




Static and dynamic mechanical performance of short Kevlar fiber reinforced composites fabricated via direct ink writing

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ABSTRACT

Additively manufactured polymer composites have advantages over those fabricated traditionally due to their improved design flexibility, short time frame of design-to-manufacturing process and reduced material waste and investment cost. Additive manufacturing of short fiber reinforced thermoplastic composites has been well investigated recently, and their mechanical performance has been well characterized. Additive manufacturing of thermoplastic composites, however, has unresolved, high porosity and low mechanical performance issues. In this study, we investigated the feasibility of using of a customized, vibration-integrated, direct write additive manufacturing setup to fabricate short Kevlar reinforced epoxy composites. Highly viscous composite inks (max. of 6.3% Kevlar fiber) were successfully extruded and 3D-printed on a print bed, at room temperature. The mechanical performance of the printed composites was examined and compared to that of unreinforced base ink specimens by performing static and dynamic 3-point bending experiments. It was observed that additively manufactured, thermoset-based, short Kevlar fiber reinforced composites possess the mechanical performance surpassing the previously reported short Kevlar fiber reinforced thermoplastic composites and near to that of continuous fiber reinforced composites. Considering their high mechanical performance in addition to low weight, and high ductility, these composite materials have a great potential to find novel structural applications in the near future.

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Introduction

Additive manufacturing (AM) or 3D printing is a fast-growing manufacturing technology which allows fabrication of complex freeform geometries via layer by layer deposition. Therefore, components can be redesigned with this manufacturability freedom and their weights can be minimized without sacrificing the function of the component. As a result, AM has found numerous applications in which weight reduction as well as manufacturing time and cost minimization are desired.

Polymers are the most common AM feedstock materials due to their low cost, lightweight and ease of processing. Polymers, however, have low material strength compared to other engineering materials (metals and ceramics) and are therefore not suitable for structural applications demanding higher mechanical performance. To enhance the mechanical performance of polymers, different types of reinforcements in fiber form (glass, carbon, natural etc.) are added in polymers creating fiber reinforced composites [1–5]. Continuous fibers are preferred to attain the maximum strength enhancement in these composites. However, using these fibers in short forms (milled or chopped) is advantageous compared to continuous (long) fibers since the material feedstocks can be prepared by only simple mixing of the fiber and the matrix materials, significantly simplifying the manufacturing process. Because of its versatile properties, additive manufacturing of short fiber reinforced composites has been used to fabricate lightweight components with superior thermal transport properties [6, 7] and large-scale parts using big area additive manufacturing (BAAM) [8–10]. Advantages, benefits and mechanical performance of additively manufactured short and continuous fiber composites can be found in the review studies [10–13] published recently.

Fused filament fabrication (FFF) is the major technology to additively fabricate short fiber reinforced thermoplastic composites. This method is based on melting of the thermoplastic matrix in a heating stage and its solidification upon the deposition on the print bed. FFF technology has been successfully applied for the fabrication of short carbon [14–16], glass [17, 18], natural [13, 19] and Kevlar [20] fiber reinforced thermoplastic composites, and improved mechanical performance compared to the neat polymer has been observed [16, 21, 22]. FFF process of fiber reinforced

thermoplastic composites commonly suffers from the drawbacks such as large porosities and low interfacial strength between printed layers [23–26]. In addition, thermoplastic matrix used in these composites usually has weak adhesion to the fiber reinforcements and has low service temperatures. Recently developed direct writing method (DW) is a viable method to fabricate thermoset-based, short fiber reinforced composites. In this technique, paste-like composite inks can be extruded into 3D shapes by altering the fluid viscosity and yield strength via rheology modifiers, such as nanoclay or fumed silica [15, 27, 28].

Among all the major fiber reinforcements (carbon, glass, natural and Kevlar), Kevlar fibers stand out as they uniquely combine low density, high strength and high ductility [29, 30]. Additive manufacturing of short Kevlar fiber-reinforced composites is difficult as these fibers cannot be broken down or milled, unlike glass or carbon fibers, due to their high flexibility. Recently, we reported additive manufacturing of short Kevlar reinforced thermoset composites for the first time [31] where a laser cutting was implemented to prepare short Kevlar fibers. This study evidenced the improvement of strength, modulus as well as the elongation at break, using the Kevlar fibers validating the unique mechanical performance of these composite systems. Kevlar volume fraction was found to be limited to only 3.5% by volume exceeding which resulted in nozzle clogging and difficulty in extrusion. Enhancing the fiber volume fraction is essential to maximize the mechanical performance of Kevlar reinforced composites.

In this study, we utilize a vibration integrated extrusion system developed recently [32] to fabricate Kevlar reinforced epoxy thermoset composites eliminating the nozzle clogging problems and maximizing the volume fraction of Kevlar reinforcement. In addition to extending the fiber volume fraction limit, this study investigates the fatigue performance of additively fabricated short Kevlar fiber reinforced composites for the first time. Although static performance of additively manufactured composites is well characterized, mechanical performance under dynamic loading is not well known for these materials due to the extended duration (weeks) of these experiments. This study also establishes the link between the microstructure and the fracture behavior of the additively manufactured composites explaining their mechanical performance. This study paves

the way for developing additively manufactured, high-strength and ductile Kevlar reinforced thermoset composites which are resistant to both static and dynamic loading. Development of these materials can make them lightweight alternatives to the engineering materials fabricated via traditional manufacturing technologies.

