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Effects of PLA-Type and Reinforcement Content on the Mechanical Behavior of Additively Manufactured Continuous Ramie Fiber-Filled Biocomposites

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Abstract: The present work aimed to examine the tensile and flexural behaviors of biocomposites reinforced with continuous plant fibers, utilizing a range of polylactic acid (PLA) matrix materials and varying fiber content. These biocomposites were fabricated using an in situ-impregnated fused filament fabrication (FFF) technique. The study incorporated three different PLA matrix materials, namely PLA, PLA-Matte (PLA-Ma), and PLA-ST, each with distinct mechanical properties. The effect of different linear densities of continuous ramie yarns on the biocomposites was also investigated. The results show that adding continuous ramie yarn significantly enhances both the tensile and flexural strengths, as well as the modulus, of the matrixes. Furthermore, there was a positive correlation between the content of ramie yarn and the increases in strength and modulus. Moreover, the introduction of ramie yarns altered the fracture behavior of the biocomposites, shifting towards brittle fracture. This change significantly impacted the fracture toughness of the matrixes and resulted in a convergence of elongation at the point of breakage.

Keywords: three-dimensional printing; PLA; ramie fiber incorporation; biocomposite; mechanical property



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1. Introduction

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized the manufacturing landscape by enabling the fabrication of intricate and customized structures layer by layer from digital designs [1,2]. This innovative technology has been applied to the field of polymers and polymer-based composites. It includes various printing methods, such as fused filament fabrication (FFF) [3–5] or fused deposition modeling (FDM) [6–8], selective laser sintering (SLS) [9–11], stereo lithography appearance (SLA) [12,13], and electrospinning [14], enabling the realization of complex structures and diversifying the application of materials. Among these methods, FFF has been one of the most popular methods for manufacturing polymer and composite parts due to its advantages, such as cost-effectiveness, ease of maintenance, and reduced environmental impact [15,16]. Numerous studies have demonstrated that the mechanical properties of pure polymers and composites reinforced with short fibers often face limitations when applied to bearing structures [17–21]. In contrast, FFF-printed components with continuous fiber reinforcement show significant advantages in performance [22–24].

The mechanical property enhancement for different matrix materials through continuous fibers has been intensively investigated [24–27]. Some research articles have reported the fabrication of continuous carbon fiber-reinforced PLA [28], nylon [29], and ABS [30] composites using the FFF method. The results indicate that the integration of continuous carbon fibers can lead to a 109% increase in tensile strength and a 53% increase in flexural

strength for PLA composites. Moreover, nylon composites with a 14% volume of carbon fiber exhibited a tensile strength nearly 11-times greater than that of their non-reinforced nylon counterparts. A similar effect was observed in ABS composites, where 10 wt% carbon fiber-reinforced ABS samples demonstrated substantial improvements, reaching 127 MPa in flexural strength and 147 MPa in tensile strength, significantly surpassing the strength of standard ABS parts [30]. Composite materials reinforcement using continuous glass fibers through AM has been also investigated with significant mechanical property improvements [31–33]. Furthermore, it has been reported that incorporating continuous Kevlar fibers not only enhances the tensile properties of PLA and nylon matrixes, but also effectively improves their impact resistance [34,35].

At present, the application of numerous non-biodegradable materials is causing significant pollution to the ecological environment. Consequently, enhancing environmental protection and improving the eco-friendliness of materials has become an urgent issue [36–40]. This also demands more advanced development in fiber-reinforced composites. Continuous plant fiber-reinforced biocomposites with the advantages of biodegradability, no toxicity, renewability, low density, good mechanical properties, economical, etc., are deemed to become the successors of continuous synthetic fiber-reinforced composites in the future [41,42]. These excellent properties make biocomposites suitable for a wide range of applications in various fields, e.g., the automobile industry, goods packing, sports equipment, and construction [43–45], which has made the research on biocomposites increasingly impactful. Matsuzaki et al. [25] first proposed the in situ-impregnation 3D printing process of continuous jute fiber-reinforced thermoplastic composites in 2016. Since then, an increasing number of researchers have engaged in the study of continuous plant fiber-reinforced biocomposites. PLA materials, as a renewable resource, are produced from lactic acid units. The biodegradation of PLA produces lactic acid, which is highly biodegradable and biocompatible [46]. Therefore, PLA materials are attracting attention as the most suitable polymeric materials for biomedical applications and for replacing existing conventional plastics [14,47,48]. Long et al. [49] and Kuschmitz et al. [50] reported that incorporating continuous flax fiber significantly enhanced the overall mechanical properties of the PLA matrix. Specifically, the tensile strength of PLA rose by 325% and the tensile modulus increased by 570%. However, the formation of defects, like voids, during the 3D-printing process was also detected, impacting the performance of the biocomposite. It was also demonstrated that the addition of reinforcing jute fibers, hemp fibers, and pineapple leaf fibers improved the tensile and flexural properties of PLA [25,51,52]. Although the development in this field is promising, the existing research lacks a horizontal comparison of PLA-based materials available in the market. Therefore, it is necessary to investigate fiber-reinforced PLA matrixes with different properties, providing a reference for the material selection in subsequent composite fabrications.

