Feasibility study of various joining techniques for the 3D printed Poly Lactic Acid and recycled wood reinforced Poly Lactic Acid composites

Abstract

Current research assesses various joining techniques such as an adhesive bond, direct three-dimensional (3D) printing, and an ultrasonic welding of 3D printed dissimilar thermoplastic materials such as PLA and wood reinforced PLA composites. The importance of the present study is to determine the effective technique for joining the 3D printed complex structural profiles. Mechanical responses such as lap shear strength and shore D hardness of the various joints were studied and compared experimentally. The results highlighted that 15-17 % of higher shear strength was obtained for the ultrasonically welded joints compared with the direct 3D printed PLA and wood PLA lap joints. Macroscopic investigation of the ultrasonic welded polymeric joint exhibits the melting of polymers and wet the interface—the results in inter-molecular diffusion of polymeric chains and entanglement of polymers under the respective conditions.

Keywords: 3D printing; Welding; Adhesion; Polymers; Ultrasonics.

1. Introduction

Industrial revolution 4.0 advances additive manufacturing technology to the next step, which is witnessed by the growth of additive manufacturing in the global market [1]. In the additive manufacturing process, the Fused Filament Fabrication (FFF) process occupies a massive space due to its versatility in processing various thermoplastic materials, low cost, and higher flexibility [2]. The main drawback of the FFF process is limited bed size (increasing in the bed size tends to increases in the cost of the printer), and dimensional shrinkage (accuracy of the components gets varied based on the printing orientation and stacking sequence). Likewise, nowadays there are various types of FFF printers such as Creatbot PEEK 300 [3], Flashforge

Creator pro [4] are available for multi-material printing and they have potential for developing a single component with multiple materials. By adopting those two arguments into consideration, the machine's cost was increased drastically while considering increasing in the bed size. So, the 3D printed components can be joined together by the secondary joining techniques, making a more prominent final component such as complex profiles [5], developing multi-material components, repairing damaged or failed components and larger sized components for disassembly with better accuracy [6]. Researchers are investigating the various joining techniques such as adhesive bonds [7], ultrasonic welding [8], and direct 3D printing [9]. Among the various joining techniques, fasteners and rivets joining techniques may increase the component's weight and undergo local deformation at the joint zone. Welding and adhesive joining techniques can overcome the limitations which were mentioned above. In general, various thermoplastics are used for 3D printing; among them, Poly Lactic Acid (PLA) is primarily preferred in biomedical applications due to its versatility and compatibility [10]. In general PLA is more brittle due to higher chance of moisture absorption which is assisted with higher permeability [11]. To reduce the brittleness of PLA matrix, natural particle reinforcement is added to the matrix which may reduce certain mechanical properties [12]. Pirondi et al. have studied the effect of infill ratio on the PLA material and elaborated the fracture toughness of the adhesive joints with respect to Fused Filament Fabrication process. The results depict that, the infill ratio less than 20% shows decrease in the fracture toughness of the 3D printed samples and also Infill ratio set increases, this peculiar behaviour fades out [13]. Freund et al., has deliberated the adhesive joining of additively manufactured lattice structures using extrusion technique. The results conclusive that, the effect of plasma treatment has reports better lap shear strength when compared with the non-surface treated samples [14].

The present work concentrates on the dissimilar joining of PLA and wood PLA composite by various joining techniques. The objective of the work is a comparative evaluation of tensile lap shear strength and interface hardness of the various lap joints employed on the dissimilar PLA and wood PLA thermoplastic materials.

2. Materials and methods

For the thermoplastic composite sample preparation, the PLA and wood PLA (with 10% wood particle) filament was purchased from WOL3D, India and the important properties such as Density of 1.25gm/cm^3 and melt flow rate of 3-6 gm/10min and detailed specification of the filaments was illustrated in Table 1.

Table 1. Physical and Mechanical properties of PLA and wood PLA composite.