Materials and methods

Preparation of short Kevlar fibers by laser cutting process

The process of cutting continuous, unidirectional Kevlar fibers (Uniweb, ACP Composites) with 15-micron diameter was carried out by using a laser cutter system (Universal Laser Systems VLS 2.30). The cut fibers were then sieved to avoid uncut parts of the Kevlar sheet and remove the unseparated fiber bundles. After the laser cutting process, we investigated the edges of the cut fibers under an optical microscope and observed that the laser cutting process created nearly 100 microns deep burned regions from the fiber edge at each side. Therefore, we selected the length of the fibers 4 folds (800 microns) larger than the total burnt length to minimize the burning effect of the laser at the cut regions. JOEL JSM-6010 PLUS/LA scanning electron microscope (SEM) was used to observe the morphology of the Kevlar fibers after the cutting and sieving processes were completed. In order to minimize charging or organic Kevlar fibers, prior to SEM imaging, a gold layer of (1–2 nm) thickness was sputter coated on the surface of the fibers under vacuum (~ 50 millitorr) for 30 s using the Denton DESK V sputter coater instrument. Fibers were consistently cut to the desired length using the described method (Fig. 1a).

In this figure, the separated, single fibers as well as the fiber bundles in which fibers are not completely separated can also be observed. Figure 1b shows close-up view of the Kevlar fibers.

Printing ink preparation procedure

EPON 826 epoxy (Hexion) was selected as the thermoset resin in this study. This epoxy has the molecular weight of 364 mol/g per the manufacturer specifications. The glass transition temperature of the viscous pastes prepared from this resin is 132 °C as reported previously [15]. The preparation of the composite ink material started by adding Garamite-7305 nanoclay from BYK additives into epoxy resin adjusting the rheology of the ink. Following this step, cut Kevlar fibers were added into the epoxy–nanoclay mixture systematically until reaching the maximum volume of Kevlar fibers. As the Kevlar fiber content was increased in the composite ink mixture, the amount of nanoclay was gradually reduced to keep the viscosity at a similar level since the Kevlar fiber addition also increased the viscosity of the ink. The nanoclay content corresponding to the Kevlar fiber amounts of 0% (base ink), 3.5% and 6.3% was obtained as 10%, 7% and 5.5%, respectively. Finally, 5% (ppm of epoxy) latent curing agent from Sigma-Aldrich (1-Ethyl-3-methylimidazolium dicyanamide) was added to the mixture. Planetary shear mixer (Thinky ARE-310) was used for 3 min at a speed of 2000 rpm to obtain homogeneous ink mixture. Schematic of the 3D printing procedure is given in Fig. 2.

Fiber content in the fabricated ink was determined using the mass fractions and the densities of each constituent. Mass fractions (parts per hundred) are all known during ink preparation process relative to the epoxy mass. Densities of epoxy, nanoclay, Kevlar fiber and curing agents are 1.16 g/cc³, 1.98 g/cc³,

Figure 1 SEM image of Kevlar fibers used in this study. **a** Low magnification SEM image showing the single and bundled fibers, **b** high magnification SEM image of single fibers.

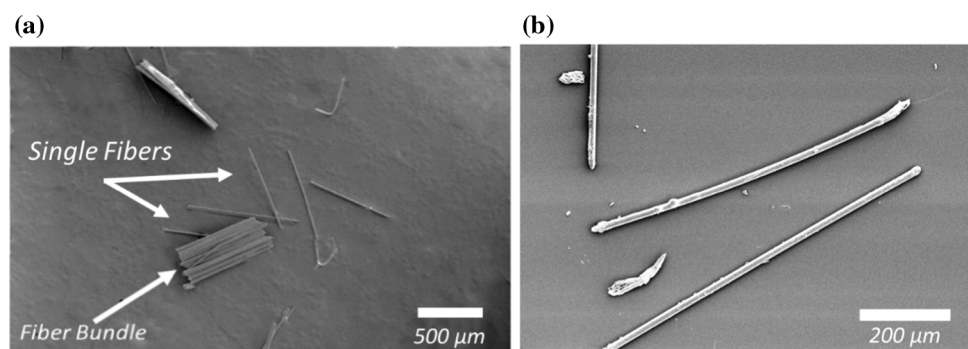
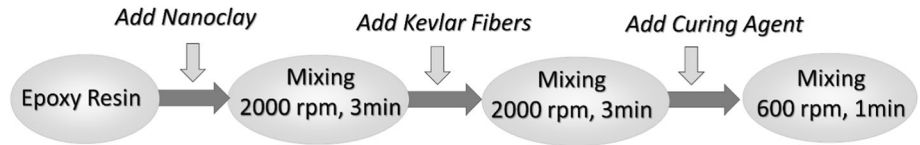


Figure 2 Schematic of the 3D printing ink preparation procedure.



1.44 g/cc³ and 1.06 g/cc³, respectively. Using these density values and the mass fractions, the volume fraction of each constituent was calculated.

