STRAIN RATE EFFECT AND MICROSCOPIC BEHAVIOR ANALYSIS OF SHORT-CUT CARBON FIBER REINFORCED COMPOSITES

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ABSTRACT

In the present paper, strain rate sensitivity has been studied for the 3D-printed short-cut carbon fiber reinforced polylactic acid composite (CF/PLA). Composite specimens have been fabricated through Fused Deposition Modeling (FDM) additive manufacturing (AM) technology and were tested subjected different tensile loading rates. Additionally, a morphological analysis was conducted using scanning electron microscopy (SEM) on the fracture surface of the tested specimens. Initial attention focused on assessing the basic mechanical property of the CF/PLA, that is to study the basic mechanical properties of composite materials, it has been shown that the CF/PLA composites exhibit a rate-sensitivity, with the tensile strength increased slightly from quasi-static to dynamic loading rates. In addition, the SEM observations of the tensile tested pieces at different rates have been obtained. It has been found that the tensile section corresponding to the low loading rate is flat, and the damage exist in the matrix. The exposed fibers were mostly in transverse direction. With the increased tensile loading rate, the section tends to become uneven, and the number of exposed fibers has increased, which are now mainly along the longitudinal direction. This indicates that, under high tensile loading rate, the stress in the fibre is highly concentrated and leads to the initial cracking, which then propagates through the matrix. These eventually form an uneven fracture surface consisting of fibre and matrix damage. It has been clearly shown that the studied short-cut fibre reinforced composite materials present strain rate dependency, by showing different mechanical properties and fracture behaviours subjected to different tensile loading rates.

1 INTRODUCTION

Compared with traditional manufacturing processes, additive manufacturing (AM) can produce more complex geometric shapes efficiently and quickly. One of the popular manufacturing methods is fused deposition modeling (FDM), which has been widely used in in-situ manufacturing. At present, the 3D printing technology of carbon fibre reinforced composites is maturing. To study the application of 3D printing, the mechanical behavior of materials should be studied first. It is common in industrial applications [1, 2]. Strain rate effect is a measurement method that has been extensively studied in many manufacturing techniques for materials [3]. polylactic acid (PLA) is a degradable and environmentally friendly material, which is also the most used material for FDM [4]. When polymers are processed by FDM, strain rate sensitivity is an important parameter for final application. The study of behavior changes caused by strain rates can provide information for fail-safe mechanisms and other dynamic analysis characteristics [5].

During the printing process, Dou et al. evaluated the dependence of mechanical properties on the parameters. The 3D printed specimens were designed [6]. The authors analysis and explored four different printing parameters. In their study, the tensile strength and modulus of the layers decreased with increasing layer height. Additionally, the tensile strength of the specimens increased with higher printing temperatures. Gunasekaran et al. examined PLA infill density changed mechanical behavior. [7]. According to tensile tests, the ultimate tensile strength increases with the increasing infill density. The infill material's impact strength, flexural strength and hardness also increased with infill density.

The strain rates of many materials such as polymers or composites have been studied [8,9,10], but samples manufactured by AM techniques have not been studied. The interlayer and structural properties are susceptible to a wide range of process Settings, such as shell number, layer height, filling percentage, filling geometric pattern, extrusion temperature, extrusion speed, etc. [11].

This paper studied the basic mechanical properties and strain rate effect of polylactic acid and short-cut carbon fibre reinforced composites (CF/PLA). CF/PLA composites show strain rate sensitivity under different strain rates (from quasi-static to dynamic). In addition, through SEM observation, the microscopic section at different rates can further explain the fracture occurrence and damage expansion form under the rate-sensitive condition.