In this work, biocomposites based on PLA, PLA-Matte, and PLA-ST, reinforced by continuous ramie yarns with various linear densities were fabricated via in situ-impregnation 3D printing. The tensile and flexural behaviors along different directions were evaluated for the materials with various ramie yarn contents. The microstructure was characterized using scanning electron microscopy (SEM) after tensile and flexural testing. The deformation and failure mechanisms of the materials were investigated via fractography.

2. Materials and Methods

2.1. Materials and Processing

In this work, PLA, PLA-Matte (PLA-Ma), and PLA-ST were selected as the matrixes for fabricating biocomposites. PLA-Ma and PLA-ST are also biodegradable green matrix materials with high elongation at break and improved fracture toughness compared to standard PLA. The commercial PLA 3D-printing filaments, with a diameter of 1.75 mm, for all three matrix materials were supplied by eSUN (Shenzhen, China). The information on the mechanical properties of the products provided by the supplier is shown in Table 1. For reinforcement, two twisted continuous ramie yarns (400 turns/meter) with linear densities

of 36 Nm/R and 15 Nm/R (Nm and R refer to the nominal count and the number of yarn strands, respectively) were provided by Hunan Huasheng Dongting Ramie Textile Co., Ltd., China. Their approximate diameters were $146 \pm 38 \mu\text{m}$ and $351 \pm 63 \mu\text{m}$, respectively, measured by a vernier caliper. The continuous ramie yarns were dried in an oven at 80°C for two hours before being used [53].

Table 1. Mechanical properties of the matrix materials provided by eSUN.

Matrix Material	Tensile Strength (MPa)	Elongation at Break	Flexural Strength (MPa)	Flexural Modulus (MPa)
PLA	65.0	8%	97.00	3600.0
PLA-Matte	42.0	50%	59.95	2878.5
PLA-ST	34.3	90%	43.00	1477.0

A modified 3D printer based on the FFF technique and continuous fiber in situ-impregnation approach were employed to fabricate biocomposite samples. The original printer designed for single-material use was manufactured by Shenzhen Creality 3D Technology Co., Ltd., China. As shown in Figure 1, during the biocomposite printing process, the dry continuous ramie yarn and matrix filament are fed into the nozzle simultaneously. The ramie yarn was impregnated in situ with the melted matrix filament, after which both materials were simultaneously extruded and deposited onto the printing bed. Additionally, the printing parameters were chosen to be a 0.3 mm printing layer thickness, a 1 mm hatch distance, a 100 mm/min printing speed, a 210°C nozzle temperature, and a 50°C bed temperature following our previous work [53].

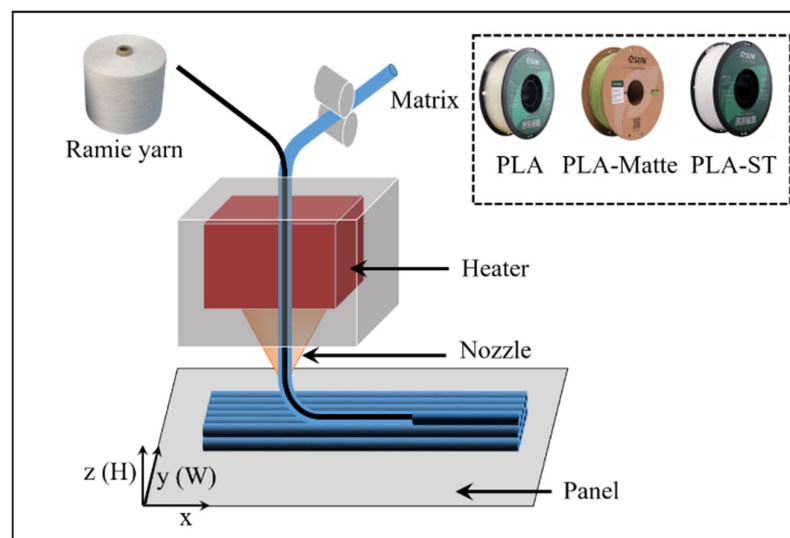


Figure 1. Method for manufacturing the biocomposite via in situ-impregnation 3D-printing process using PLA, PLA-Matte, and PLA-ST matrix materials.

2.2. Testing of Mechanical Properties and Characterization

A universal mechanical testing machine (E44, MTS Co., Eden Prairie, MN, USA), with a 30 kN load cell, was used to evaluate the mechanical properties of the printed samples at room temperature. Tensile tests were conducted at a cross-head speed of 1 mm/min. The matrix tensile samples (without ramie yarns) were fabricated as necked dogbone samples according to ASTM D638-14 [54]. It is important to properly select the geometry of laminated composites to guarantee that the fibers are perfectly aligned and do not discontinue. Therefore, a rectangular sample shape with a dimension of $100 \text{ mm} \times 11 \text{ mm} \times 0.9 \text{ mm}$ (3 printing layers) was selected for the fiber-reinforced biocomposite tensile samples in this study. The printing path for each printing layer is shown in Figure 2a following our previ-

ous study [53] on the in situ-impregnated 3D printing of the PLA-ramie fiber biocomposite, which proved the effectiveness of such a printing path. In the tensile process, the strain of the samples was measured using an extensometer, and the modulus of elasticity was determined through the slope of the stress–strain curve in the strain range of 0.2–0.5% [55].