Rheological characterization

Rheological properties of all samples were characterized using a Discovery HR-2 Rheometer (TA Instruments, New Castle, DE). Testing geometry was set up on an 8 mm flat plate with a gap height of 500 μm. Prior to each test, samples were subjected to a 1-min conditioning phase at a constant shear rate of 0.1 s⁻¹ followed by a 2-min rest period for reformation of the ink structure similar to the previous study [14]. Viscosity of the samples was measured as a function of shear rate by sweeping through controlled shear rates (0.004–19 s⁻¹), and storage and loss moduli were measured as a function of shear stress in a similar fashion (10–10000 Pa).

3D printing of the Kevlar ink using direct write method

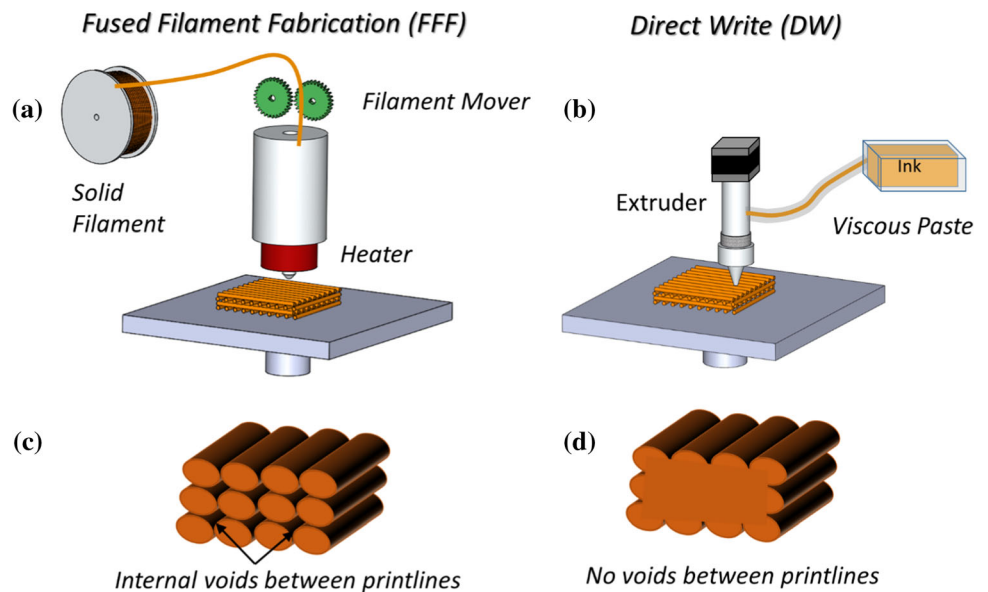
Figure 3b shows the schematic of the direct write (DW) 3D printing technique used in this study in comparison with the conventional fused filament

fabrication (FFF) technique (Fig. 3a). Figure 3c and d represents the unavoidable internal voids observed in the FFF process and the lack of these voids in the DW fabricated specimens, respectively.

DW extrusion of the prepared ink was performed through 2 mm nozzle with a printing speed of 40 mm/s using a customized displacement controlled direct write extrusion setup. This system allowed the extrusion of highly viscous composite inks loaded with high volume of fiber reinforcement as described recently [32]. Nozzle clogging at high fiber loadings was resolved by integrated vibration motors which shake the nozzle and avoid clogging with accumulated fibers. Details of the vibration integrated extrusion system can be found here [32].

The build plate of the 3D printer was covered with a Teflon sheet before the printing process in order to prevent adhesion between the printed specimens and the build plate and for easy removal of the cured specimens. The printing process was performed at room temperature, and the curing process of the printed specimens was carried out inside an oven for 15 h at 100 °C. Specimens were 3D printed in rectangular prism shapes (73 × 13 × 3.2 mm) according to the flexural test standards explained in “Mechanical characterization” section. Images of the printed

Figure 3 Extrusion-based 3D printing, **a** conventional FFF 3D printing, **b** direct write 3D printing, **c** FFF sample cross section showing internal voids and **d** DW sample cross section.



specimens before and after the curing process is performed are shown in Fig. 4.

Mechanical characterization

Mechanical characterization of the 3D printed specimens was assessed by performing 3-point bending tests for both static and dynamic (fatigue) loading. Sample geometries and test setup defined in ASTM D7264/D7264M-07 standard (standard test method for flexural properties of polymer matrix composite materials) were used to run both test types [33]. ISO 13003:2003 (Fiber-reinforced plastics—determination of fatigue properties under cyclic loading conditions) [34] and ASTM STP 588 (manual on statistical planning and analysis for fatigue experiments) [35] were used to determine the test parameters for the fatigue experiments.

Additionally, span-to-thickness ratio was kept to be 16:1 for all created samples, and to ensure the validity of this ratio, the span length was tuned for each specimen before executing the tests. Schematic of the flexural test setup and the actual test frame which is used in the experiments are shown in Fig. 5a, b.

Figure 5c depicts the schematic for the fatigue test workflow which was performed on a servo-hydraulic test machine (Labiotech, Ankara, Turkey) which is equipped with 10 kN capacity load Cell (GTM, SN: 65393). UTEST Material Testing software was used to control the mechanical testing system. The system was tested under load control, applying a sinusoidal wave load with a frequency of 7 Hz at a load ratio, R (minimum load/maximum load), of 0.1.

