. EXPERIMENTATION

The research team designed a LOM 3D printer prototype (shown in Fig. 1) using a 40W laser to cut the PLA-infused woven jute fiber. This prototype is programmed and operated using MKS DLC 32 motherboard and controlled by MKS TS 35 R V2.0 touchscreen. Five Tronxy SL42S TH40 stepper motors were used to control the X, Y, and Z axis, the material feeding, and the take-up roller, respectively. The building platform of the LOM printer is 220×220×300 mm. The material feed-up roller feeds the jute fiber continuously. After the laser cuts the PLA-infused fiber, the material take-up roller takes the waste away, leaving the original cut part in the building platform. This process allows the LOM printer to continue feeding another layer of material just above the original cut part. This process keeps repeating until the model is printed completely.

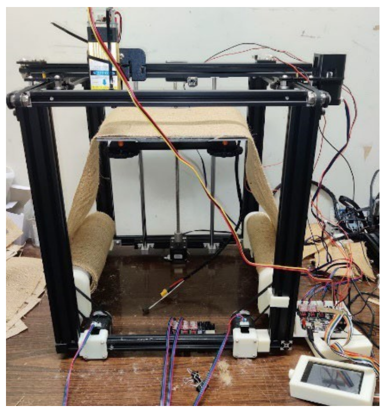

Figure 1. The LOM 3D printer prototype built.

2.1 Materials

Fiber reinforcements used in this research are woven jute fabrics with a fiber density of 5 threads/cm, and an average area density of 338 g/m^2. The average thickness of a single ply of this fabric is 0.071 mm. The PLA polymer used is in the form of a white powder.

2.2 Mechanical test samples preparation

Continuous jute fiber roll was precut into 220×254 mm sheets to make jute woven fiber/PLA prepregs. PLA powders were coated onto cut woven jute fibers evenly by hand layup technique and then sandwiched by Dupont Kapton HN Films, followed by thermal compressing in a Carver 4120 thermal press (shown in Fig. 2(a)) at 180°C under 5 bar pressure for 10-15 minutes. Prepregs made by this process are shown in Fig. 2(b). The pre-made prepregs were then loaded onto the LOM 3D printer prototype. Test sample stl. files of tensile tests (following ASTM D3039/D3039M - 14) and flexural tests (following ASTM D7264/D7264M - 07) were created using SolidWorks, converted to cutting contours of every single layer by Fusion 360 slicer software, and uploaded to the prototype. The dimensions of jute/PLA tensile and flexural test samples are 250×25×2.5 mm and 60×13×4 mm, respectively. Crosssections of test samples were cut by the LOM prototype and laid up with enough plies that make the test samples reach their desired thicknesses (shown in Fig. 3). All LOM-made samples are then thermally pressed using the thermal press for improved quality.

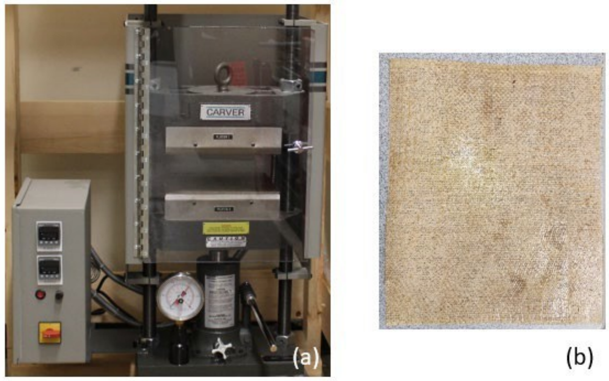

Figure 2. (a) Carver 4120 thermal press, (b) Woven jute/PLA prepreg made.