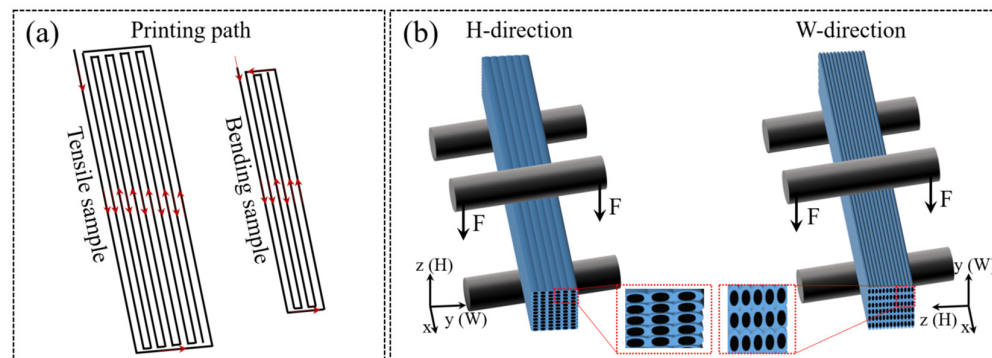


Figure 2. (a) The printing path for each printing layer of tensile and bending samples, and (b) the schematic diagram of the three-point bending test in H- and W-directions.

Three-point bending tests were performed with a cross-head speed of 1 mm/min and a gauge length of 60 mm. The dimension of the samples for the three-point bending tests was set as 90 mm × 6 mm × 6 mm (20 printing layers) in this work. Such a sample size was utilized and justified in our previous work [56] on carbon fiber-reinforced polyamide composites with similar testing conditions. The printing path for each printing layer of bending samples is shown in Figure 2a. In this work, the three-point bending tests, including two directions, through thickness height direction (H-direction) and width direction (W-direction), were carried out as shown in Figure 2b. Notice that the H-direction is parallel to the building direction of the samples. The main difference between the two bending directions is in how the fibers are arranged. The fiber distribution in the H-direction was denser than in the W-direction. The initial linear slope of the stress–strain curves was used to calculate the flexural modulus. The flexural strength was determined through the strength at yielding. Additionally, the fracture toughness was characterized by integrating the regions beneath stress–strain curves before fracture. All the mechanical tests were repeated five times to ensure the reliability of the experiment data.

The testing processes were recorded by a high-resolution digital camera (EOS 5D, Mark IV, Canon, Tokyo, Japan), paired with a macrolens (EF 100 mm, Canon, Tokyo, Japan). The yarn volume fraction was calculated using optical microscope images and Image J software (Image J2 version, SciJava, National Institutes of Health, Bethesda, MD, USA) [57]. The post-testing local micro-morphological features of the biocomposite tensile and three-point bending samples were characterized by Field Emission Scanning Electron Microscopy (FE-SEM, Hitachi Co., S-4800, Tokyo, Japan).

3. Results and Discussion

3.1. Tensile Properties

Figure 3 shows the tensile engineering stress–strain curves of different matrix and biocomposite materials. The tensile properties of the three matrixes obtained from the tensile tests of the dogbone samples, as shown in Figure 3a, do not exactly match the data provided by the supplier in Table 1. The tensile strength values of non-reinforced PLA, PLA-Matte, and PLA-ST decreased by 29.23%, 14.29%, and 5.21%, respectively, compared to the supplier's data. This was likely due to the presence of printing defects, such as voids, formed during the sample printing process [58]. In addition, the tensile elongation at break of PLA-Ma was measured as 51.03%, which is generally in accord with the supplier's data. However, the measured tensile elongation at break values for the PLA and PLA-ST matrixes were 3.71% and 64.83%, which decreased by 53.63% and 27.97%, respectively,

compared to the presented values. This indicates that the presence of printing defects has a more significant effect on the ductility of PLA and PLA-ST.

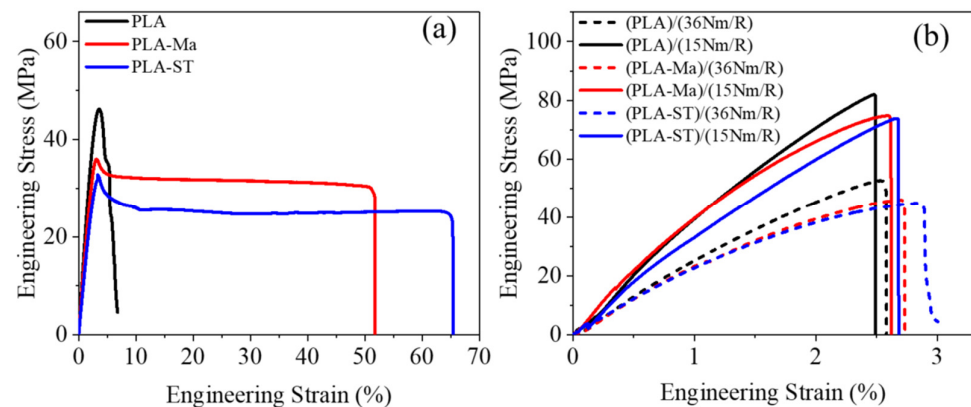


Figure 3. The tensile stress–strain curves of (a) different matrixes and (b) biocomposites with matrixes of PLA, PLA-Ma, and PLA-ST reinforced by different ramie yarns.