2 EXPERIMENTAL PROCEDURE

The 3D-printed CF/PLA samples were produced from a standard 1.75 mm PLA filament with an Anycubic i3 Mega 3D printer. In this paper, short-cut carbon fiber PLA composites were purchased from Youline 3D Technology Co., LTD, in which the carbon fibre content was 3%-10% and the density was 1.25 g/cm^3, and the contained short-cut fibre length was about 3 mm. The nozzle and table temperatures were 220 ℃ and 60 ℃, respectively. The printing speed was 50 mm/s. The working principle of the 3D printer is shown in Figure 1. The printing wire enters the high-temperature chamber through the roller, enters the nozzle, and is extruded and printed on the platform through the motor control. All the test parts were manufactured according to ASTM D638-2014 standards, and the printing height of all samples was 0.2 mm, tetrahedral filling, and filling density is 100%. The break section micromorphology of samples was investigated through Tungsten filament scanning electron microscope (EVO10).

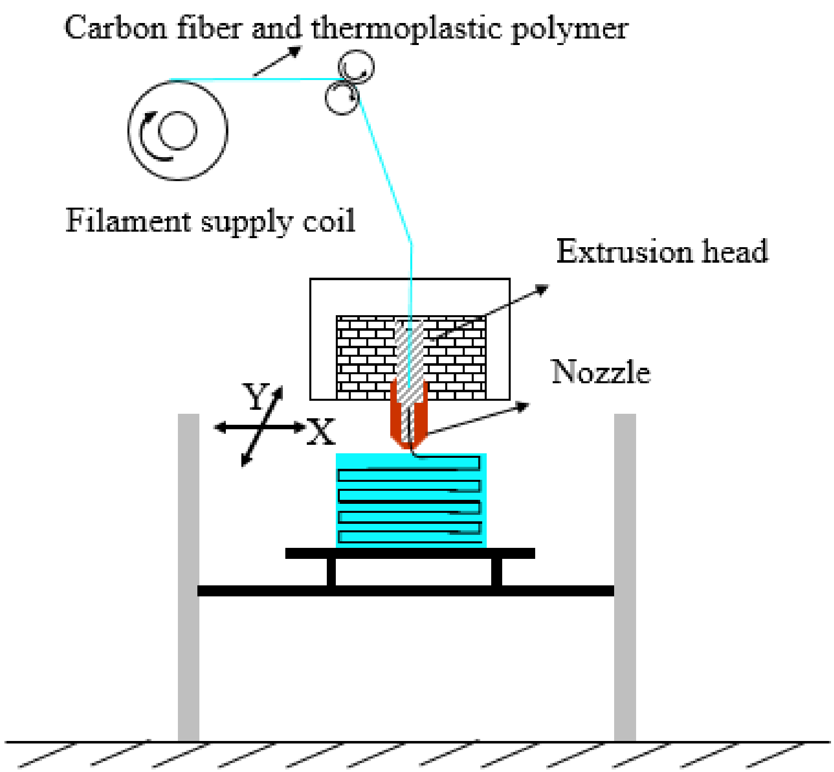

Figure. 1: Schematic Representation of FDM Process.

Quasi-static axial tensile tests were performed on specimens at room temperature by using electronic universal material testing machine MTS-E44 with a constant speed of 3 mm/min (strain rate 10^{-4}). The hydraulic servo testing machine was used for dynamic tensile test, and the tensile rates were 28.5 mm/s and 285 mm/s, respectively. Combined with quasi-static test, the strain rates were 4.34e^{-4}/s, 0.5/s and 5/s, respectively. The test setup and the main components was shown in Figure 2.