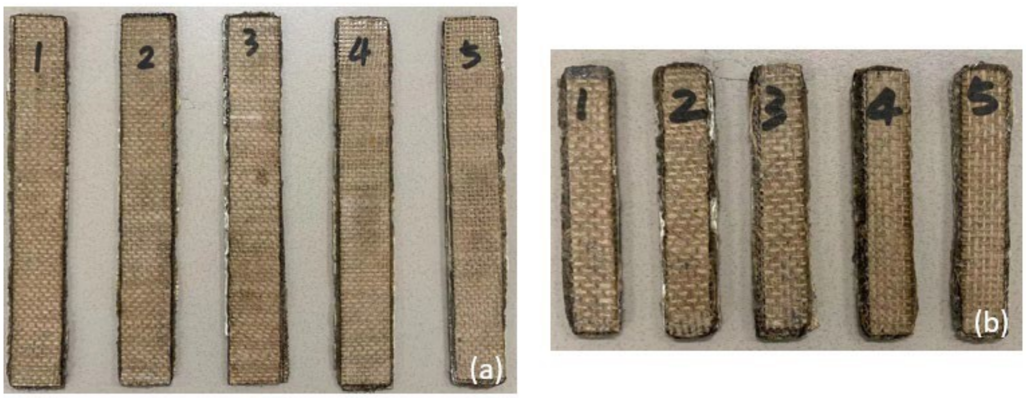

Figure 3. Jute/PLA (a) tensile, (b) flexural test specimens made through the LOM process.

3D CAD models of pure PLA samples were first created using SolidWorks following the dimensions recommended by ASTM D638 – 14 for tensile tests and ASTM D790 – 10 for flexural tests, and then 3D printed by a Raise3D Pro2 Plus 3D printer using pure PLA filaments. The dimensions of pure PLA tensile and flexural test samples are 165×13×3.2 mm and 127×12.7×3.2 mm (shown in Fig. 4), respectively. All test samples are printed as solid (0% hollow inside).

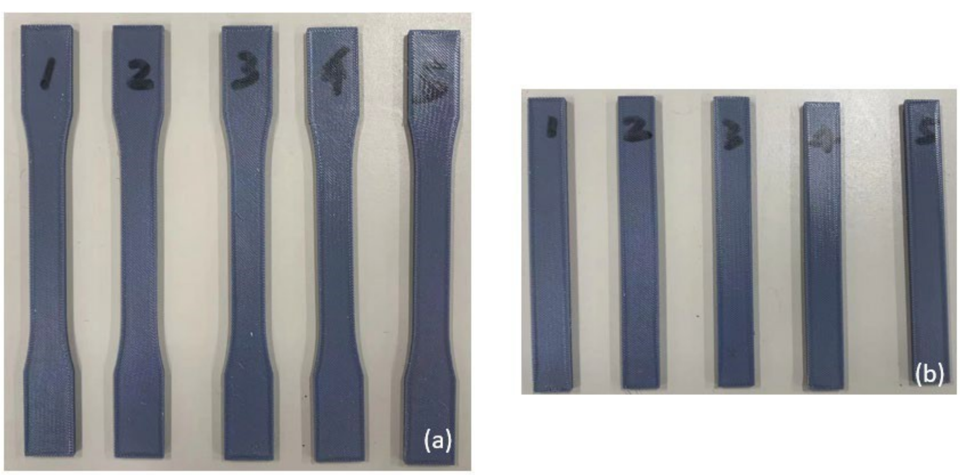

Figure 4. Pure PLA (a) tensile, (b) flexural test specimens 3D printed through FDM.

Lastly, single-ply jute fabric was cut into 150×24 mm rectangles for tensile tests based on ASTM D5035 – 06 standard and the thickness was measured as 0.86 mm (shown in Fig. 5). At least 5 test samples were made for each test.

Figure 5. Woven jute fibers cut for tensile tests.

2.3 Test methods

2.3.1 Tensile test

Tensile tests are generally performed on flat specimens. In this study, an INSTRON 5582 Universal Testing Machine (UTM) was used for all tensile and flexural tests. Test speeds of the jute/PLA composites, pure PLA, and woven jute samples are 2.0 mm/min, 5.0 mm/min, and 300 mm/min, respectively. The tensile stress-strain data were automatically obtained by the UTM system. The ultimate tensile strengths were recorded with the maximum tensile stresses achieved in the tests, and elastic moduli were later obtained by calculating the average slope of tensile stress-strain curves of the five samples tested.

2.3.2 Flexural test

Flexural test speeds of the jute/PLA composites and pure PLA samples are both 1.0 mm/min. The flexural stress-strain data were automatically obtained by the same UTM system. The ultimate flexural strengths were recorded with the maximum tensile stresses achieved in the tests, and flexural moduli were later obtained by calculating the average slope of flexural stress-strain curves of the five samples tested.

2.3.3 SEM imaging

A JEOL JSM-6010LA Analytical Scanning Electron Microscope (SEM) was used for SEM imaging of the failed jute/PLA composites from tensile and flexural tests (shown in Fig. 6). The cross sections of two composite samples were cut using a sharp utility knife and observed at 7kV under 30 Pa vacuum using different magnification levels. SEM images of different locations at both cross sections were obtained.