The tensile engineering stress–strain curves for fiber-reinforced biocomposites are presented in Figure 3b. Compared to the tensile properties of the three matrixes exhibited in Figure 3a, the addition of continuous ramie yarns significantly affected their tensile elongation at break. Unlike non-reinforced matrix materials, the tensile elongation at break of the biocomposites reinforced by continuous ramie yarns was within the range of 2.5% to 3.0%, which indicates the fracture behavior of the biocomposites was dominated by impregnated ramie yarns.

As illustrated in Figure 3, the tensile properties of the biocomposites are also significantly affected by yarn contents. In order to investigate the effect of yarn content on the properties of biocomposites, the yarn contents were first determined. Figure 4 demonstrates how the biocomposite yarn content is calculated. Firstly, the positions of the yarns and the matrix were determined from the OM images of the sample cross-section. Then the areas of ramie yarns (A_r) and the sample cross-section (A) were marked and estimated by image processing through Image J software. The yarn volume fraction, V_f , can be presented as follows [28]:

$$V_f = \frac{A_r}{A} \times 100\% \quad (1)$$

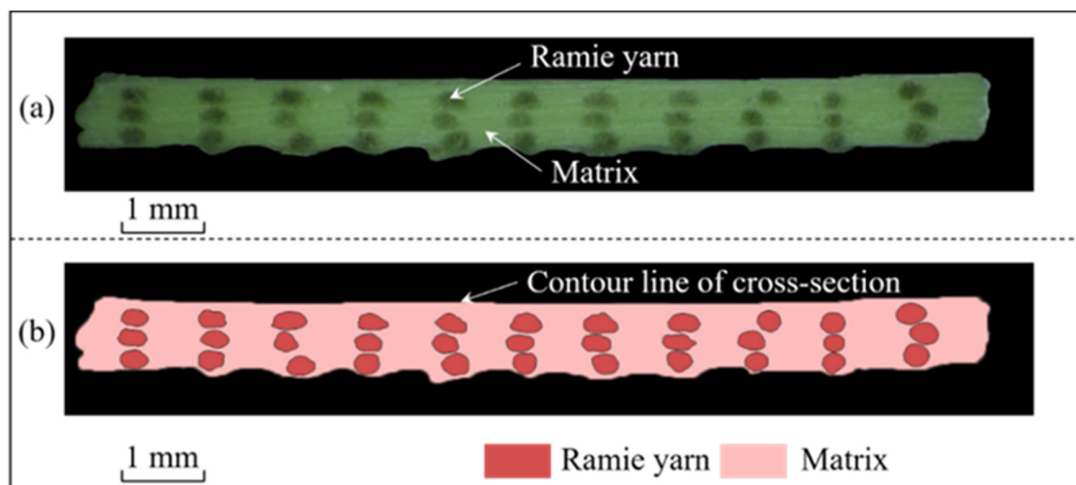


Figure 4. Methods for measuring yarn volume fraction (V_f) of biocomposites, (a) an OM image of biocomposite sample cross-section; (b) schematic image for estimation of yarn volume fraction (V_f).

The yarn volume fractions (V_f) of 5.12% and 24.04% for biocomposites reinforced with 36 Nm/R and 15 Nm/R ramie yarns were obtained through the method illustrated in Figure 4, respectively. Figure 5 exhibits the effect of V_f on the tensile strength and tensile modulus of the biocomposites. It can be observed that the incorporation of reinforcing yarns significantly enhances both the tensile strength and tensile modulus, and such improvements become more significant with higher yarn contents in the biocomposites. PLA-based biocomposites with 5.12% and 24.04% yarn contents significantly outperformed the non-reinforced PLA (0% yarn content, tensile strength of 46.13 MPa, and modulus of 1822.45 MPa), where tensile strengths increased to 52.59 MPa and 81.49 MPa, which were 14.00% and 76.65% higher compared to the pristine PLA, respectively. Meanwhile, their tensile moduli were 2873.36 MPa and 4753.68 MPa, with an increase of 57.66% and 160.84%, respectively. For biocomposites with a 5.12% yarn content based on PLA-Ma and PLA-ST, their tensile strengths were improved by 27.75% and 35.97% compared to pristine PLA-Ma and PLA-ST (45.99 MPa and 44.65 MPa), respectively. Their tensile moduli were increased by 82.98% and 100.58% to 2677.01 MPa and 2477.12 MPa, respectively. When the yarn content reached 24.04%, the tensile strengths of PLA-Ma-based and PLA-ST-based biocomposites were increased by 107.19% and 132.97% to 74.59 MPa and 73.85 MPa, respectively. Their tensile moduli were increased by 186.05% and 233.55% to 4184.89 MPa and 4119.37 MPa, respectively. However, it was worth highlighting that incorporating the same amount of ramie yarn did not alter the ranking in tensile strength and modulus among biocomposites based on the three matrix materials. PLA-based biocomposites consistently showed the highest tensile strength and modulus, followed by PLA-Ma-based and PLA-ST-based biocomposites. Compared to other studies on PLA-based biocomposites reinforced with natural fibers, the tensile strength obtained from ramie fiber-reinforced PLA material biocomposites studied in this work was 50.91% higher than bamboo fiber biocomposites [59], 10.42% higher than wood fiber biocomposites [60], 25.37% higher than jute fiber biocomposites [61], and 37.88% higher than flax fiber biocomposites [62], which was evidence that the biocomposites reinforced with ramie yarn in this study had excellent tensile properties.

