J MATER RES TECHNOL. 2019;8(5):3741–3751

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

www.jmrt.com.br

Original Article

Mechanical characteristics of wood, ceramic, metal and carbon fiber-based PLA composites fabricated by FDM

Zhaobing Liu[a,b,c], Qian Lei[d,*], Shuaiqi Xing[a]

[a] School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan 430070, China
[b] Hubei Digital Manufacturing Key Laboratory, Wuhan University of Technology, Wuhan 430070, China
[c] Institute of Advanced Materials and Manufacturing Technology, Wuhan University of Technology, Wuhan 430070, China
[d] R&D Department, Shandong Kinshi Bitumen Co., Ltd, Rizhao 276806, China

ARTICLE INFO

Article history:
Received 21 February 2019
Accepted 21 June 2019
Available online 12 July 2019

Keywords:
3D printing
Composites
FDM
Mechanical properties
PLA

ABSTRACT

Fused deposition modeling (FDM) has gained much attention in recent years, as it revolutionizes the rapid manufacturing of customized polymer-based composite components. To facilitate the engineering applications of these FDM-printed components, understanding their basic mechanical behaviors is necessary. In this paper, the mechanical characteristics, including tensile and flexural properties of samples fabricated by FDM with different additives, i.e. wood, ceramic, copper, aluminum and carbon fiber, based polylactic acid (PLA) composites are comprehensively investigated. The effects of different PLA composites, build orientations and raster angles on mechanical responses are compared and analyzed in detail. It is found that ceramic, copper and aluminum-based PLA composite parts have similar or even increased mechanical properties compared with virgin PLA made parts. In most cases, PLA composite samples that are FDM-printed in on-edge orientation with +45°/−45° raster angles have the highest mechanical strength and modulus. It is worth noting that the results in this research provide a useful guideline for fabricating complex functional PLA composite components with optimized mechanical properties.

1. Introduction

Three-dimensional (3D) printing, also known as additive manufacturing (AM) has been developed to enable the manufacturing of complex 3D components without expensive molds based on layer by layer fabrication using computer-aided design (CAD) models. Over the past decades, this technology has flourished in various industrial sectors such as aerospace, civil, biomedical, food and others. A series of critical reviews relating to the above fields can be found in Refs. [1–4].

In 3D printing, a technique commonly adopted for components to obtain some mechanical response is the so-called fused deposition modeling (FDM) [5]. In FDM, a filament of thermoplastic printing material is melted through an extrusion nozzle of printer and deposited line by line and

* Corresponding author.
E-mail: leiqian_9036@163.com (Q. Lei).
https://doi.org/10.1016/j.jmrt.2019.06.034

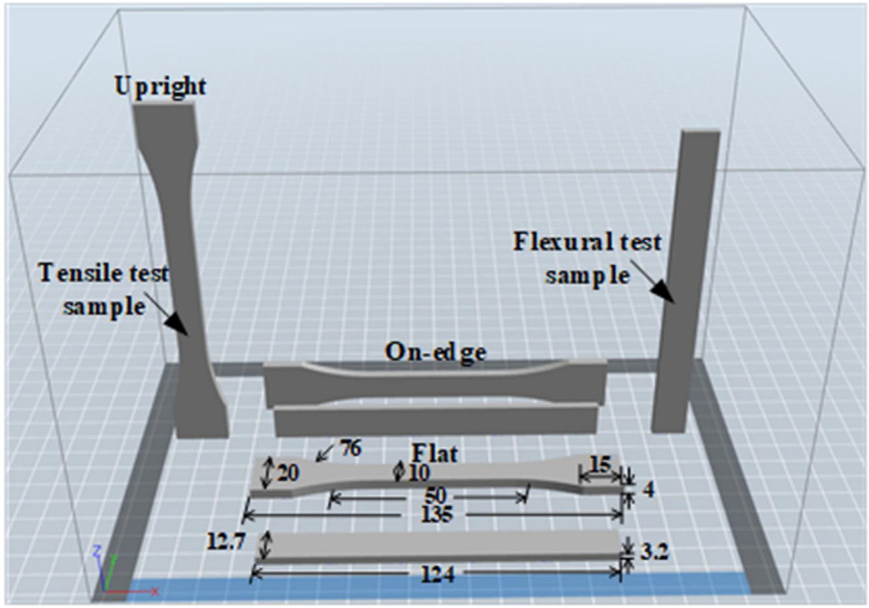

Fig. 1 – Dimensions of tested samples and printing orientations (unit: mm).

further layer by layer to form a 3D geometry of the designed component. During the printing process, the mechanical characteristics of 3D printed materials by FDM are greatly affected by several variables, like nozzle and platform temperature, printing speed and orientation, layer deposition height, raster angle, infill pattern and so on [6,7].

To achieve desired performance of 3D printed components, different thermoplastic polymers have been employed in FDM, including PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), nylon (a kind of polyamide), PETG (polyethylene terephthalate glycol-modified), PEI (polyethylenimine) and PEEK (polyether ether ketone) [8]. Among these materials, PLA, as a biodegradable green material has received considerable attentions in biopolymer research owing to its excellent biocompatibility and sustainability [9]. Since the beginning of its commercialization in 2002, researchers have been trying to explore its potential applications, such as tissue engineering scaffolds in medical field [10,11]. However, compared with traditional engineering materials, like metals and fiber reinforced composites, the mechanical properties of PLA are intrinsically lower [12–14]. In order to modify the capabilities of virgin PLA, researchers have endeavored to investigate PLA-polymer matrix reinforced composites by adding various additive materials, like natural or synthetic fibers, metals, ceramics into PLA [11,15–21]. However, the emerging of these new PLA composites brings new challenges to the FDM-printing of functional components with satisfactory mechanical properties. To the best of authors' knowledge, research on the comparing and understanding of basic mechanical responses of various PLA composites is still limited.