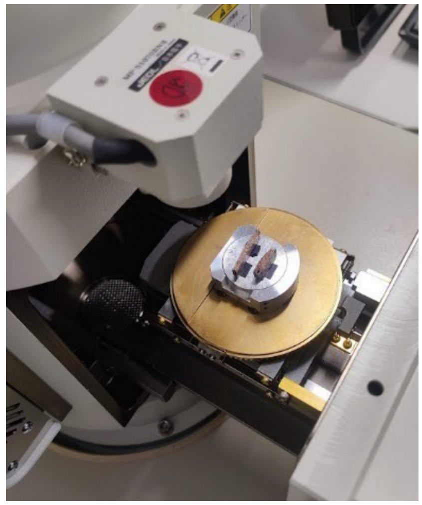

Figure 6. Failed mechanical test samples loaded into the SEM.

3. RESULTS AND DISCUSSIONS

The results of all mechanical testing performed in this study are listed in Table 1 and Fig. 7.

Table 1: Mechanical Properties of Pure PLA and Woven Jute Fiber Reinforced PLA Samples

Material	**Tensile Strength *TS* (MPa)**	**Elastic Modulus *E* (GPa)**	**Flexural Strength *σ* (MPa)**	**Flexural Modulus E_f (GPa)**
Pure PLA	19.28	0.70	41.95	0.89
Jute fabric	15.05	N/A	N/A	N/A
Woven jute fiber-reinforced PLA	22.23	1.33	43.12	1.67

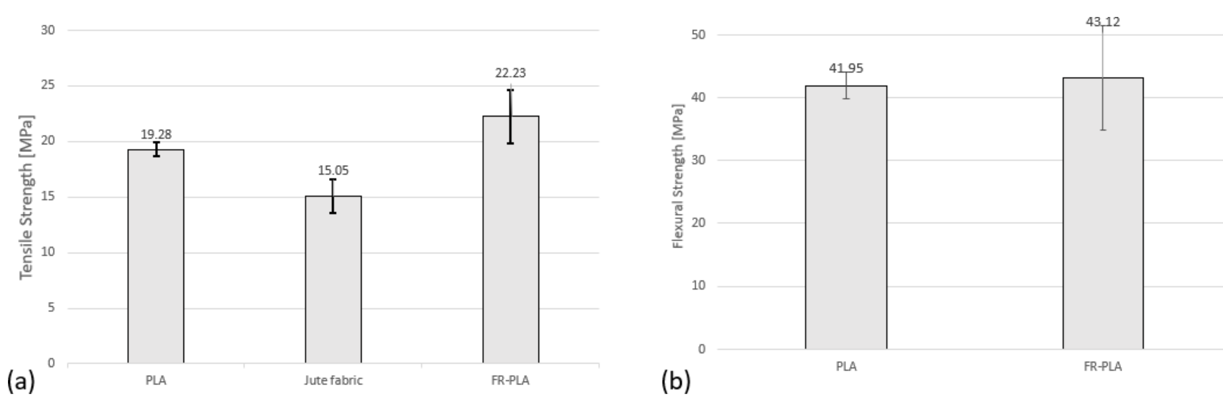

Figure 7. Comparisons of (a) tensile, and (b) flexural strengths of pure PLA, jute fabric (tensile only), and fiber-reinforced PLA (FR-PLA).

3.1 Tensile test

The values of measured tensile properties of pure PLA, jute fabric, and woven jute fiber reinforced ones are presented in Table 1. It can be found that the 3D-printed pure PLA materials are relatively weak and the measured values of tensile strength and elastic modulus are much lower than recorded values from other resources (37 MPa [12] – 50 MPa [13] for tensile strength and 2.3 GPa [14] – 3.986 GPa [15]). This may be due to the difficulties for 3D-printed PLA parts to be completely non-porous and that all neighboring printed filaments are perfectly bonded. The measured tensile strength of jute fabric is also lower compared to reported values from other studies (300 – 700 MPa [16]), which is probably because of the areal density of the jute fiber used in this study and the fact that the fabric had not been chemically treated.

The tensile properties of pure PLA were significantly strengthened by the woven jute reinforcement: the average tensile strength was found to be 22.23 MPa and the average elastic modulus to be 1.33 GPa for woven jute fiber reinforced PLA polymer, significantly better compared to those of pure PLA. The stress-strain curves of tensile tests performed on pure PLA and woven jute fiber-reinforced PLA are shown in Fig. 8.