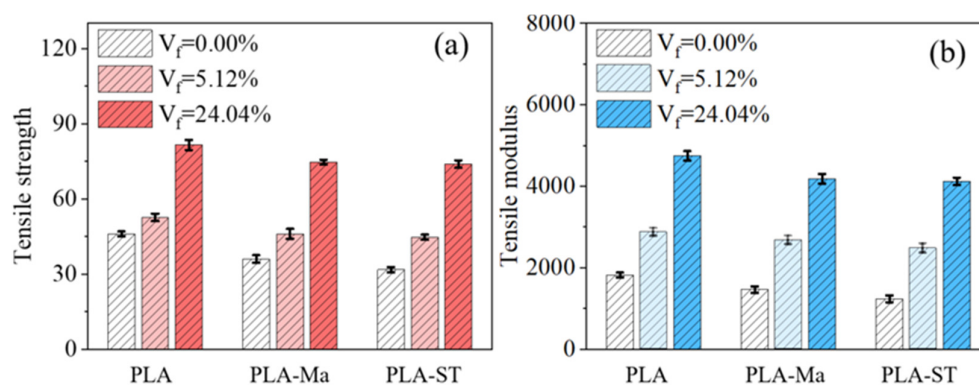


Figure 5. Influences of ramie yarn volume fraction on (a) tensile strength and (b) tensile modulus of biocomposites with different matrixes.

Figure 6 shows the tensile fracture surfaces of the PLA-based and PLA-ST-based biocomposites. The tensile fracture forms of biocomposite samples, including matrix fracture, fiber pullout, and fiber breakage, were observed. In addition, the fracture surfaces of the biocomposites reinforced with various fiber contents were slightly different. The biocomposites with 36 Nm/R show less fiber pullout and more fiber breakages, whereas the ones with 15 Nm/R show a significant amount of fiber pullout, as shown in Figure 6b,d,f,h. This was likely due to the difficulties in matrix impregnation using thicker fibers, resulting in undesired fiber/matrix separation [25,53].

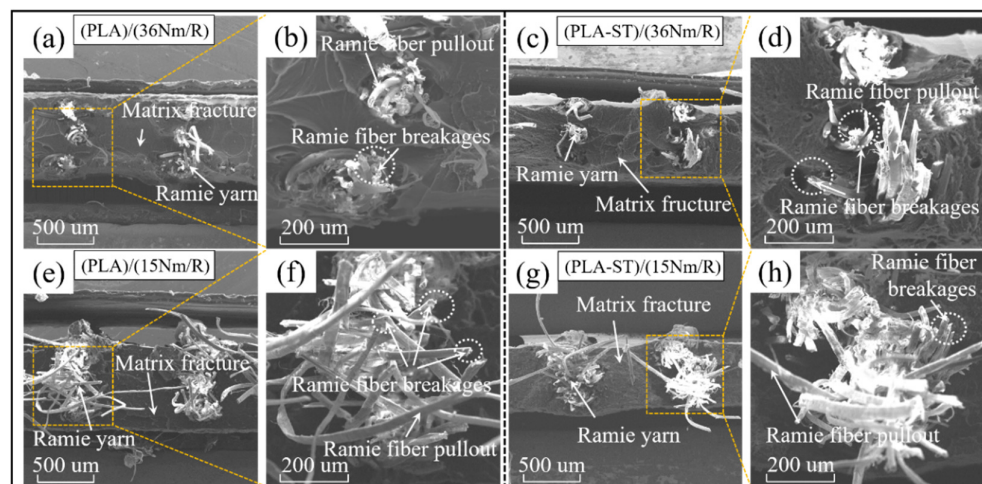


Figure 6. SEM micrographs of tensile fractured surfaces for the PLA-based and PLA-ST-based biocomposites reinforced with different ramie yarns: PLA/36 Nm/R (a,b), PLA-ST/36 Nm/R (c,d), PLA/15 Nm/R (e,f), and PLA-ST/15 Nm/R (g,h).

3.2. Flexural Properties

3.2.1. Effect of Matrix Type and Yarn Content

Figure 7 presents the engineering stress–strain curves of three-point bending tests for the three matrix materials and biocomposites, reinforced with 36 Nm/R and 15 Nm/R ramie yarns. It can be observed that the three non-reinforced materials exhibit plastic fracture during the bending process, with the beginning point of fracture marked by yellow dots. Meanwhile, the reinforced biocomposites exhibited brittle fractures, likely caused by the instant stress concentration when the fibers broke. Moreover, with the addition of ramie yarn, the fracture strains of the three matrix materials converged, and as the yarn content increased, the fracture strains of the biocomposites tended to decrease. The fracture strains of the biocomposites based on the three matrix materials were in the range of 2.63–3.03% at a yarn content of 5.12%. When the yarn content was raised to 24.04%, the fracture strains decreased to the range of 2.42–2.73%. The flexural strength, modulus, and energy absorption of the matrix materials and biocomposites are shown in Table 2. The results demonstrate that the addition of ramie yarns can significantly enhance the flexural strength and modulus. As the yarn content increases, both the flexural strength and modulus of the biocomposites increase as well. Compared to non-reinforced materials, the flexural strength of the biocomposites with a 24.04% yarn content based on PLA, PLA-Ma, and PLA-ST increased by 33.87%, 73.48%, and 102.71%, while the flexural modulus increased by 106.12%, 129.62%, and 219.89%, respectively. Compared to other studies on the flexural properties of PLA-based biocomposites, the flexural strength of biocomposites reinforced with ramie fibers in this work was 6.51% higher than jute fiber biocomposites [63], 77.52% higher than hemp fiber biocomposites [64], and 166.28% higher than flax fiber biocomposites [65]. In comparison, the flexural properties of PLA biocomposites reinforced with ramie fiber in this study showed an excellent performance. In addition, although the addition of ramie yarn enhanced the flexural strength and modulus, the ability to absorb energy decreased significantly due to the brittle fracture behavior, as discussed above.