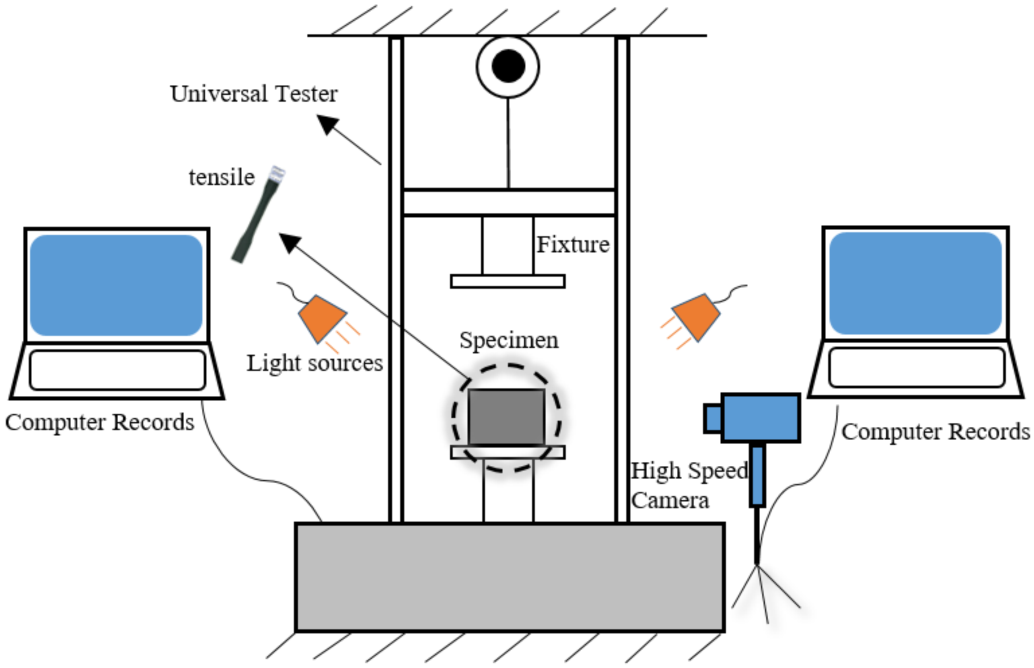

Figure. 2: Mechanical tensile experimental setup.

As shown in Figure 3, samples were respectively tested under the condition of quasi-static tensile. The internal illustration in Figure 3 is the sample of CF/PLA sample after quasi-static tensile. It can be observed that the macroscopic morphology of the tensile fracture is straight and the tensile deformation is uniform. There is no obvious plastic deformation at the fracture. Under the same quasi-static tensile test conditions, the tensile damage position is in the gradient position from wide to narrow, which accords with the fracture mode of standard parts. Under the test results, the average strength and average modulus of CF/PLA standard tensile parts are 32.40 MPa and 2.40 GPa.

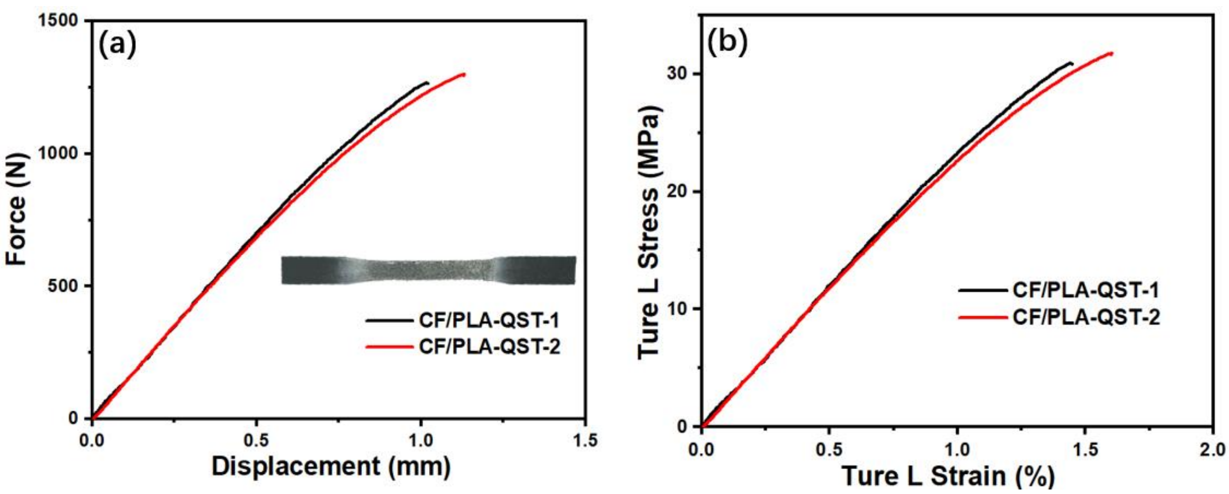

Figure. 3: Quasi-static tensile test of force-displacement curve (a) and stress-strain curve (b).