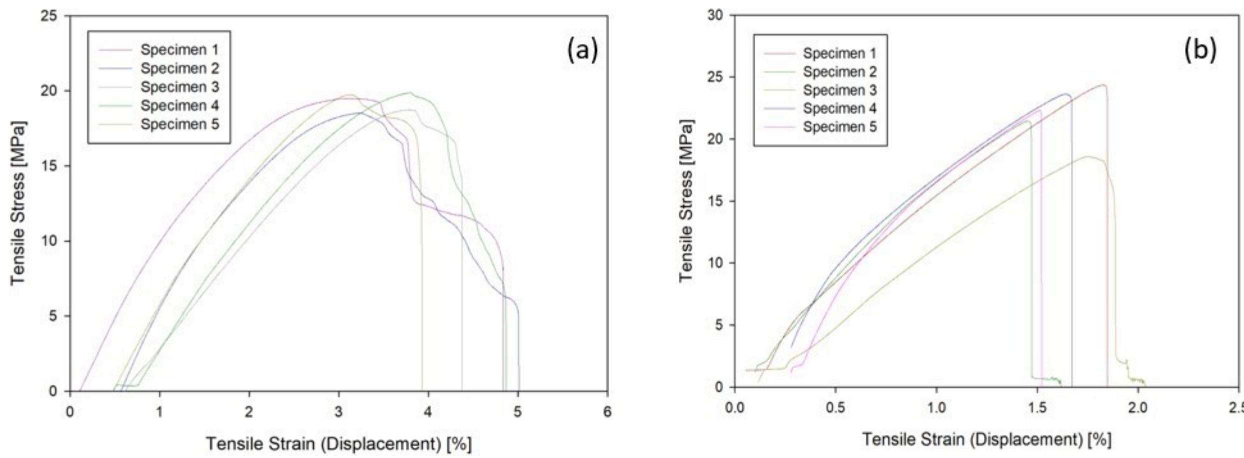

Figure 8. Tensile test stress-strain curves of (a) pure PLA, and (b) woven jute fiber-reinforced PLA.

3.2 Flexural test

From the values of flexural strengths and moduli of both pure PLA samples and woven jute fiber reinforced ones presented in Table 1, it can be found that the measured values of flexural strength of 3D printed pure PLA materials are similar to recorded values from other resources (43.6 MPa – 59.6 MPa [17]), but their flexural modulus is again much lower comparing to values reported (2.96 GPa [18] – 4 GPa [12]). This is likely caused by the pour interlaminar bondings of 3D-printed PLA samples. The flexural properties of pure PLA were improved little by the woven jute reinforcement: the average flexural strength was measured to be 43.12 MPa for woven jute fiber-reinforced PLA polymer, while the flexural modulus was increased to 1.67 GPa (87.6% increment). This may be due to poor bindings among reinforcement fabrics compared to pure PLA 3D-printed parts. The stress-strain curves of flexural tests performed on pure PLA and woven jute fiber-reinforced PLA are shown in Fig. 9.

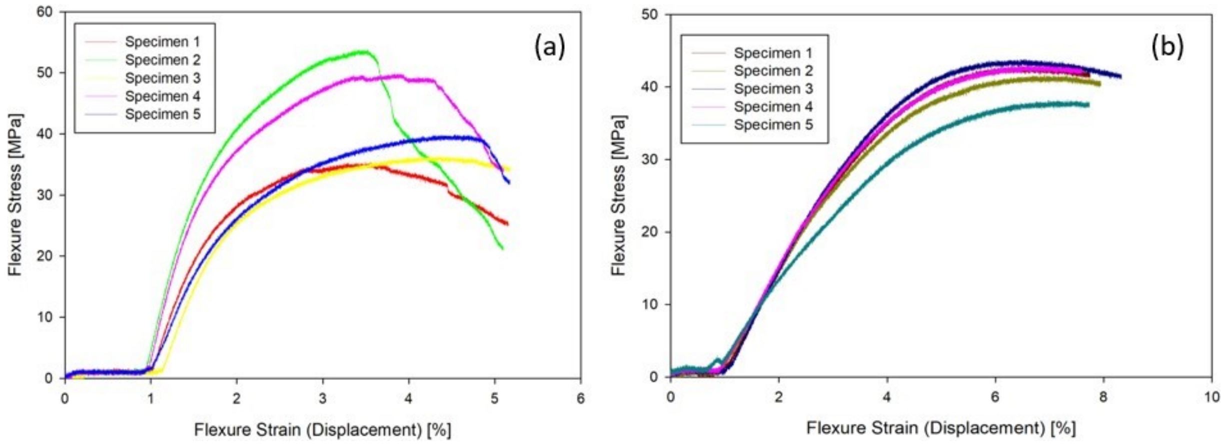

Figure 9. Flexural test stress-strain curves of (a) pure PLA, and (b) woven jute fiber-reinforced PLA.