The aim of this paper is to understand the mechanical behaviors of FDM-printed wood, ceramic, copper, aluminum and carbon fiber-based PLA composite parts. In addition to the type of PLA composites, the effects of two important printing variables in FDM, i.e. raster angles and building orientations on mechanical properties are comprehensively investigated and analyzed. Finally, the above analysis is further verified by the observations of optical images from fracture surfaces of tensile and flexural tests.

2. Materials and methods

2.1. Materials

The filaments of virgin PLA (Ingeo 4043D, NatureWorks LLC) and PLA with different additive powders (wood, ceramic, copper, aluminum and carbon fiber) with the diameter of 1.75 mm were used as printing materials, which were purchased from Dongguan Zhehan Plastic & Metal Manufacture Co., Ltd. The blend ratio of PLA and each additive was chosen as approximately 3:2 in this research, which is believed to have the effectively modified mechanical properties compared to the virgin PLA.

2.2. Equipment

The FDM printer (Model: Creator Pro, Flashforge Co., Ltd., China) was used in this research. The control accuracy of the printer is about ±0.1–0.2 mm. Mechanical properties were tested in a universal testing machine (Model: DNS-100, manufactured by Sinotest Equipment Co., Ltd., China) with a load of 100 kN. The samples were loaded up to material failure at a displacement rate of 50 mm/min and 10 mm/min for tensile tests and flexural tests, respectively. In flexural tests, the support separation was set to 80 mm. The data acquisition rate for both kinds of tests was set to 100 Hz for loads and displacements. After mechanical testing, the fracture morphology of all the samples were evaluated by an optical microscopy (Model: ICX41M, Sunny Optical Technology Co., Ltd., China).

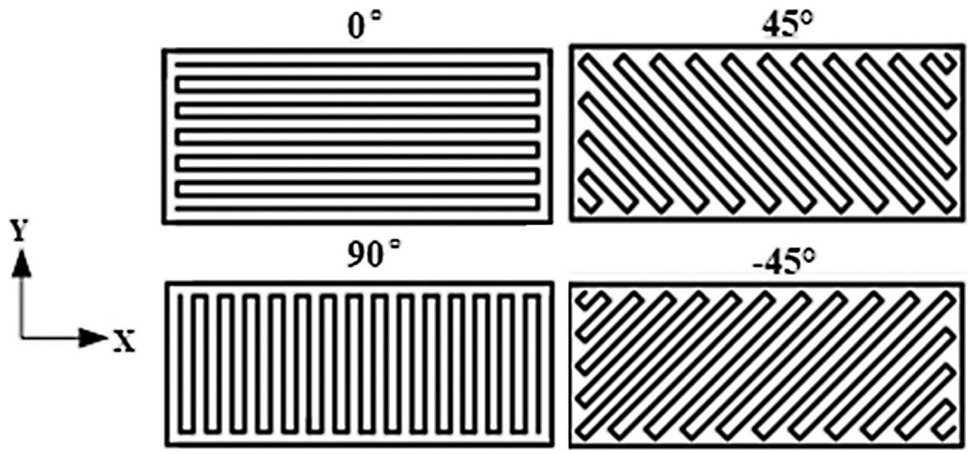

Fig. 2 – Layer deposition with different raster angles.

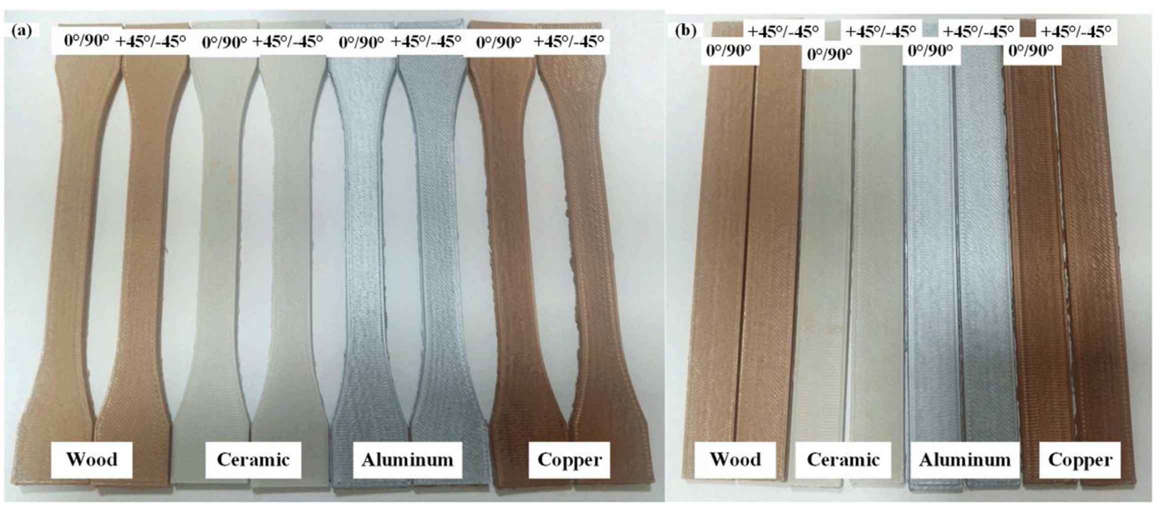

Fig. 3 – 3D printed samples of wood, ceramic, aluminum and copper-based PLA in flat orientation: (a) tensile tests, (b) flexural tests.