In figure 4, the tensile strenght improved by 28% from 32.4 MPa to 41.68 MPa, when the strain rate increased from 10^{-4}/s to 5/s, but the modulus has barely changed, Embedded in Figure 4a is the post-tensile failure diagram, from which it can be observed that the rate of quasi-static to dynamic tensile gradually increases, and the failure form almost didn't change. However, as the rate increases, the fracture failure is no longer flat, and even due to rapid tensile, the fracture of the tensile component is no longer complete and leaves a notch. On the other hand, this can also reflect the subtle tensile failure mechanism of materials at different strain rates. However, in order to further explain the mechanism of fracture failure, microscopic observations are necessary.

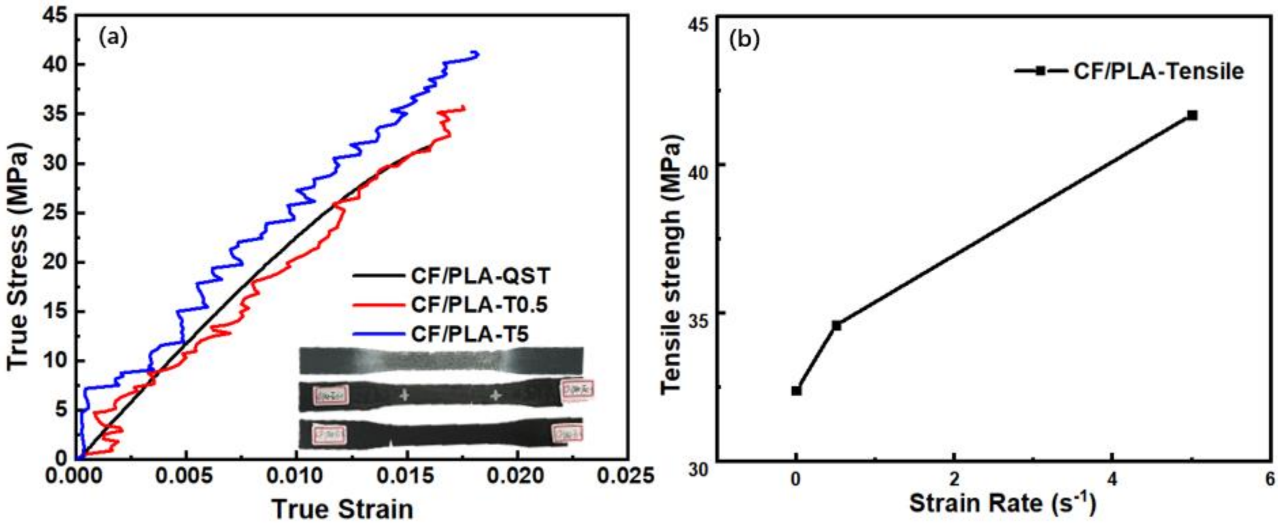

Figure. 4: Strain rate effect result of CF/PLA material.

To further analysis the failure mechanism of short-cut carbon fibre reinforced composites under strain rate effect, cross-section of the CF/PLA samples after testing were measured by SEM. As is shown in Figure 5. The fracture morphology of the samples after quasi-static tensile test are shown in the figure a1 and a2, the fracture surface is relatively flat as a whole, and the transverse visible fibres are mostly about 100-400 μ m in length, and the fibre fracture is relatively flat. This may be due to the fact that the stress is concentrated on the matrix under low-speed tensile, so the specimens mainly suffered matrix failure, and the fracture was relatively flat without fibre fracture. With the increase of tensile rate, the fracture surface is no longer flat overall under the condition of 0.5/s strain rate (b1, b2), and the longitudinal fibre increases at the fracture site, with the length between 10-300 μ m. The fibre fracture is relatively flat. It was observed from SEM that the fracture of the specimen with strain rate of 5/s (c1, c2) was uneven, and the number of fibres increased in each direction, and uneven fibre fracture could be observed. This may be because the stress concentration gradually change from the matrix to the fibre with the increase of the tensile rate, so the fibre pulling out phenomenon is gradually found in the tensile failure, which further explains the difference of the tensile fracture at different rates