The cyclic stresses are normally well below the yield strength of the material. Therefore, the level of the maximum load for the first test was taken as 50%

of the average yield load for each group and the tests were terminated after exceeding the 2 million cycles. If specimen was failed before the runout cycle, the load was decreased until the desired run out cycle was achieved for the next specimens. If specimen did not fail in 2 million cycles, then the load level was increased gradually, and the dynamic testing was repeated. This process (testing/load level increase) continued until the material failure was reached as described by the ASTM test protocol [35]. The material failure was defined as the point when the load on the specimen dropped below the load level which is 25% of the initial load value. At least 4 samples were tested to quantify the standard deviation and validate the repeatability of the mechanical tests.

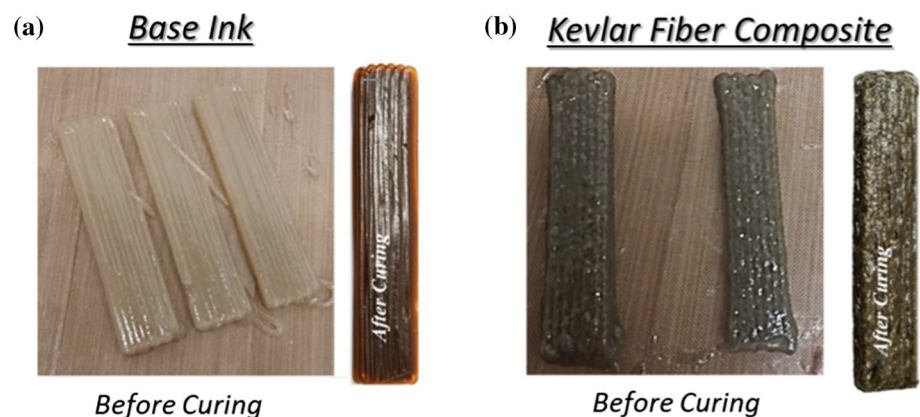
For all mechanical test measurements, Student's t test statistical analysis was performed to quantify the statistical significance between the results. Significance was defined as the low p value ($p < 0.05$) according to the t tests.

Results and discussion

Rheology of the 3D printed composites

Viscosity measurements on the printing inks are given in Fig. 6. This figure indicates that the neat epoxy showed the minimum viscosity having the range of 15–38 Pa throughout the entire shear rate spectrum. The addition of the nanoclay and Kevlar fibers was both found to be very effective in terms of modifying rheology and enhancing the viscosity nearly 3 orders of magnitude as shown in this figure. Maximum viscosity was observed in highly loaded Kevlar fibers (6.3%) in which medium amount (7%) of nanoclay was used to optimize the viscosity. All

Figure 4 Specimens fabricated via direct ink writing, **a** 3D printed base ink specimens, **b** 3D printed, fiber reinforced Kevlar specimens.



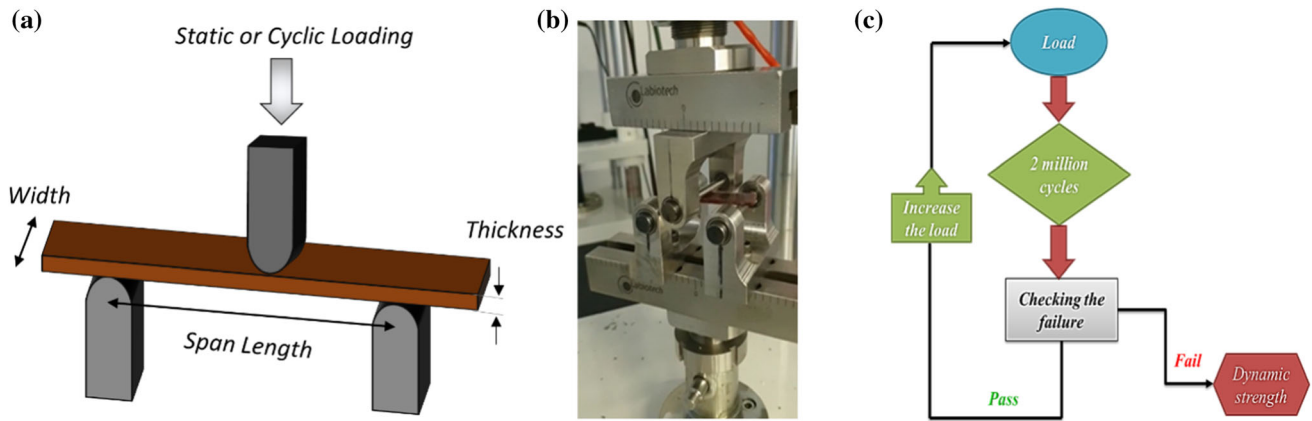


Figure 5 Images describing the 3-point bending test procedure, **a** schematic of the test setup, **b** photo of the experimental test fixture, **c** the workflow of fatigue characterization.