Sl. No	**Properties**	**Unit**	**Type of polymer**	
			PLA	**Wood PLA**
1	Tensile strength	MPa	65	55
2	Flexural Strength	MPa	60	74
3	Glass transition Temperature	℃	60	63
4	Melting temperature	℃	170	175

The samples with a dimension of 75 mm in length, 20 mm in width, and 3 mm in thickness were printed in an FDM 3D printer (Make: Pratham 3.0, India) with an infill density of 100 %, printing speed of 20 mm/sec, nozzle temperature of 210℃, and bed temperature of 60℃ for both PLA and wood PLA composites. Fig 1 shows the schematic layout for the sample preparation and testing of dissimilar polymer joints. Three types of polymeric lap joints were made: adhesive bond, direct 3D printing, and ultrasonic welding.

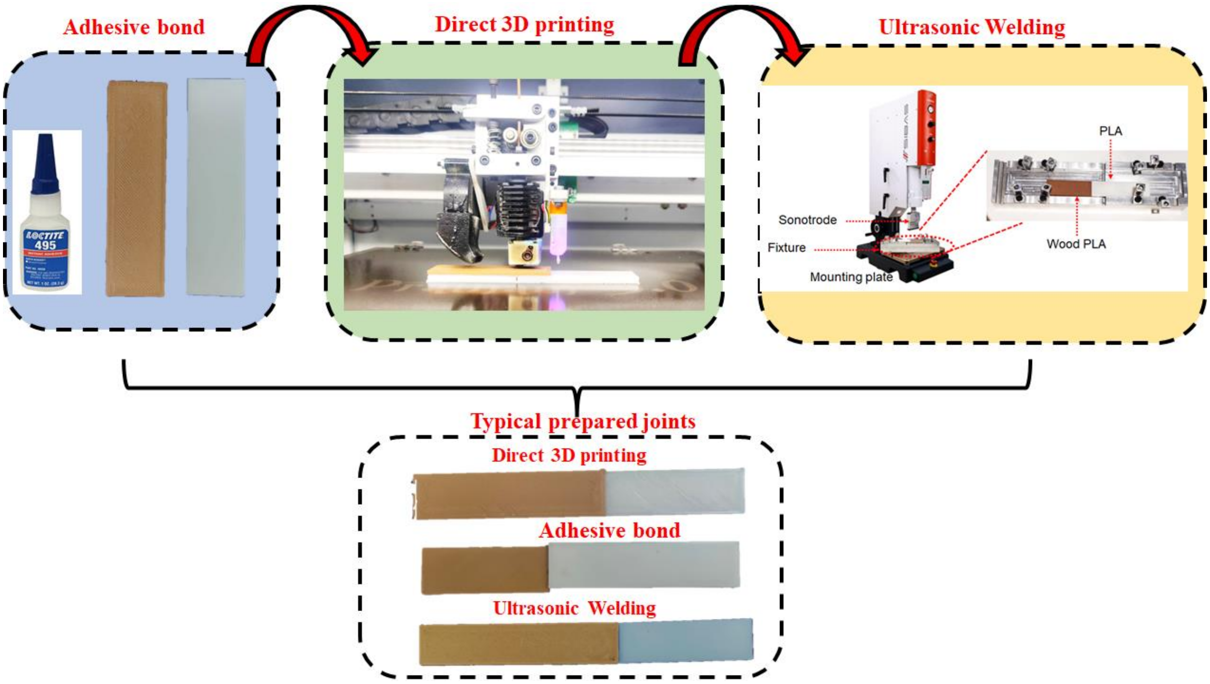
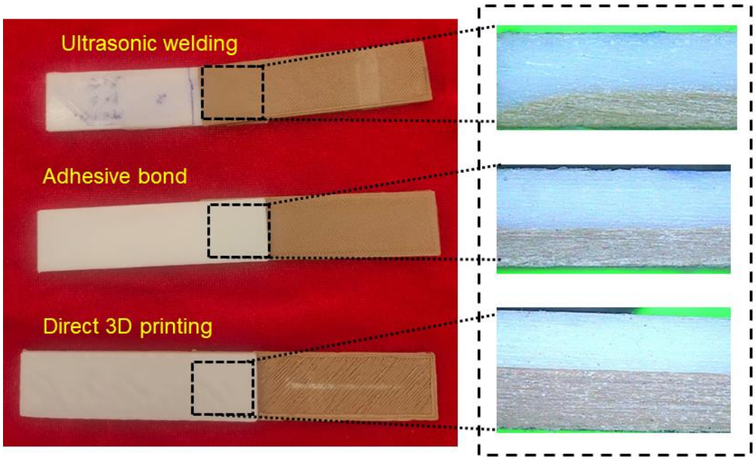