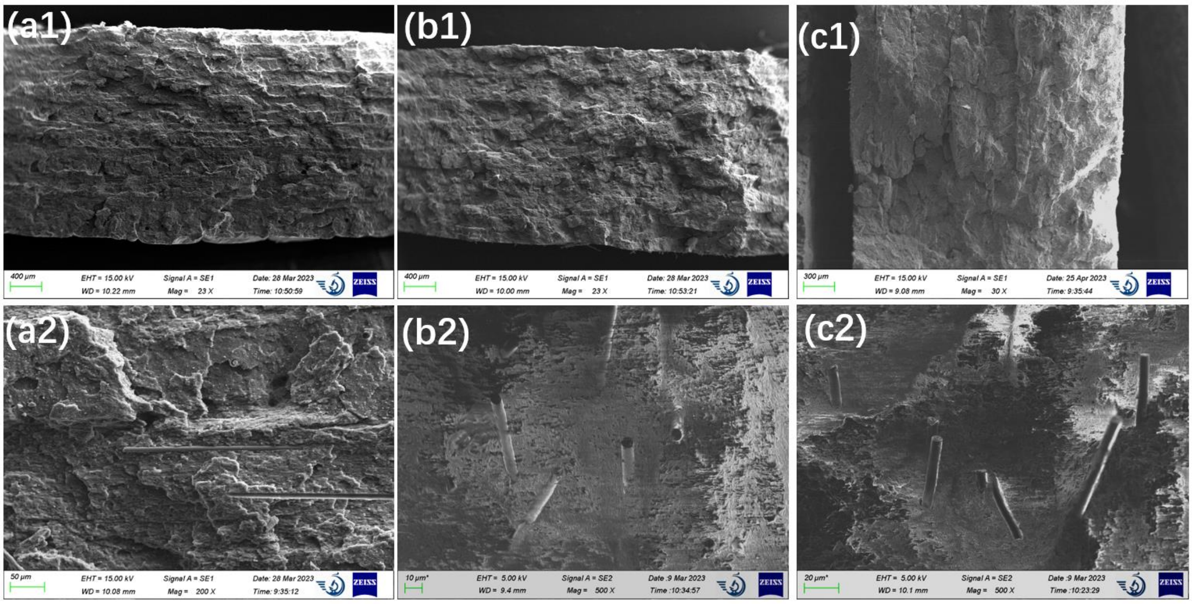

Figure. 5: Scanning electron microscope images of quasi-static (a1, a2), strain rate of 0.5/s (b1, b2) and strain rate of 5/s (c1, c2) at different tensile rates.

4 CONCLUSIONS

In this study, a standard tensile test piece based on thermoplastic resin was manufactured by 3D printing method, all the materials were printed under the same conditions, according to the test, the strength and modulus of the material were 32.40 MPa and 2.40 GPa. respectively. The response of strain rate under different tensile rates were studied. It can be seen from the mechanical results that CF/PLA has obvious strain rate sensitivity. The results showed that the CF/PLA samples were dominated by uniform brittle fracture. With the increase of tensile rate, the specimen tends to present a type of brittle fracture, but the fracture surface is no longer flat. Furthermore, SEM was used to investigate the tensile failure mechanism at the microscopic scale. It was found from the results that, both tensile fracture and fibre-matrix debonding were observed. With the increase of strain rate, the fracture surface gradually became uneven. It was found that the stress concentration was transferred from the matrix to the fibre, which explained the change in the roughness of fracture surfaces under different tensile rates.

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