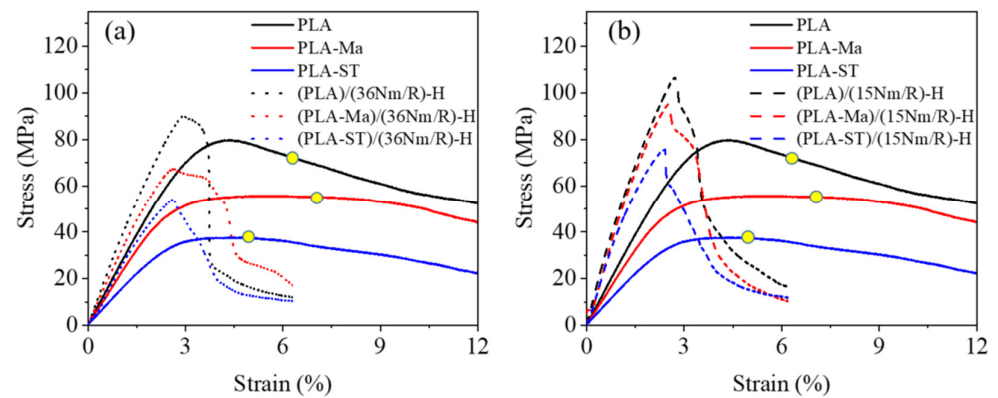


Figure 7. Three-point bending stress–strain curves of the matrixes and biocomposites reinforced by (a) 36 Nm/R and (b) 15 Nm/R ramie yarns under the H-direction.

Table 2. The flexural properties of different matrix materials and biocomposites reinforced by 36 Nm/R and 15 Nm/R ramie yarns.

Matrix Material	Ramie Yarn	V_f (%)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Energy Absorption (KJ/m ³)
PLA	—	0.00	79.56 ± 1.65	2555.32 ± 39.62	3672.56
	36 Nm/R	5.12	90.15 ± 0.55	3838.84 ± 41.56	1518.26
	15 Nm/R	24.04	106.51 ± 1.34	5267.09 ± 24.89	1668.24
PLA-Ma	—	0.00	54.78 ± 1.25	2172.31 ± 35.73	3206.92
	36 Nm/R	5.12	67.36 ± 1.68	3156.83 ± 40.02	1070.32
	15 Nm/R	24.04	95.03 ± 0.86	4988.07 ± 38.57	1376.71
PLA-ST	—	0.00	37.28 ± 0.48	1424.36 ± 31.98	1340.84
	36 Nm/R	5.12	53.82 ± 1.06	2309.21 ± 26.82	781.27
	15 Nm/R	24.04	75.57 ± 0.78	4556.32 ± 19.79	1081.4

Figure 8 presents the SEM micrographs of 15 Nm/R ramie yarn-reinforced biocomposites after the three-point bending test, which are similar to the ones with 36 Nm/R ramie yarn. It can be seen that the biocomposites with different matrix materials exhibit different flexural behaviors. The biocomposites based on PLA-Ma and PLA-ST show depressions in the pressurized portion during the bending process compared to PLA-based biocomposites, as shown in Figure 8a–c. This is more obvious when PLA-ST is used, since the PLA-Ma and PLA-ST are generally softer than PLA. The fracture cracks of the PLA-based biocomposites are smoother, whereas the ones in PLA-Ma- and PLA-ST-based materials show obvious unevenness and pits, as presented in Figure 8d–f. This is mainly due to the fact that PLA is relatively brittle compared to PLA-Ma and PLA-ST, as shown in Figure 3. Figure 9 presents the SEM micrographs of biocomposites based on PLA and PLA-ST reinforced with 15 Nm/R and 36 Nm/R ramie yarns after bending in both directions, respectively. As shown in Figure 9a,b,d,e, the 36 Nm/R ramie yarn-reinforced biocomposites have larger cracks with more pronounced compression marks and depressions in the compressed regions. This was attributed to the fact that, when the biocomposites had a lower yarn content, the overall structure became softer due to the higher proportion of matrix material, and their resistance to crack propagation decreased.

