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POLYESTER COMPOSITES WITH IMPROVED TENSILE PROPERTIES BY THINNER CURAUA FIBER REINFORCEMENT

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Abstract

In recent years curaua fiber reinforced polymer composites have been gaining attention in both research works and industrial applications. It was found that thinner curaua fibers, with very small diameters, may reach tensile strength over 1000 MPa. Therefore the objective of this work was to evaluate the tensile properties of polyester composites reinforced with thinner curaua fibers for improved mechanical performance. Standard specimens were fabricated with up to 40% in volume of very thin, d<0.06 mm, continuous and aligned curaua fibers embedded in an orthophtalic polyester matrix. The specimens were post-cured at 60 °C and tensile tested in an Instron machine. The fracture of representative specimens was analyzed by scanning electron microscopy. The results showed a significant improvement in the mechanical properties with the amount of thinner curaua fibers as compared to other works on curaua composites.

Introduction

Fiber reinforced polymer composites are accepted as one of the most successful class of engineering materials developed after the expansion on the use of plastics from the mid part of last century. The introduction of synthetic fibers such as glass, carbon and aramid conferred exceptional mechanical strength and stiffness to both thermoplastic and thermoset polymers [1]. As a consequence, these composites are today being extensively used in industrial sectors from leisure and sports to automobile and aerospace. Environmental and energy issues are, however, challenging the status of the synthetic fiber composites. According to Wambua et al. [2], synthetic fibers and glass fiber in particular, have serious drawbacks. In fact, burning fossil fuel for the energy required to process the glass fiber releases large amounts of CO_2, a greenhouse gas believed to be responsible for global warming [3]. Additionally, glass fiber composites, also known as fiberglass, are not recyclable and cannot be burnt in thermoelectric plants. Thus, as a waste, the fiberglass is increasingly contributing to long term world pollution [4].

The above-mentioned facts have motivated in the last decades both research and engineering applications of natural fibers as substitutes for synthetic fibers in polymer composites [5-8]. A great number of natural lignocellulosic fibers obtained from many plants [9] are renewable, recyclable, degradable and, as compared to synthetic fibers, less expensive, less abrasive and more flexible for impact resistance. By contrast, lignocellulosic fibers possess limitations such as poor wettability, incompatibility with most polymer matrices and high moisture absorption that impair the fiber/matrix adhesion [2].

Although lignocellulosic fiber reinforced composites have successfully replaced synthetic fiber composites, mainly in interior vehicle components [10-12], most of their mechanical properties are inferior, which limits the possibility of competition in structural engineering parts. For instance, lignocellulosic fiber composites usually display mechanical strength and elastic modulus no greater than, respectively, 150 MPa and 10 GPa [2]. Fiberglass, on the other hand, may present strength and modulus above 1000 MPa and 70 GPa respectively [1]. This indicates that the mechanical properties of lignocellulosic fiber composites should be improved if competition with fiberglass, as an structural material, is pursued. In a recent work [13] it was shown that thinner lignocellulosic fibers can be comparatively stronger and thus could be applied as a more effective reinforcement for polymer composites with improved mechanical properties. Among the possible fibers with this characteristic stands the curaua fiber for which the thinnest fibers could reach over 1000 MPa. Taking into account that the previous work [13], which was a preliminary investigation based on flexural tests, the objective of the present work is to evaluate the tensile properties of polyester composites reinforced with the thinnest fibers found in a commercially supplied lot.

Experimental Procedure

The materials used in this investigation were: curaua fibers as composite reinforcement and a commercial unsaturated orthophtalic type polyester resin, hardened with 0.5% of methyl-ethyl-ketone, as composite matrix. The curaua fibers, illustrated in Fig. 1, were supplied as a lot of 5 kg by the Brazilian firm Amazon Paper, which commercializes lignocellulosic fibers cultivated in the Amazonian region of Brazil. A statistical analysis of the dimensions was performed on 100 randomly separated fibers from the lot.

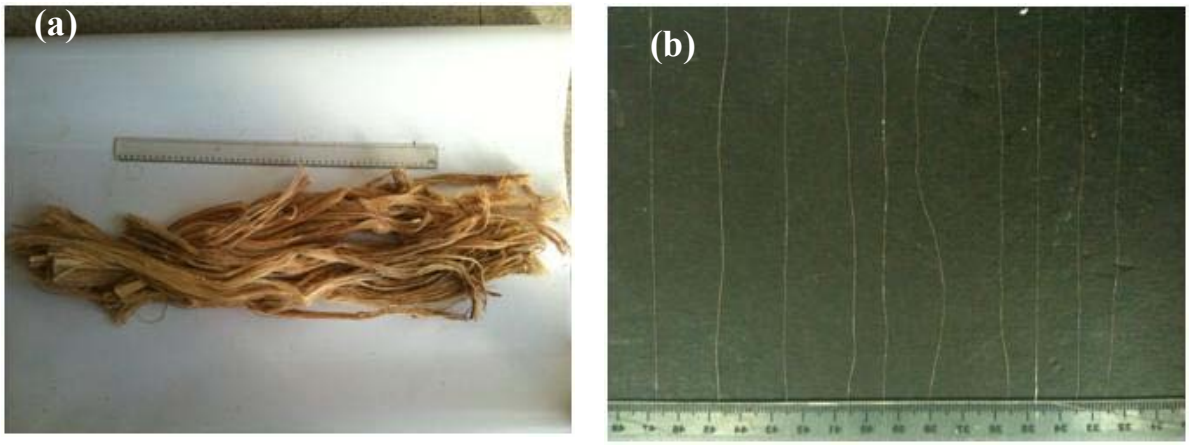

Figure 1. Bundle of curaua fibers (a) and individual fibers separated from the as-received lot (b).