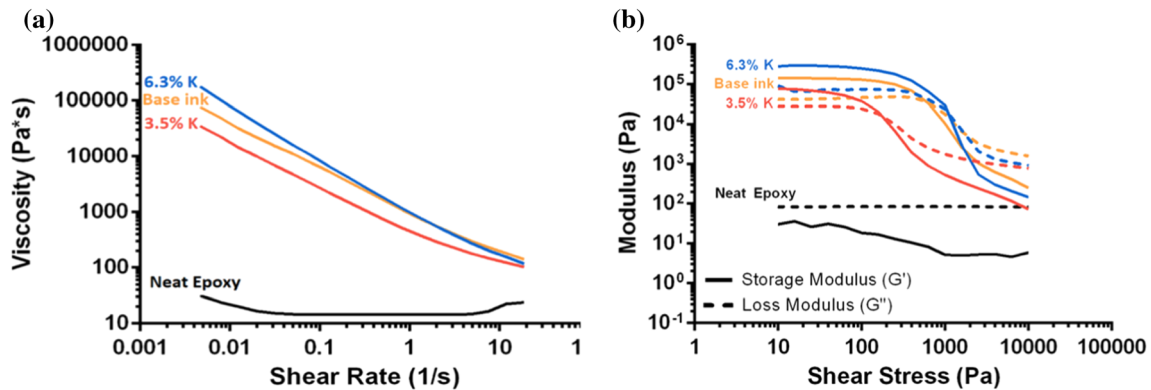


Figure 6 Rheology measurement of the inks used in this study. **a** Viscosity measurements, **b** storage and loss modulus of the inks.

inks showed different levels of shear thinning behavior. Shear thinning was minimal in the neat epoxy compared to all other composite inks (epoxy/nanoclay or epoxy/nanoclay/Kevlar) which showed significant level of shear thinning (nearly 3 orders of magnitude). As described previously [14], shear thinning is a desired property used in direct ink writing process in which viscous inks undergo high level of shear within extrusion nozzles and transform from highly viscous solid to low-viscosity liquid state. As the material is extruded, it retains its shape transforming back to viscous, solid state.

Plots of storage (G') and loss (G'') moduli are shown in Fig. 6b. The neat epoxy resin samples exhibited a loss modulus of approximately 85 Pa which was greater than its storage modulus independent of shear stress indicating its liquid-like behavior. The addition of nanoclay and Kevlar fibers significantly increased the moduli of all of the fabricated composite inks compared to the neat epoxy.

The highly loaded Kevlar fibers (6.3%) exhibited the highest storage modulus that plateaued around 300 kPa with a shear yield stress of approximately 1000 Pa indicating the behavior switch from solid-like to liquid-like. The lower loaded Kevlar fibers (3.5%) and base epoxy exhibited lower shear yield stresses of approximately 160 Pa and 630 Pa, respectively.

Mechanical performance of the Kevlar reinforced composites

Static flexural properties

Static flexural strength and static flexural modulus results of the additively fabricated Kevlar fiber reinforced composites at different fiber volume fractions (0%, 3.5% and 6.3%) are given in Fig. 7a, and b, respectively. Both flexural strength and flexural modulus showed gradual increase as the fiber content increased in the composite. Maximum strength and

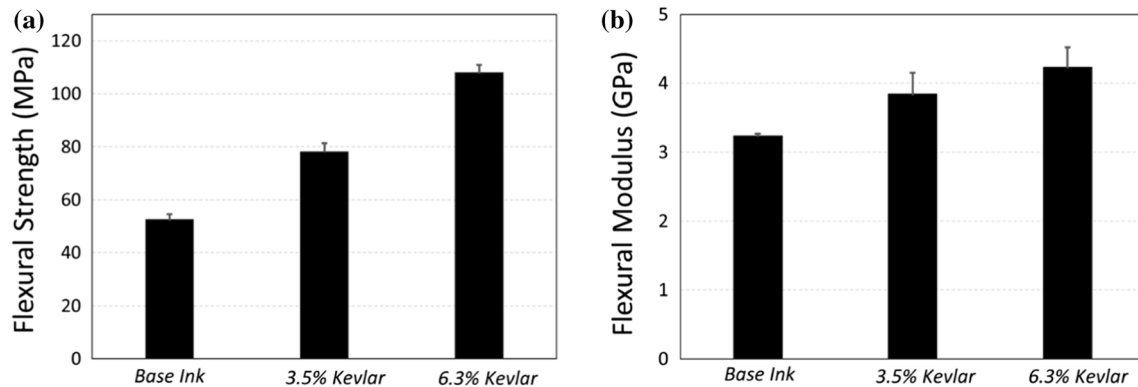


Figure 7 Mechanical properties of additively fabricated, Kevlar-fiber reinforced composites as a function of fiber loading levels, **a** flexure strength and **b** flexural modulus variation.

of 108 ± 13.37 MPa was achieved for the highest Kevlar volume content of 6.3% which marks 105% increase compared to the unfilled base ink as shown in Fig. 7a. Similarly, maximum flexural modulus was achieved to be 4.23 ± 0.29 GPa for the flexural modulus at maximum Kevlar content marking 39% increase in modulus compared to that of the base ink.

Furthermore, flexural strain at break measurements of 6.3% Kevlar fibers exceeded that of the base ink by 96% due to the higher ductility of Kevlar fibers as shown in Fig. 8. Unlike the stiffer glass and carbon fibers, Kevlar fibers significantly enhance the ductility of the epoxy/nanoclay composite which can lead to unique applications of 3D-printed composites such as those requiring high energy absorption, impact resistance and high toughness.