2.3. *Test sample preparation*

To evaluate the mechanical properties, dog-bone and rectangular shaped parts were fabricated by the FDM printer according to ASTM D638 and ASTM D790 standards. For each test, five same samples were prepared to make sure the obtained values of mechanical properties reliable. The dimensions of tested samples are presented in Fig. 1. In this study, three printing orientations (Namely, Flat, On-edge, and Upright) were considered to build the samples as illustrated in Fig. 1. For each printing orientation, two kinds of printing paths were designed with raster angles of 0°/90° and +45°/−45°, as depicted in Fig. 2, where, for instance, 0° means the axial direction along the sample length in the corresponding printing orientation, and 90° is the transverse direction. The printing path with +45°/−45° raster angles follows the similar routine as that of 0°/90° does. Key printing parameters adopted in this work are provided in Table 1.

Table 1 – Key printing parameters used in this work.

Materials	Virgin PLA, wood, ceramic, copper, aluminum and carbon fiber-based PLA
Platform temperature	65°
Nozzle temperature	200°
Printing speed	80 mm/min
Nozzle diameter	0.4 mm
Infill pattern	Linear
Object infill density	100%
Layer height	0.3 mm
Raster angle	0°/90°, +45°/−45°

3. Results and discussion

3.1. *Formability*

In this section, printing formability of all the PLA composite parts is evaluated in terms of printing raster angles as well as orientations. For example, successful FDM-printed samples of wood, ceramic, aluminum and copper-based PLA in

Table 2 – Formability of all materials under different printing conditions.

Samples for mechanical testing	Printing orientations	Layer deposition	Formability					
			PLA	PLA+wood	PLA+ceramic	PLA+copper	PLA+aluminum	PLA+carbon fiber
Tensile tests	Flat	0°/90°	√	√	√	√	√	√
		+45°/−45°	√	√	√	√	√	√
	On-edge	0°/90°	√	√	√	√	√	√
		+45°/−45°	√	√	√	√	√	√
	Upright	0°/90°	√	√	×	×	×	√
		+45°/−45°	√	√	×	×	×	√
Flexural tests	Flat	0°/90°	√	√	√	√	√	√
		+45°/−45°	√	√	√	√	√	√
	On-edge	0°/90°	√	√	√	√	√	√
		+45°/−45°	√	√	√	√	√	√
	Upright	0°/90°	√	√	×	×	×	√
		+45°/−45°	√	√	×	×	×	√

Note: √ denotes successful printing, × means failure printing.

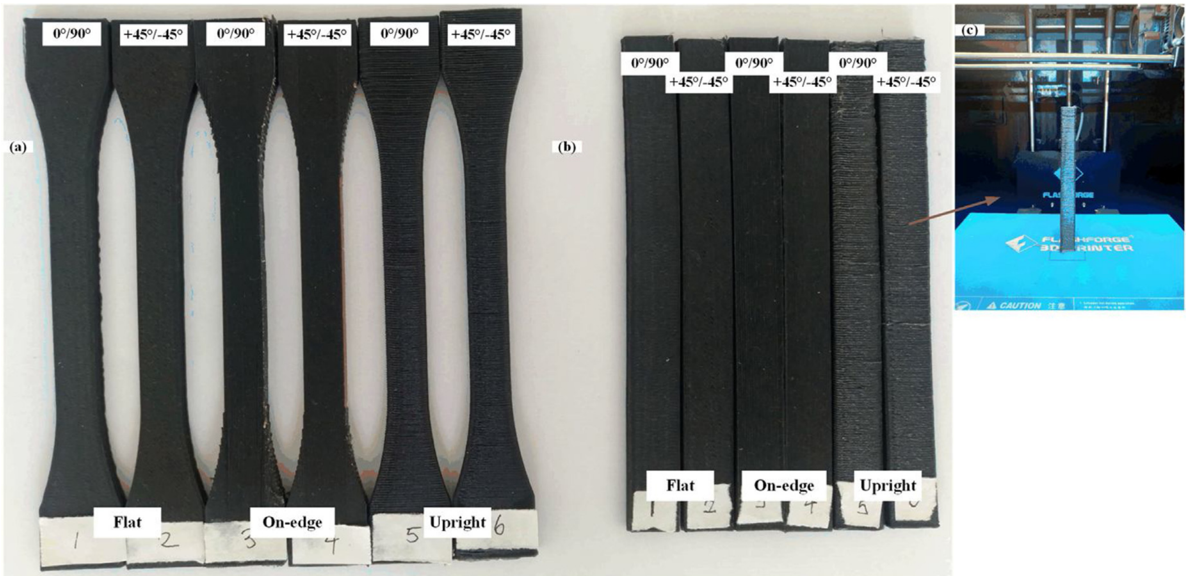

Fig. 4 – 3D printed samples of carbon fiber-based PLA in flat, on-edge and upright orientations: (a) tensile tests, (b) flexural tests, (c) an example of successfully printed sample in upright orientation.

flat orientation are presented in Fig. 3. In particular, Fig. 4 shows that FDM-printed samples of carbon fiber-based PLA in flat, on-edge and upright orientations. It is worth noting that printing in upright orientation was performed without any printing of support structure, as shown in Fig. 4(c). Moreover, in FDM-printing of these PLA composite parts, wood-based PLA sample is the most difficult one to be fabricated. Delamination defect, as illustrated in Fig. 5 usually occurs if the printing variables cannot be controlled properly. A summary of printing formability of virgin PLA and its composites under different printing conditions is given in Table 2. It is observed that ceramic, copper and aluminum-based PLA samples could not be completely printed in upright orientation.