3.3 SEM imaging

The SEM imaging results are shown in Fig. 10 below. It can be seen from Fig. 10(a) at a magnification level of 700, the PLA polymer matrix are well filled and binds well with the jute fibers while there are large voids located at some other locations in the composites, preventing direct contact and binding between the reinforcement fiber and the polymer matrix. The team assumes this is one of the reasons the mechanical properties of the made composites are restricted at the current level. At an even higher magnification level (×1,500) as shown in Fig. 10(b), where a PLA-filled section is shown, it can be seen that there is no gap between the reinforcement fiber and the polymer resin, and the fiber-matrix binding is good.

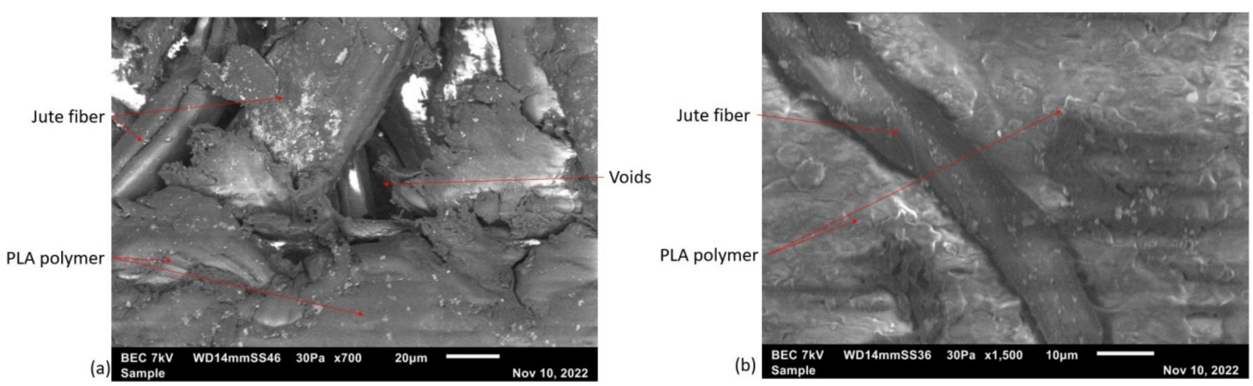

Figure 10. SEM imaging of (a) jute fiber and PLA polymer with voids (×700), (b) the interface of jute reinforcement fiber and PLA polymer matrix (×1,500).

4. CONCLUSIONS

Based on the study of the mechanical properties of the pure PLA polymer and woven jute fiber-reinforced PLA composites, the following conclusions can be made:

1. Pure PLA polymer samples are relatively weak in tensile and flexural properties, which is mainly due to the difficulties in making the test specimens completely solid through the FDM 3D printing process.

2. Jute fabrics used in this study are measured to be much weaker than the ones previously reported. This might be caused by the processing used in making the jute fabric products by the supplier. Higher-quality natural fiber fabrics should be obtained and implemented in making similar biocomposites.
3. By incorporating woven jute fibers into PLA polymers through the LOM 3D printing process, tensile properties can be significantly improved (almost doubled in most cases) due to the reinforcing effects of the woven jute fibers, while flexural properties improved little, due to poor interlaminar bindings.
4. Although the binding situation at fiber-matrix interfaces is good in the biocomposites made in this study at locations where the PLA polymer is well-filled, there are still locations where large voids exist where the jute fiber and PLA polymer are not in contact with each other, leading to no binding at these locations, which limited further mechanical properties enhancements of the biocomposites.
Findings from this study have shown strengthened mechanical properties of woven jute/PLA biocomposites made through the LOM 3D printing process. It can be seen from the pure jute fiber test that the low mechanical properties of the woven fabric used in this study and large voids in the made samples leading to poor fiber/matrix binding have restricted further improvements in the mechanical properties of biocomposites made through the LOM process. The research team will investigate other natural fibers with higher mechanical properties (e.g., flax, hemp, etc.) and try to improve and/or optimize the 3D printing process to further increase the quality of the biocomposites in the future of this research.

5. ACKNOWLEDGEMENTS

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