SEM images of the fractural cross sections for the composite specimens reinforced with 6.3% Kevlar are shown in Fig. 9. These images display that Kevlar fibers have homogeneous distribution within the

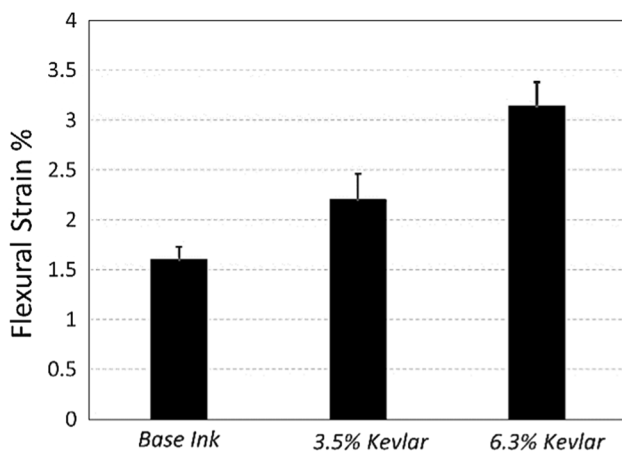


Figure 8 Strain variation as a function of fiber loading levels.

composite, and they are well-aligned in the printing direction indicated by the perpendicular orientation along the fracture surface.

Highly cross-linked thermoset polymers such as epoxy used in this study show brittle failure behavior compared to thermoplastic and elastomer polymers. This brittle nature of thermoset polymers is not preferred as it leads to sudden and unpredictable material failure. As shown in Fig. 9, it is clearly shown that Kevlar fibers demonstrate deformable, ductile behavior (showing bending/kinking) which can explain the dramatic enhancement in failure strain of the Kevlar fiber reinforced composites. The SEM images also demonstrate that the direct write printing leads to strong adhesion between the print layers in contrast to the FFF process, since the different print layers are not distinguishable in these images. High porosity, however, is visible in terms of different sizes of voids which will be further evaluated in the next section.

Table 1 summarizes the static mechanical testing results for the short Kevlar reinforced epoxy composites. In the table, previously reported flexure test results for Kevlar/ABS [20] and Kevlar/Nylon [24] thermoplastic composites are also given. The comparison indicates that flexural strength and modulus are higher than the short Kevlar fiber reinforced ABS studied previously. However, it must be noted that, in this study, the printing was performed in two orientation (0/90) which may lower the strength and modulus in the longitudinal direction. Comparison of our results with additively manufactured, continuous Kevlar reinforced Nylon composites shows that continuous Kevlar leads to slightly higher strength and modulus enhancement compared to short

Figure 9 SEM images of the fractured surface of Kevlar reinforced composites, **a** low magnification SEM image and **b** high magnification SEM image.

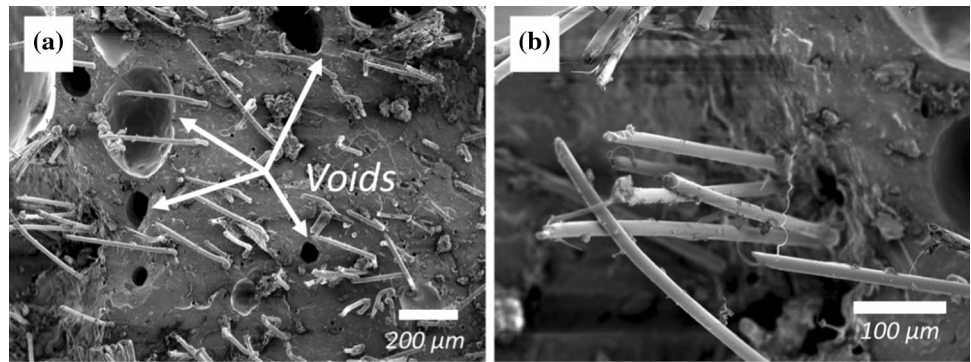


Table 1 Mechanical performance comparison of Kevlar fibers in both thermoplastic and thermoset matrices

Sample name	Fiber type	Print direction	Fiber volume fraction	Flexural strength (Mpa)	Flexural modulus (GPa)	Flexural strain (%)
Base ink (this Study)	–	0°	–	52.63 ± 1.94	3.24 ± 0.03	1.18 ± 0.02
Kevlar/epoxy (this study)	Short	0°	3.5	78.30 ± 1.38	3.84 ± 0.31	0.71 ± 0.03
Kevlar/epoxy (this study)	Short	0°	6.3	108 ± 13.37	4.23 ± 0.29	0.83 ± 0.03
Kevlar/ABS [20]	Short	0°/90°	4.42	45.50 ± 0.66	1.62 ± 0.04	N/A
Kevlar/Nylon [24]	Continuous	0°	10	125.80 ± 3.27	6.65 ± 0.23	N/A

Kevlar/epoxy composites investigated in our study. Considering the much lower volume of Kevlar fibers (6.3%) compared to the continuous Kevlar fiber reinforced composites (10%), and the much smaller fiber length (~ 800 microns), it is remarkable to achieve comparable mechanical properties. This unprecedented mechanical performance of additively manufactured short Kevlar fiber reinforcement might be due to the strong adhesion and wetting between the short Kevlar fibers and the epoxy matrix. In addition, although porosity is present, interlayer porosity is not shown in the fabricated samples as assessed by the SEM images shown above which may play a role in enhancement of static mechanical performance of these composites.

Dynamic flexural properties

To investigate fatigue strength of short Kevlar fiber-reinforced composites, rectangular flexure test specimens were prepared similar to those used for static flexural tests. Figure 10a shows the fatigue strength measurements in terms of number of cycles (S–N curve), and Fig. 10b represents the median fatigue strength measured at 2 million cycle for each set.