3.2. *Mechanical properties*

Most previous works reported that mechanical properties of FDM-printed polymer components rely on the printing variables, in which printing raster angle and orientation play an important role on mechanical performance of these components. In order to assess the mechanical characteristics of PLA composites, the effects of printing raster angle and build orientation on mechanical properties were analyzed in this study through tensile and flexural tests. The stress–strain curves for tensile and flexural tests are presented in Figs. 6 and 7, respectively. As shown, for PLA and its composites, the stress–strain curves, in the initial stage, follow the Hooke's law (strain proportional to the stress) until ultimate yield stress. After the ultimate yield point, negligible necking continued until the brittle fracture occurred without visible strain hardening. Moreover, from the results, it can be concluded that tensile and flexural properties strongly depend on the variation of raster angle as well as build orientation. For PLA and its composites, the best tensile and flexural properties could be obtained when external loading direction is parallel to the build orientations and raster angles of printed filaments are oriented longitudinally (e.g. the cases in flat and on-edge orientations). On the contrary, the worse tensile and flexural properties could be obtained when the tested specimen are loaded along the build orientation (e.g. the cases in upright orientations) due to weak interlayer bonding.

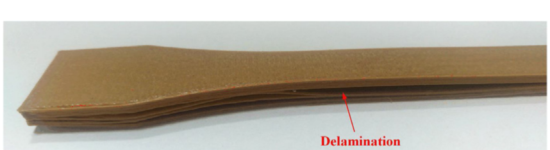

Fig. 5 – Delamination defect in the printing of wood-based PLA.

As for tensile and flexural properties between PLA and its composites with different filler materials, an obvious difference of mechanical behaviors would be witnessed. In order to quantify and facilitate the analysis of tensile and flexural properties, the tensile and flexural modulus, ultimate strength, and strain at break were calculated and summarized in Tables 3 and 4. Results have demonstrated that tensile and flexural properties are very sensitive to the filler materials. Overall, by adding ceramic, copper and aluminum powders into virgin PLA, the tensile and flexural modulus, strength as well as strain at break are still close or even increased compared to that of virgin PLA under different printing orientations and raster angles. The maximum tensile modulus of 1056.31 MPa and flexural modulus of 4621.37 MPa for ceramic-based PLA samples were obtained. While, the second largest tensile strength of 58.28 MPa and the maximum flexural strength of 118.67 MPa were obtained for copper-based PLA samples. As for wood and chopped carbon fiber-based PLA samples, the tensile and flexural modulus and strength are both decreased to some extent. It is evident that there is no obvious improvement on elongation or deflection at break for all PLA composites compared to that of virgin PLA.

Table 3 – Mechanical properties of tensile tests for different PLA composites.

Mechanical properties of tensile tests	Printing orientations	Layer deposition	Materials					
			PLA	PLA+wood	PLA+ceramic	PLA+copper	PLA+aluminum	PLA+carbon fiber
Tensile modulus, MPa	Flat	0°/90°	707.1	656.8	1042.5	1002.6	838.4	596.4
		+45°/−45°	712.2	696.7	1056.3	1016.9	779.5	670.0
	On-edge	0°/90°	901.0	808.1	962.4	883.2	649.7	745.7
		+45°/−45°	800.5	784.1	907.2	836.2	760.9	717.4
	Upright	0°/90°	696.2	645.0	–	–	–	427.1
		+45°/−45°	738.7	673.0	–	–	–	584.3
Tensile strength, MPa	Flat	0°/90°	42.4	29.5	43.2	40.3	40.2	32.8
		+45°/−45°	47.0	33.4	46.3	49.3	42.8	31.6
	On-edge	0°/90°	63.4	35.9	46.5	53.7	46.8	38.2
		+45°/−45°	67.6	38.7	45.0	58.3	51.1	41.3
	Upright	0°/90°	30.5	19.1	–	–	–	16.8
		+45°/−45°	27.8	19.1	–	–	–	20.0
Elongation at break, %	Flat	0°/90°	6%	5%	5%	8%	5%	8%
		+45°/−45°	5%	5%	5%	5%	7%	6%
	On-edge	0°/90°	7%	5%	6%	6%	7%	6%
		+45°/−45°	8%	6%	7%	7%	7%	6%
	Upright	0°/90°	3%	4%	–	–	–	5%
		+45°/−45°	4%	3%	–	–	–	4%

Table 4 – Mechanical properties of flexural tests for different PLA composites.