Figure 1 Schematic layout of various joints of 3D printed samples.

In direct 3D printing, the lap joint was done directly by PLA and wood PLA filaments. In this research, a single head nozzle unit is opted for the direct 3D printing process, and the estimated time for changing the filament was calculated from the slicing software. Based on that, the PLA and wood PLA filaments were changed, and the samples were printed directly on the printing bed shown in Fig 1.

In adhesive joining, the Loctite adhesive (495), a cyanoacrylate-based adhesive purchased from Henkel Adhesive Technologies, Japan, is used to join the polymeric materials. The adhesive joints are made with a cross-section such as 20*20*3 mm^3. The surface of the samples is sand blasted before applying the adhesives on the respective contact surfaces. At last, the ultrasonic welding joints are made by the ultrasonic welding machine (Make: Sibbas Ultrasonic welding, India) with a machine variable frequency of up to 35 kHz. For ultrasonic welding, the samples are equipped with the energy detectors grooves of 0.25 mm were made on the joining section. The joint was made again with the overlap area 20*20*3 mm^3, and machine parameters such as welding pressure of 1.5 bar, frequency of 20 kHz, and welding time of 1 sec were maintained for the polymeric ultrasonic welding.



Sl No	Type of sample	Overall thickness in the overlap region
1	Ultrasonic welding	5.9±0.7
2	Adhesive bond	6.3±0.3
3	Direct 3D printing	6.1±0.2

Figure 2 Cross sectional thickness of the overlap area of the prepared lap joints.

The lap joints are prepared as per the standard and the thickness of the prepared joints in the overlap area was analysed using optical microscope, further the thickness is calculated using ImageJ software. The mean total thickness of overlap area for all the respective configurations is shown in figure 2. From the prepared joints, the adhesive bonded joints which possess higher overlap thickness because of the added adherend material which add up the secondary layer in the joint interface. In case of ultrasonic welding, the welding pressure has plunged the material and materials gets fused and joined together which may end up in decreases in the thickness of the overlap joint at the interface. For the prepared lap joints, lap shear strength was tested in the Universal Testing Machine (Make: Tinus Olsen, UK) with a strain rate of 1 mm/min and according to ASTM D 5868-01 (2001) standard specification [15]. The shore D hardness test was performed using the Shore durometer (Model- STD-D, Gse India) to analyse the interface and base material hardness of the various polymeric materials and joints. The hardness test experiment was conducted as per the ASTM D 2240-15 (2015) standard [16]. The indentation was taken at three spots and its average value is considered as the average shore hardness values of the various joints. Finally, the macroscopic examination of the various PLA and wood PLA polymeric joint interfaces was analysed by an optical microscope (Make: Metji, India).