It was expected that the highest fatigue strength would be obtained from the reinforced specimens that have the largest content of Kevlar fibers similar to what was observed in static flexural tests. However, it was seen that the highest recorded fatigue strength values were obtained in the 3.5% of Kevlar fibers samples, where a notable improvement was observed for this set compared to the other sets. Standard deviation shown in Fig. 10b indicates that the increase in fatigue strength in 3.5% Kevlar fiber reinforced composite compared to the base ink and the decrease in this strength as more fibers (6.3%) were added into the composite were statistically significant as indicated with the low *p* values: *p* = 0.024 and *p* = 0.029 for the two comparisons, respectively. Compared to the base ink, 3.5% Kevlar reinforced specimens showed 43% increase in fatigue strength. Increasing the fiber content to 6.3% resulted in 15% decrease in the strength compared to the 3.5% Kevlar reinforced composites.

These measurements revealed that the dynamic (fatigue) strength of the composites reinforced with the highest level (6.3%) of Kevlar fibers is weaker than that of the composites reinforced with Kevlar fibers at the medium volume level (3.5%) in this

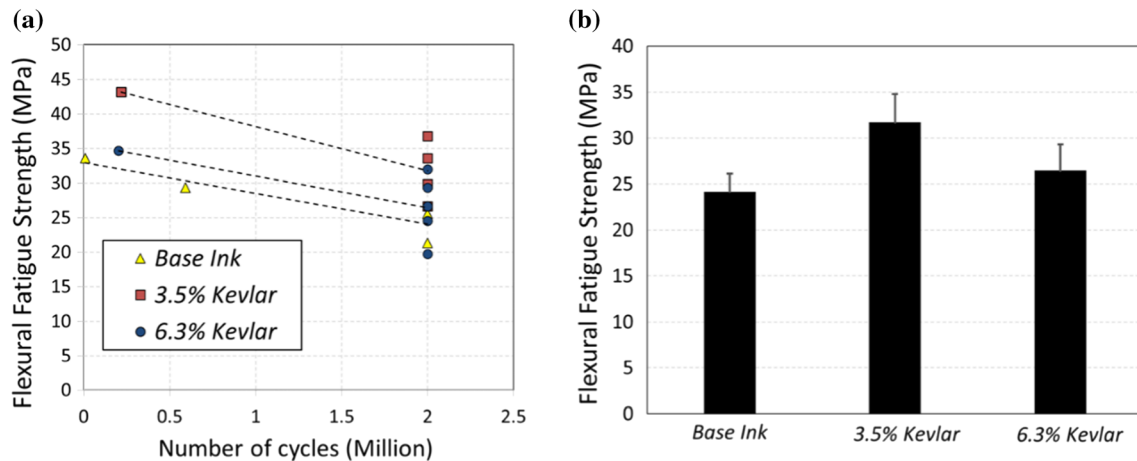


Figure 10 Dynamic flexural strength of additively manufactured composites as a function of number of load cycles. **a** *S–N* curve, **b** bar graph showing the flexural fatigue strength.

study. To understand this peculiar behavior, the transverse surfaces (normal to the printing direction) of the composites were imaged via optical microscopy as shown in Fig. 11. These images show 3 different sections of the polished cross-sectional surfaces of each set (base ink, 3.5% Kevlar and 6.3% Kevlar). These images indicate that as the Kevlar fiber volume is enhanced, porosity is enhanced as well. Figure 11g, h shows that increase in porosity is significant at the high (6.3%) Kevlar concentration.

Image analysis was conducted on the images in Fig. 11 quantifying the porosity. The porosity measurement values performed on the specimens used for the dynamic flexure testing are provided in Table 2. According to this table, porosity increases from 1.39 to 2.05% and finally 12.04% as the Kevlar volume fraction was enhanced from 0 to 3.5% and 6.3%. Therefore, the loss of the fatigue strength at highly loaded Kevlar composites might be explained by the increase in the porosity in these specimens.