Mechanical properties of flexural tests	Printing orientations	Layer deposition	Materials					
			PLA	PLA+wood	PLA+ceramic	PLA+copper	PLA+aluminum	PLA+carbon fiber
Flexural modulus, MPa	Flat	0°/90°	2075.2	1696.8	3022.3	2174.0	2492.1	1738.4
		+45°/−45°	2446.4	1749.8	3128.3	2227.0	2470.9	1729.7
	On-edge	0°/90°	2286.8	2704.3	4503.0	3118.9	3207.5	2844.3
		+45°/−45°	2538.4	2651.3	4621.4	3845.1	3275.8	2939.2
	Upright	0°/90°	2605.9	1992.8	–	–	–	1325.7
		+45°/−45°	2478.3	1653.0	–	–	–	1272.6
Flexural strength, MPa	Flat	0°/90°	69.7	40.4	57.8	55.5	62.8	50.3
		+45°/−45°	79.5	52.1	70.1	66.3	64.7	47.6
	On-edge	0°/90°	104.5	70.4	97.2	107.6	91.5	74.2
		+45°/−45°	109.5	71.0	100.1	118.7	97.8	75.6
	Upright	0°/90°	51.9	37.9	–	–	–	30.9
		+45°/−45°	42.4	27.1	–	–	–	25.9
Deflection at break, %	Flat	0°/90°	3%	2%	2%	3%	4%	4%
		+45°/−45°	4%	4%	3%	3%	5%	5%
	On-edge	0°/90°	4%	3%	3%	3%	6%	5%
		+45°/−45°	3%	4%	3%	3%	7%	5%
	Upright	0°/90°	2%	3%	–	–	–	3%
		+45°/−45°	2%	2%	–	–	–	3%

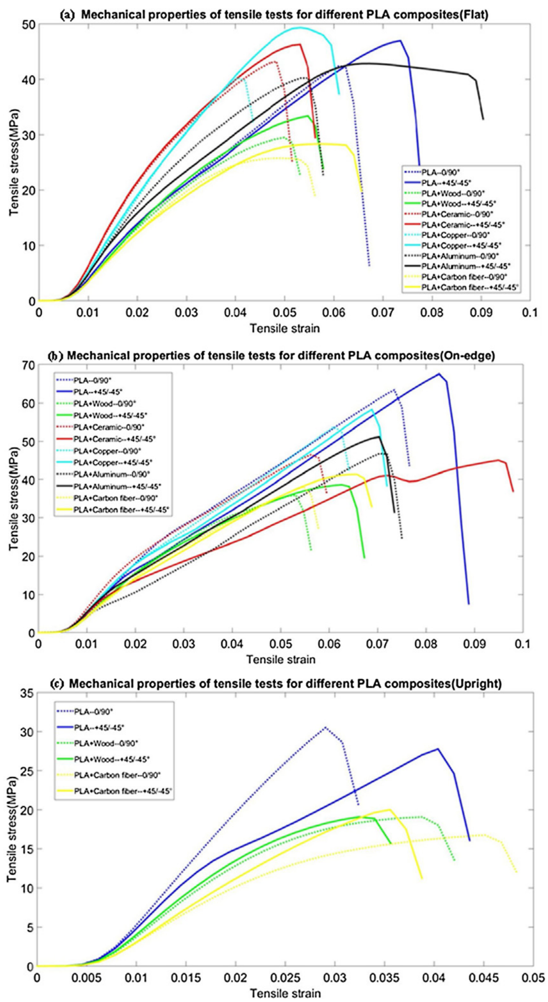

Fig. 6 – Tensile stress–strain curves of different PLA composites with two raster angle combinations under different printing orientations: (a) flat, (b) on-edge, (c) upright.

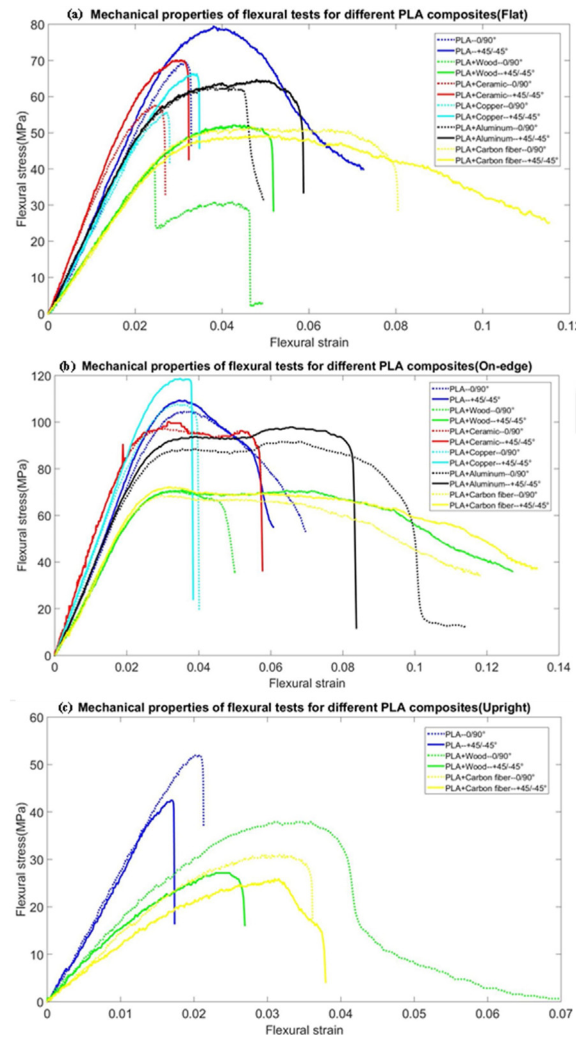

Fig. 7 – Flexural stress–strain curves of different PLA composites with two raster angle combinations under different printing orientations: (a) flat, (b) on-edge, (c) upright.