3. Results and Discussion

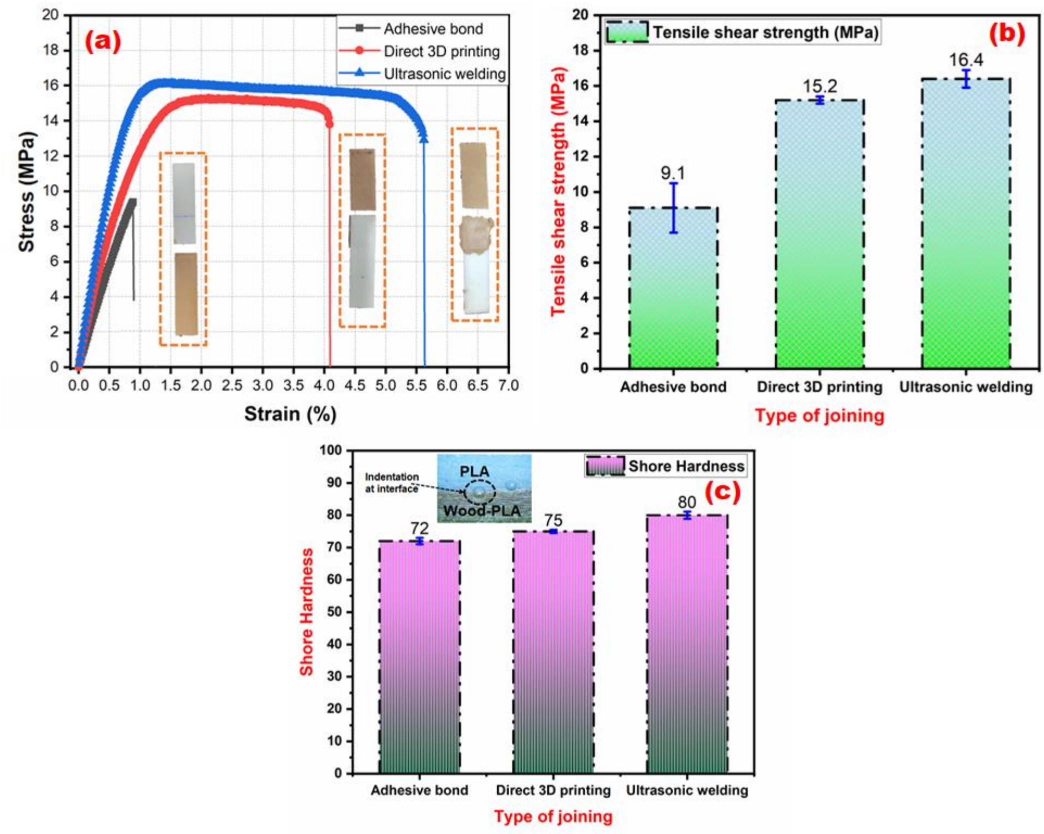


Figure 3 Mechanical properties of the PLA and wood PLA polymeric joints, (a) stress-strain plot of various lap joints, (b) shear strength of tested joints, and (c) shore D hardness of polymeric joints.

Fig 3 shows the mechanical properties of the various PLA and wood PLA polymer joints, and Fig 3 (a) shows the stress-strain curves of various lap joints. The stress-strain plot revealed that the maximum lap shear stress was reported by ultrasonic welded PLA and wood PLA composites. Figure 3 (b) shows the average lap shear strength of the adhesively joined, direct 3D printed, and ultrasonic welded PLA and wood PLA joints. The results show that the average lap shear strength of 9.1±1.4 MPa, 15.2±0.2 MPa, and 16.4±0.5 MPa was attained on the adhesive bonded, direct 3D printed, and ultrasonically welded PLA and wood PLA joints. The adhesive bonded samples exhibit the adhesive failure on both the PLA and wood PLA adhesive joints. They exhibit the minimum shear strength and contain adhesives deposited on the wood PLA samples. In neat PLA samples, there is a presence of minor compositions of wood PLA samples indication of adhesive may deposit some wood particles on the first layer of PLA. The adhesive failure was observed on the respective samples and which is clearly shown in figure 4 (a and b). A similar result was observed by Khosravani et al., on the adhesively bonded single lap joints of 3D printed PETG polymer [17].