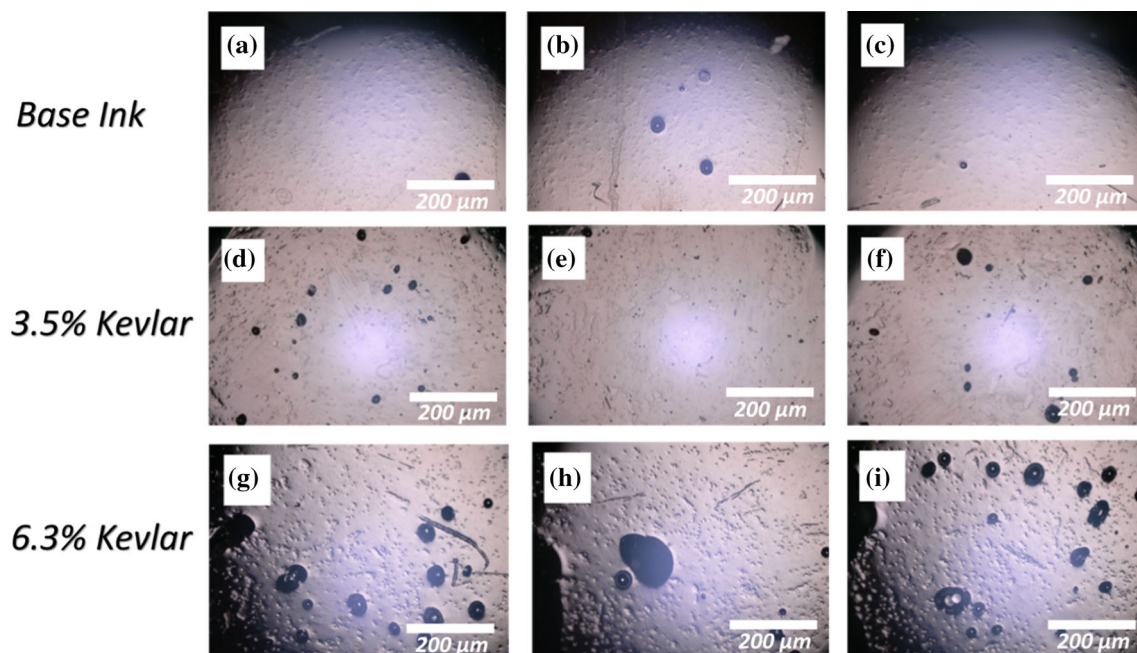


Figure 11 Optical microscope images of the dynamic fractured surface of Kevlar reinforced composites in this study. **a–c** Base ink sample, **d–f** composite samples reinforced with 3.3% Kevlar fibers

and **g–i** composite sample reinforced with 6.3% Kevlar fibers. Scale bars in the bottom right corner are the same for each image and equal to 0.5 mm.

Table 2 Static and fatigue flexural strength and the porosity of additively manufactured composites

Sample name	STATIC flexural strength (MPa)	FATIGUE flexural strength (MPa)	Porosity % in the fracture surface (%)
Base ink	52.63 ± 1.94	3.24 ± 0.13	1.39
Kevlar 3.5%	78.30 ± 1.38	3.84 ± 0.31	2.05
Kevlar 6.3%	108 ± 13.37	4.23 ± 0.29	12.04

These pores most likely acted as crack initiation sites and resulted in premature failure in cyclic loading. In static testing however, the high strength of Kevlar reinforcement surpassed the adverse effects of these voids on the flexural strength, and therefore, static strength continued increasing as more fibers were added within the composite as summarized in Table 2. Therefore, fatigue strength was found to be more prone to the detrimental effects of porosity in this study. Similar behavior was also reported in the previous studies on different material systems [36, 37].

Conclusion

In this study, we examined additive manufacturing of short Kevlar fiber reinforced thermoset composites. Vibration-integrated, direct write additive manufacturing methodology was utilized to fabricate Kevlar reinforced printing inks. Composite inks were fabricated by laser cutting of continuous fibers and mixing laser cut short fibers with epoxy and rheology modifying nanoclay. A custom-made direct write additive manufacturing setup allowed us to achieve the highest volume (6.3%) of Kevlar reinforcement within thermoset composites up to date. Static and dynamic mechanical properties of these composites were characterized by performing flexure tests. Enhancement in flexural strength, flexural modulus and failure strain was obtained in Kevlar reinforced specimens compared to the base ink structure. Static flexural strength and modulus of 108 ± 13.37 MPa and 4.23 ± 0.29 GPa were attained for 6.3% Kevlar fiber reinforced composites, respectively. Dynamic test results showed that cyclic loading significantly reduced the flexural strength of the additively manufactured samples. In addition, it was observed that addition of 3.5% Kevlar fibers enhanced the fatigue strength, but further addition of fibers to 6.3% resulted in reduction in fatigue strength. The lowered strength of 6.3% of Kevlar fibers samples might be

due to the presence of higher defect density and porosity in these samples. The porosity is a result of void formation during the high shear mixing in air and the manual transfer of the composite ink mix from the mixing cup to the extrusion barrel. To eliminate the porosity and to further enhance the mechanical properties of the additively manufactured composites, shear mixing under vacuum and the automated transfer of the mixed feedstock into the barrel must be performed. These concepts must be investigated in the future studies. Therefore, the future efforts are needed to further enhance the Kevlar loading and reduce the porosity to maximize both the static and dynamic mechanical properties of additively manufactured, Kevlar reinforced composites. In addition, the manufacturing process needs enhancement to obtain better separation of the Kevlar bundles which will further increase the mechanical performance and help achieve the use of full reinforcement potential of the short Kevlar fibers. It must be noted that the mechanical tests presented in this study are performed along the longitudinal direction where the Kevlar fibers are aligned along the test direction. If the testing is performed in other directions, the mechanical strength of the composite will be lowered as the Kevlar fibers will carry less load in this case compared to the one performed in the longitudinal direction.

The true benefit of additive manufacturing can be revealed as it is applied on the manufacturing of topology optimized components. Therefore, the future work should be devoted for the redesign of the existing components in such a way that the component mass is redistributed or removed to minimize the weight or maximize the functionality via topology optimization tools. This optimized geometry can then be fabricated via additive manufacturing leading to the significant improvement of the redesigned part compared to the original design. Future work should also be dedicated to fabricate functional parts for the practical applications of the additively

manufactured Kevlar composites. Potential applications of these composites include topology optimized, lightweight components with weight savings and special applications requiring high strength and ductility such as customized armor systems which can be 3D printed to design and fit the body of different individuals or defense systems.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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