In addition to the effects of filler materials, mechanical properties are also greatly affected by printing orientations and raster angles. For example, in flat orientation, tensile modulus and tensile strength in layer deposition (+45°/−45°) are higher than those in layer deposition (0°/90°). It is noted that, in most cases, layer deposition (+45°/−45°) can be adopted in flat and on-edge orientations to increase the mechanical properties, expect the case in upright orientation.

3.3. *Fracture morphology*

To further understand the mechanical behaviors of FDM-printed PLA composite parts, an analysis of fracture morphology for all samples was performed. Figs. 8 and 9 show the optical images of fracture morphology of samples after tensile and flexural tests, respectively. It is evident that more dense interlayer structures that are very close to the virgin PLA were observed from images in the cases of ceramic, copper and aluminum-based PLA samples than those of wood and carbon fiber-based PLA ones. In other words, the low mechanical strength of wood and carbon fiber-based PLA samples could be attributed to defects such as high porosity, poor compaction and adhesion between filament layers. Take FDM-printed wood-based PLA samples for instance, the above-mentioned defects are witnessed more obviously from images B1–B6 in Fig. 8 for tensile tests and b1–b6 in Fig. 9 for flexural tests. This would explain the reasons why the mechanical strength of ceramic, copper and aluminum-based PLA composites, no matter in tensile or flexural tests, is higher than that of wood and carbon fiber-based PLA composites.

As discussed previously, raster angle and build orientation also lead to the variation of mechanical behaviors for PLA parts with the same shape. Optical images have demonstrated that in flat and on-edge orientations, low porosity could be noticed for the samples with +45°/−45° raster angles compared to the ones with 0°/90° raster angles. This phenomenon could further confirm the high mechanical strength achieved by samples with +45°/−45° raster angles in most cases of PLA composite parts in Tables 3 and 4. Furthermore, the interlayer structure of samples printed in on-edge orientation usually

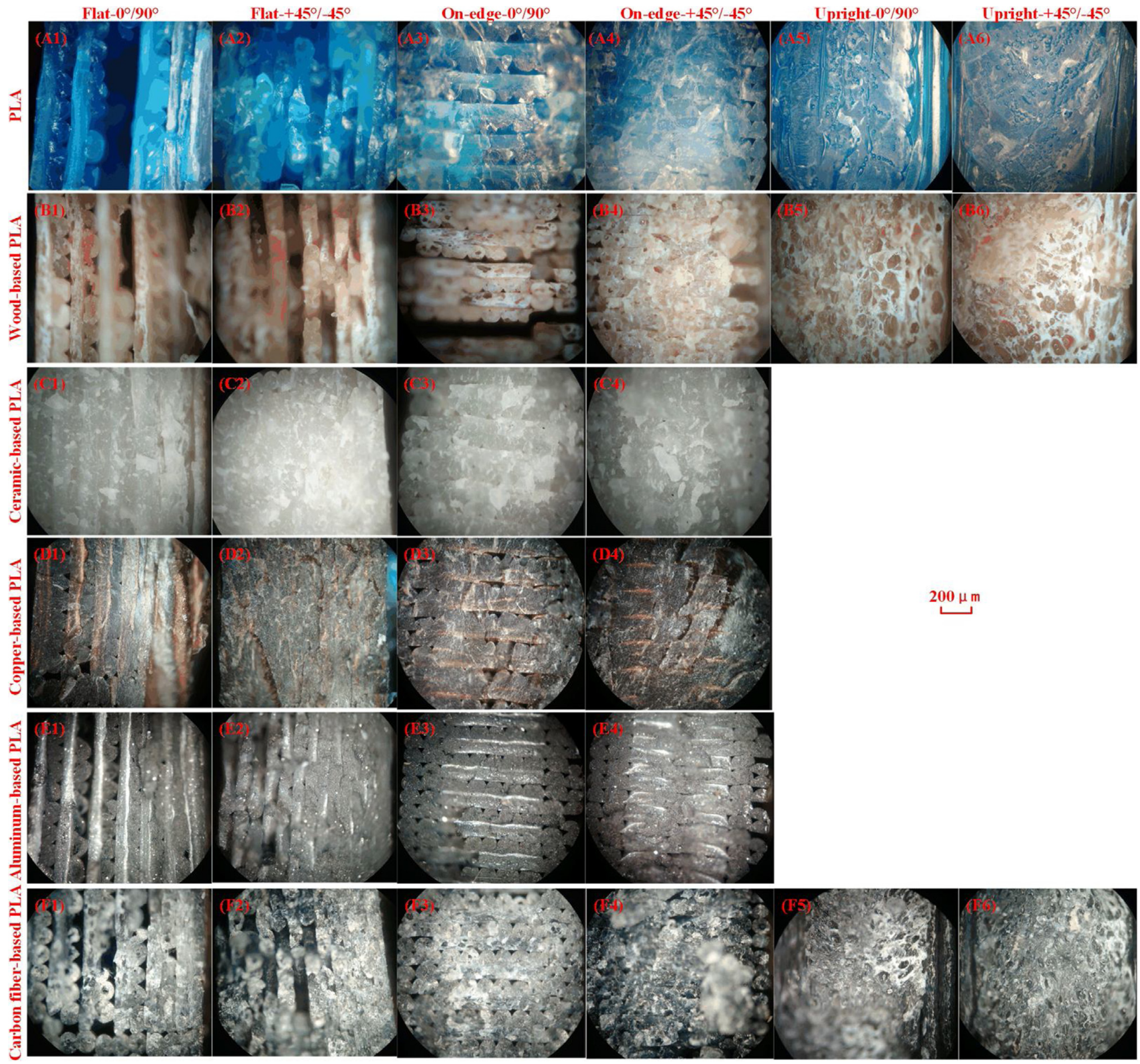

Fig. 8 – Optical images of fracture morphology for all printed samples after tensile tests.