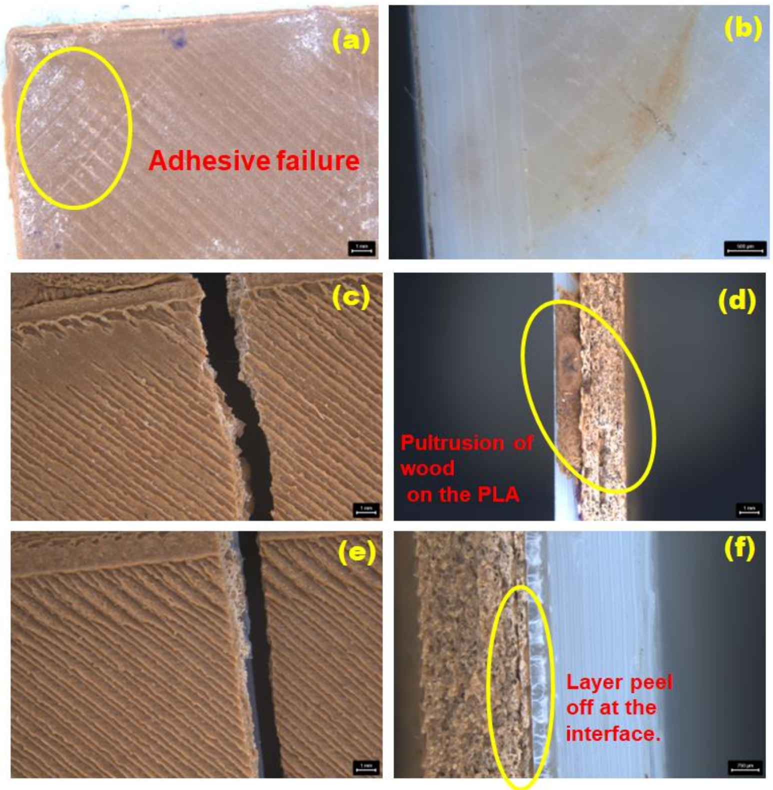


Figure 4 Fractured samples of various joints (a, b) adhesive bonded PLA and wood PLA sample, (c, d) ultrasonic welded PLA and Wood PLA sample, and (e, f) 3D printed PLA and Wood PLA sample.

The direct 3D printed samples attain higher shear strength than the adhesive joints due to filament impingement on the respective joining layer of the PLA matrix. From the failure mechanism, layer debonding [18] is observed on the respective joining layer and which is shown in figure 4 (e and f). Moreover, the time delay for the next layer may result in the formation of voids in the interface. These may end up in the observance of lower shear strength compared with ultrasonically welded joints. Ultrasonically welded joints exhibit the highest shear strength, and this is due to the excellent bonding of PLA with wood PLA because of the uniform melting and wood particle intermingling on the PLA matrix in the base of the welded zone. For the ultrasonic welding and direct 3D printed joints, the samples exhibit matrix deformation, and the failure starts from the edges of the joint interface. From the results, the adhesive bonded samples exhibited a brittle mode of failure. The lowest strain at break of 0.8% was observed on the adhesively bonded joints, and 4.1% and 5.6% were observed on the direct 3D printed and ultrasonic welded polymeric joints [19].

Figure 3 (c) shows the shore D hardness of PLA and wood PLA composite at the joint interfaces of various joints. The results highlight that the shore hardness value of the various joints such as adhesive joining, direct 3D printing, and ultrasonic joining are 72±0.3, 75±0.5, and 80±0.9. The maximum hardness value was observed on the ultrasonic welded joint interface. It is due to higher melting of high melt flow index wood PLA composite and wetting of polymeric interface results in inter-molecular diffusion of two materials at the interface. This is clearly shown in figure 4 (c and d). The ultrasonic joint interface exhibits lower porosity compared with the other two joints. A similar result was obtained by Sudhir Kumar et al. on the 3D printed wood polymer composite [20].