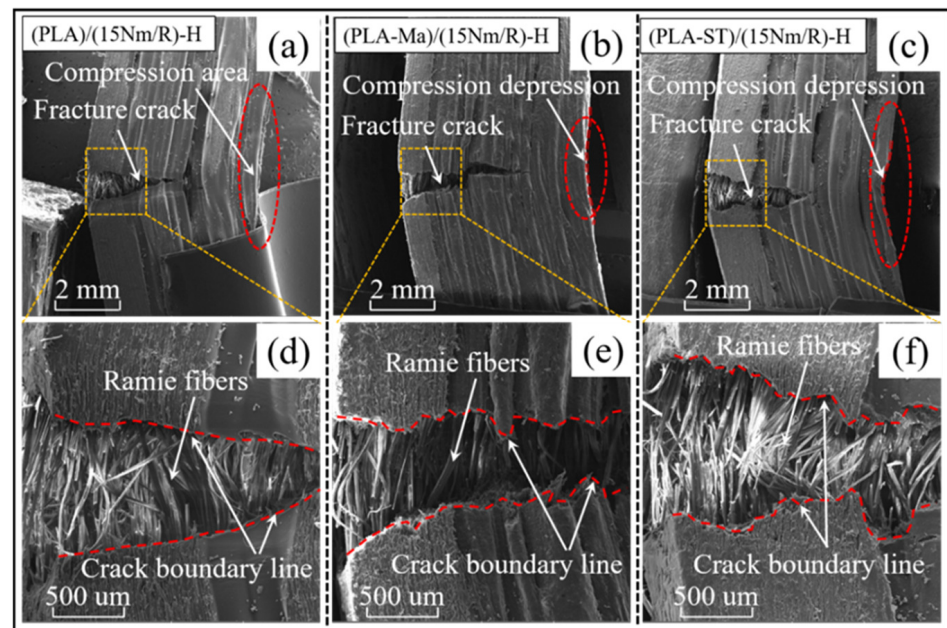


Figure 8. SEM micrographs of 15 Nm/R ramie yarn-reinforced PLA (a,d), PLA-Ma (b,e), and PLA-ST (c,f) biocomposites after the three-point bending test.

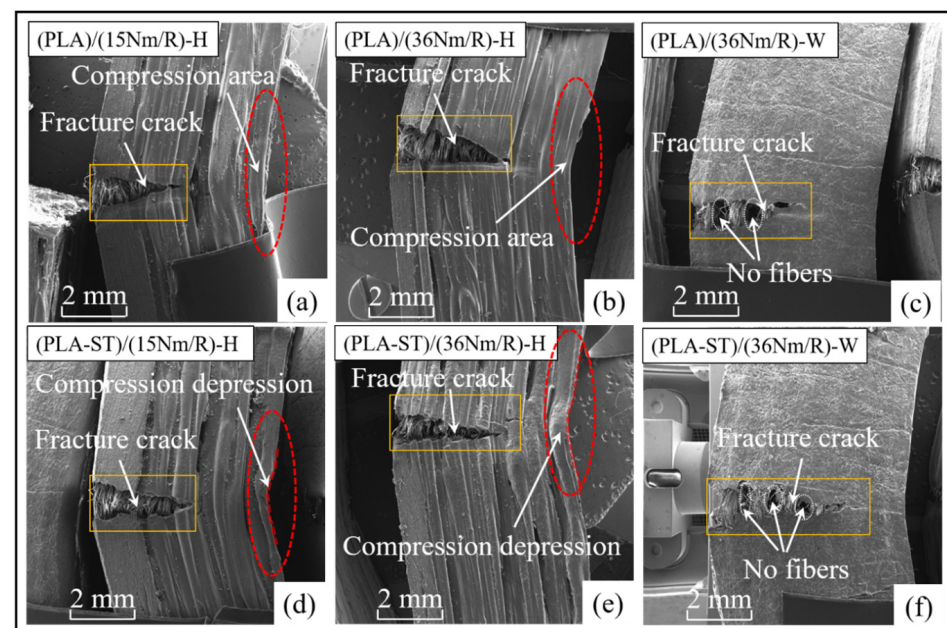


Figure 9. SEM micrographs of biocomposites reinforced with (a,d) 15 Nm/R and (b,c,e,f) 36 Nm/R ramie yarns after the H-direction and W-direction three-point bending tests.

3.2.2. Effect of Bending Direction

The bending engineering stress–strain curves of the biocomposites in different bending directions are presented in Figure 10. It can be observed that the overall flexural behavior of the biocomposites in the W-direction is generally consistent with that in the H-direction, both exhibiting brittle fractures. However, the initial linear slope is lower and the overall fracture strain is slightly larger in the W-direction. For the 36 Nm/R ramie yarn-reinforced PLA, PLA-Ma, and PLA-ST biocomposites, the fracture strains altered from 3.04%, 2.63%, and 2.65% in the H-direction to 3.43%, 3.45%, and 3.18% in the W-direction, respectively. Meanwhile, 15 Nm/R ramie yarn-reinforced PLA, PLA-Ma, and PLA-ST biocomposites changed from 2.73%, 2.50%, and 2.42% in the H-direction to 2.98%,