has better compaction and adhesion than the counterparts in flat orientation with the same raster angle, as more layers need to be printed in this scheme but the layer bonding direction is perpendicular to the loading direction, which would carry more loading force. For the samples in upright case, there is no obvious difference in optical images observed between 0°/90° raster angles and +45°/−45° raster angles. However, due to the weak interlayer bonding, the upright samples cannot carry more load, thereby leading to the weakest mechanical strength among the samples in all build orientations.

4. Conclusions

In this paper, the mechanical properties of PLA and its composites have been evaluated taking the effects of important printing variables, i.e. build orientation and raster angle into consideration. The key research findings are summarized as follows:

i) Virgin PLA, wood and carbon fiber-based PLA have better printing formability than the ceramic, copper and aluminum-based PLA in upright orientation.
ii) The similar or even enhanced mechanical properties of FDM-printed ceramic, copper and aluminum-based PLA samples have been obtained compared with virgin PLA. Adding wood and chopped carbon fiber into virgin PLA significantly lower its mechanical properties. Moreover, PLA composite samples that are FDM-printed in on-edge orientation with +45°/−45° raster angles have the highest mechanical strength in most cases. While, all the samples printed along upright orientation have the weakest mechanical strength and modulus due to weak interlayer bonding.

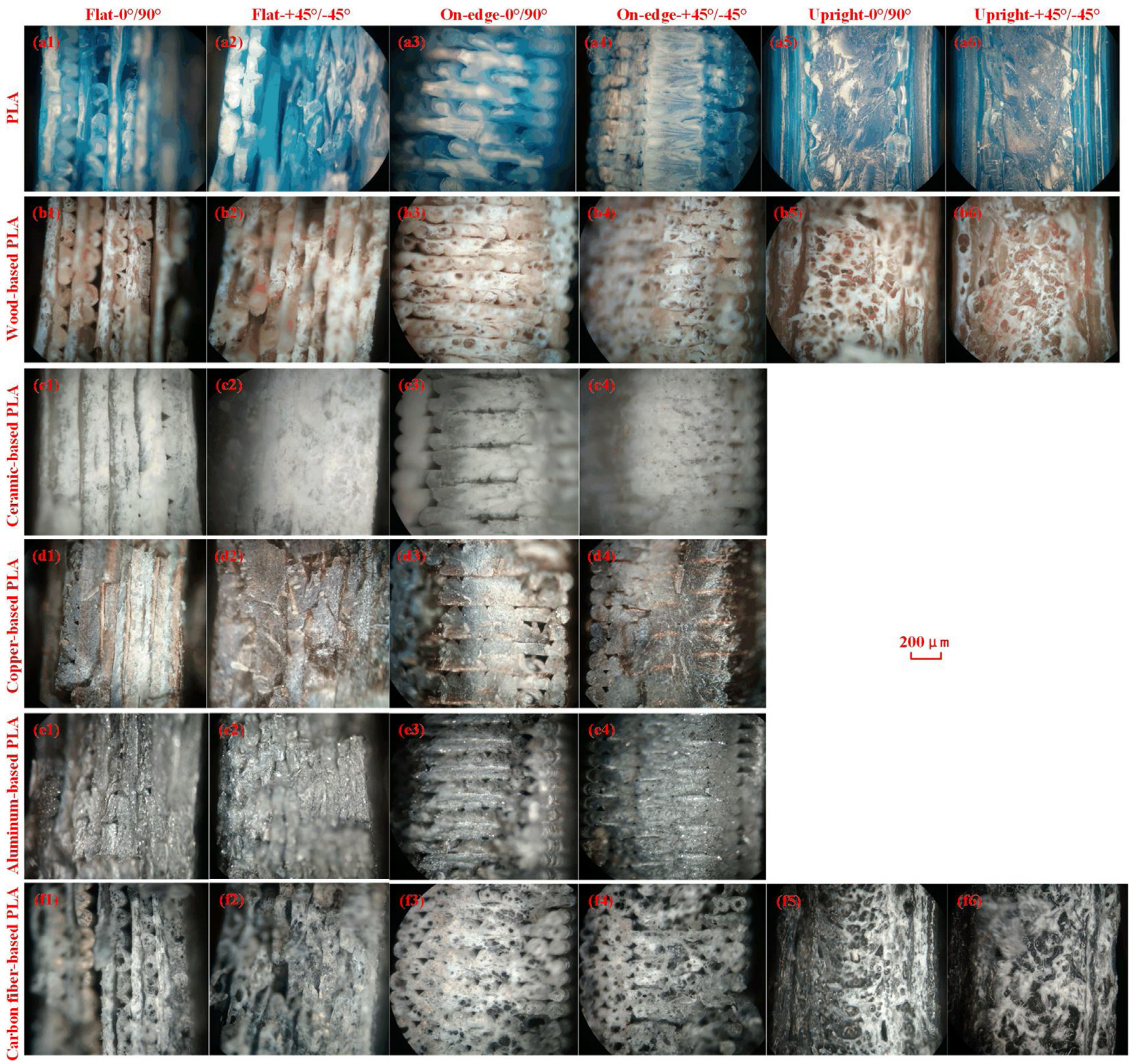

Fig. 9 – Optical images of fracture morphology for all printed samples after flexural tests.