From the observation, the lap shear strength and shore D hardness of ultrasonic welded PLA and wood PLA joints have improved by 15-17% and 6-7% compared with direct 3D printed lap joints.

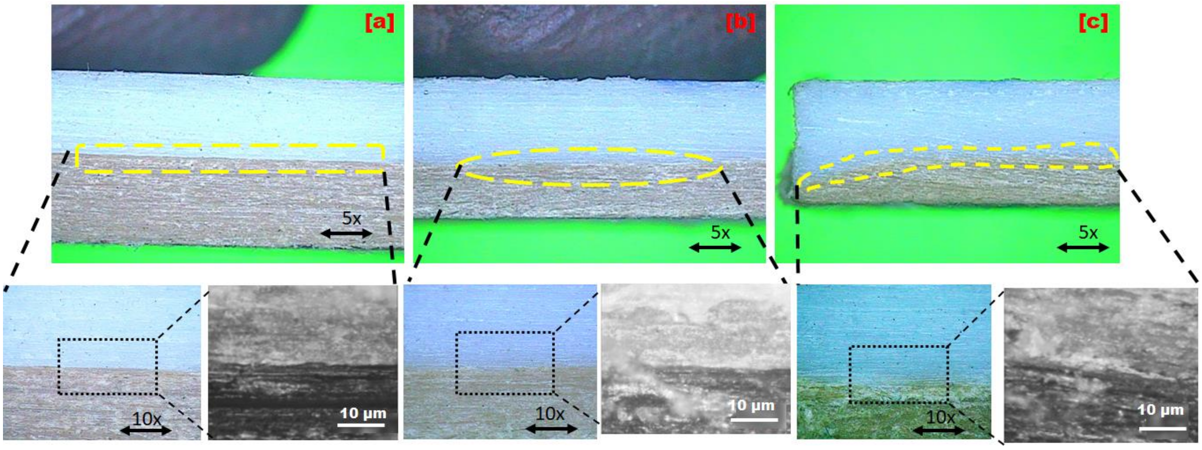


Figure 5 Micrographs of the joint interfaces of PLA and wood PLA composites. (a) Adhesive bond, (b) Direct 3D printing, and (c) Ultrasonic welding

Fig 5 shows the micrographs of the joint interface of PLA and wood PLA composites. Fig 5 (a) shows the presence of a thin adhesive layer on the adherent surface. It indicates the development of an interfacial layer between the PLA and wood PLA polymeric samples. It may contain an air gap or a void during the fabrication stage of the adhesive PLA and wood PLA joints. This may affect the quality of the joints in terms of the obtained maximum shear strength value [21]. Fig 5 (b) shows the direct 3D printed lap joints of PLA and wood PLA samples. In 3D printed samples, the top layer of the PLA samples is melted and fused to the next layer of the wood PLA sample. So, wavy marks such as craters and valleys are observed at the joint interface surface. It may increase the interfacial adhesive strength for the respective layers. Likewise, Fig 5 (c) represents the ultrasonically welded PLA and wood PLA samples. The sample exhibits better polymeric flow and wets out on the PLA surface interface. This results in good interfacial strength at the joint interface.

4. Conclusion

This work compared various lap joints of 3D printed PLA and wood PLA composite samples by various joining techniques such as an adhesive bond, direct 3D printing, and ultrasonic welding were investigated concerning mechanical and microstructural characterization. The results highlight that the ultrasonically welded samples can exhibit higher lap shear strength of 16.4 MPa and shore D hardness value of 80 compared with other types of joints such as adhesive and direct 3D printing. Among the various joints, the adhesive bonded composite experiences, the adhesive failure and which is very brittle when compared with other joints. This study promisingly reports the benchmark of the various joining technique for joining dissimilar thermoplastic materials in developing multi-materials for the weather proofing applications such as wood PLA composite as external surface and PLA as the internal layer for lower hydrophilic tendency application.

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