2.61%, and 2.62% in the W-direction, respectively. As shown in Table 3, the biocomposites exhibited lower flexural strength and the modulus bent in the W-direction compared to that in the H-direction. More specifically, when bent in the W-direction as opposed to the H-direction, the flexural strength and modulus of 36 Nm/R ramie yarn-reinforced PLA, PLA-Ma, and PLA-ST biocomposites were reduced by 6.31%, 10.51%, and 7.30% for flexural strength, and 14.48%, 13.45%, and 5.74% for flexural modulus, respectively. For 15 Nm/R ramie yarn-reinforced PLA, PLA-Ma, and PLA-ST biocomposites, the flexural strength and modulus were reduced by 7.96%, 5.95%, and 8.39% and 12.84%, 3.81%, and 16.58%, respectively. This phenomenon is related to the distribution of reinforcing ramie fibers with respect to the bending direction, as shown in Figure 9c,f. When the biocomposites were bent in the W-direction, the distribution of fibers in the W-direction was dispersed, resulting in areas without fibers, which affected the flexural properties and the size of the crack expansion of biocomposites in the W-direction. In summary, biocomposites exhibit different mechanical performances in different bending directions, with a better bending performance in the direction of concentrated fiber distribution. This finding is useful for the design of the printing process for load-bearing components according to their actual loading scenario during applications. Any industries involving biocomposites may benefit, such as construction, robotics, automotive, sports, and other industries [66,67].

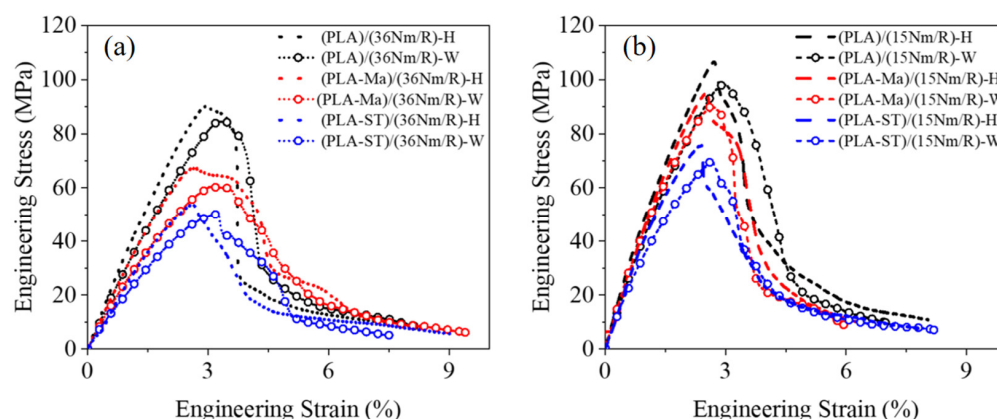


Figure 10. Three-point bending engineering stress–strain curves of the biocomposites reinforced with (a) 36 Nm/R and (b) 15 Nm/R ramie yarns under the H-direction and W-direction.

Table 3. The flexural properties of the biocomposites reinforced by 36 Nm/R and 15 Nm/R ramie yarns with bending in both the H-direction and W-direction.

Matrix Material	Ramie Yarn	Direction	Flexural Strength (MPa)	Flexural Modulus (MPa)
PLA	36 Nm/R	H	90.15 ± 0.55	3838.84 ± 41.56
	36 Nm/R	W	84.46 ± 0.94	3282.84 ± 31.42
	15 Nm/R	H	106.51 ± 1.34	5267.09 ± 24.89
	15 Nm/R	W	98.03 ± 1.23	4590.88 ± 33.46
PLA-Ma	36 Nm/R	H	67.36 ± 1.68	3156.83 ± 40.02
	36 Nm/R	W	60.28 ± 2.01	2732.33 ± 29.67
	15 Nm/R	H	95.03 ± 0.86	4988.07 ± 38.57
	15 Nm/R	W	89.69 ± 0.69	4797.78 ± 31.14
PLA-ST	36 Nm/R	H	53.82 ± 1.06	2309.21 ± 26.82
	36 Nm/R	W	49.89 ± 0.83	2176.69 ± 20.94
	15 Nm/R	H	75.57 ± 0.78	4556.32 ± 19.79
	15 Nm/R	W	69.23 ± 0.91	3800.93 ± 30.41

4. Conclusions

In this work, an investigation was conducted on the tensile and flexural properties of 3D-printed biocomposites with various PLA matrix materials and ramie yarn volume

fractions, including a study on the flexural behavior of samples in different bending directions. The tensile and flexural fracture behavior of the biocomposites were also investigated through SEM.

The tensile results show that the incorporation of continuous ramie yarn can significantly enhance the tensile strength and modulus of the materials, with a higher yarn content resulting in increased tensile properties. In addition, incorporating ramie yarn in the matrix materials tends to alter the fracture mode to brittle fracture and the elongation at break became close. Similar to the results of tensile properties, the flexural strength and modulus of the biocomposites improved compared to non-reinforced materials and positively correlated with the yarn content. The PLA-based biocomposite reinforced with the 15 Nm/R ramie yarn showed optimal flexural properties. In addition, the fracture toughness of the materials was very sensitive to the fiber content. The flexural behavior of the samples varied between bending directions, showing slightly worse results in the W-direction compared to the H-direction, which was likely due to the distribution of reinforced ramie fibers with respect to the direction of bending. The SEM images revealed that, during the bending process, biocomposites with PLA-Ma and PLA-ST showed an obvious depression in the compression region, which was not observed in the PLA-based biocomposites.

Based on the research in this paper, in the next work, we will explore in depth the brittleness characteristics created by ramie yarn in the biocomposites and try to address the potential drawbacks in terms of material toughness and resilience.

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