iii) The fracture surfaces for the samples after tensile and flexural tests have been analyzed in detail. The low mechanical properties of wood and carbon fiber-based PLA composite parts would be attributed to defects such as high porosity, poor compaction and adhesion between filament layers, compared to virgin PLA, as well as ceramic, copper and aluminum-based PLA composite samples.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgment

The authors would like to thank the financial support from the Fundamental Research Funds for the Central Universities (WUT:2017IVA017 and 2017III047) for undertaking this work.

REFERENCES

[1] Liu ZG, Wang YQ, Wu BC, Cui CZ, Guo Y, Yan C. A critical review of fused deposition modeling 3D printing technology in manufacturing polylactic acid parts. Int J Adv Manuf Technol 2019;102(9–12):2877–89.
[2] Wang X, Jiang M, Zhou ZW, Gou JH, Hui D. 3D printing of polymer matrix composites: a review and prospective. Compos B Eng 2017;110:442–58.
[3] Mohammed JS. Applications of 3D printing technologies in oceanography. Methods Oceanogr 2016;17:97–117.
[4] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, et al. Design for additive manufacturing: trends,

opportunities, considerations, and constraints. CIRP Ann—Manuf Technol 2016;65:737–60.

[5] Kuznetsov VE, Solonin AN, Urzhumtsev OD, Schilling R, Tavitov AG. Strength of PLA components fabricated with fused deposition technology using a desktop 3D printer as a function of geometrical parameters of the process. Polymers 2018;10(3):313.

[6] Song Y, Li Y, Song W, Yee K, Lee KY, Tagarielli VL. Measurements of the mechanical response of unidirectional 3D-printed PLA. Mater Des 2017;123:154–64.

[7] John RCD, Alejandro H, Espera JR, Chen QY, Rigoberto CA. Mechanical characterization of 3D-printed polymers. Addit Manuf 2018;20:44–67.

[8] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Allison MB, et al. Materials for additive manufacturing. CIRP Ann—Manuf Technol 2017;66:659–81.

[9] Eynde MVD, Puyvelde PV. 3D printing of polylactic acid. In: Advances in polymer science. Berlin, Heidelberg: Springer; 2017, http://dx.doi.org/10.1007/12_2017_28.

[10] Senatov FS, Niaza KV, Stepashkin AA, Kaloshkin SD. Low-cycle fatigue behavior of 3d-printed PLA-based porous scaffolds. Compos B Eng 2016;97:193–200.

[11] Montjovent MO, Mark S, Mathieu L, Scaletta C, Scherberich A, Delabarde C, et al. Human fetal bone cells associated with ceramic reinforced PLA scaffolds for tissue engineering. Bone 2008;42:554–64.

[12] Shipesh RR, Harshit KD. Effect of process parameters on tensile strength of FDM printed PLA part. Rapid Prototyp J 2018;24(8):1317–24.

[13] Mercado-Colmenero Jorge Manuel, Rubio-Paramio Miguel Angel, la Rubia-Garcia Mª Dolores, Lozano-Arjona David, Martin-Doñate Cristina. A numerical and experimental study of the compression uniaxial properties of PLA manufactured with FDM technology based on product specifications. Int J Adv Manuf Technol 2019, http://dx.doi.org/10.1007/s00170-019-03626-0.

[14] uz Zaman Uzair Khaleeq, Boesch Emilien, Siadat Ali, Rivette Mickael, Baqai Aamer Ahmed. Impact of fused deposition modeling (FDM) process parameters on strength of built parts using Taguchi's design of experiments. Int J Adv Manuf Technol 2019;101(5–8):1215–26.

[15] Stoof D, Pickering K, Zhang YJ. Fused deposition modelling of natural fibre/polylactic acid composites. J Compos Sci 2017;1(1):8.

[16] Chaitanya S, Singh I. Ecofriendly treatment of aloe vera fibers for PLA based green composites. Int J Precis Eng Manuf Technol 2018;5(1):143–50.

[17] Ferreira RTL, Amatte IC, Dutra TA, Bürger D. Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers. Compos B Eng 2017;124:88–100.

[18] Blok LG, Longana ML, Yu H, Woods BKS. An investigation into 3D printing of fibre reinforced thermoplastic composites. Addit Manuf 2018;22:176–86.

[19] Tao YB, Wang HL, Li ZL, Li P, Shi SQ. Development and application of wood flour-filled polylactic acid composite filament for 3D printing. Materials 2017;10(4):339.

[20] Lebedev SM, Gefle OS, Amitov ET, Zhuravlev DV, Berchuk DY, Mikutskiy EA. Mechanical properties of PLA-based composites for fused deposition modeling technology. Int J Adv Manuf Technol 2018;97(1-4):1–8.

[21] Ayrilmis N, Kariz M, Kwon JH, Kuzman MK. Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials. Int J Adv Manuf Technol 2019;102(5-8):2195–200.