Figure 2 presents histograms corresponding to the distribution of length and diameter of the as-received curaua fibers. The diameter of each fiber was actually the mean value obtained by 10 different measurements performed in a profile projector at five distinct locations (two with 90° rotation at each location). The histograms in Fig. 2 reveal a relatively large variation in both length and diameter, which is a consequence of the non-uniform physical characteristics of a lignocellulosic fiber [5-9]. It should be noticed that the length varies from 650 to 1000 mm with an average of 846 mm, while the diameter range was 0.04-0.30 mm with an average of 0.10 mm.

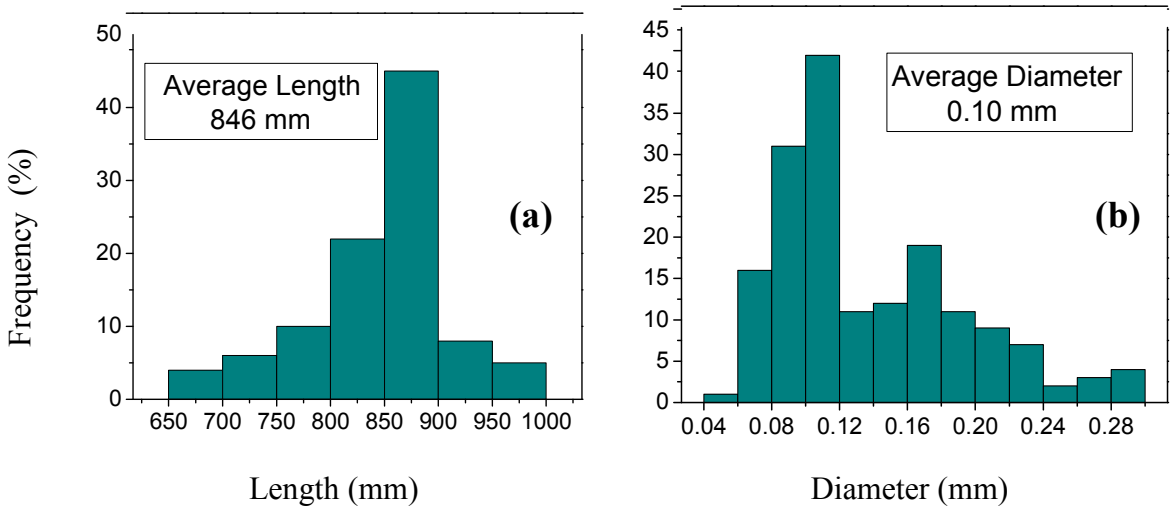

Figure 2. Histograms for the distribution of: (a) length and (b) diameter of the as-received curaua fibers.

In order to have the strongest composites, according to a recent finding [13], the thinnest curaua fibers were selected to serve as reinforcement. Therefore, by considering the diameter distribution in Fig. 2 (b), only fibers with diameter within the interval from 0.04 and 0.06 mm were selected. These thinnest curaua fibers, with an average diameter of 0.05mm, were layed down inside silicone dog bone-shaped molds with distinct volume fractions up to 40 %. The fibers were continuously aligned along the 35 mm length of the mold, coinciding with the tensile axis. The still fluid polyester resin was poured onto the fibers. The already processed composites were allowed to undergo an initial cure at room temperature for 24 hours. Afterwards, a post-cure was conducted at 60°C for 4 hours. For each volume fraction of curaua fibers, 10 specimens were fabricated.

Each specimen was tested at 25 ± 2°C in a model 5582 Instron machine at a strain rate of 3 x 10^{-3} s^{-1}. Samples cut from the fracture tip of representative specimens were analyzed by scanning electron microscopy (SEM). These samples were first attached by conducting carbon tape to a metallic support and then gold sputtered. The SEM analysis was conducted in a SSX-550 Shimadzu microscope operating with secondary electrons accelerated at a maximum voltage of 15 kV.

Results and Discussion

Typical force versus elongation curves are shown in Fig. 3. In this figure, four representative composite curves are illustrated for each different volume fraction of thinner curaua fiber. These curves were directly recorded from the Instron machine data acquisition system. The common aspect of all curves is that they present practically no plastic strain. The initial curvature is a consequence of specimen's adjustment to the tensile grips until the linear elastic begins. The abrupt drop at the end of this linear stage indicates that the thinnest curaua fiber reinforced polyester composites behave as brittle materials.

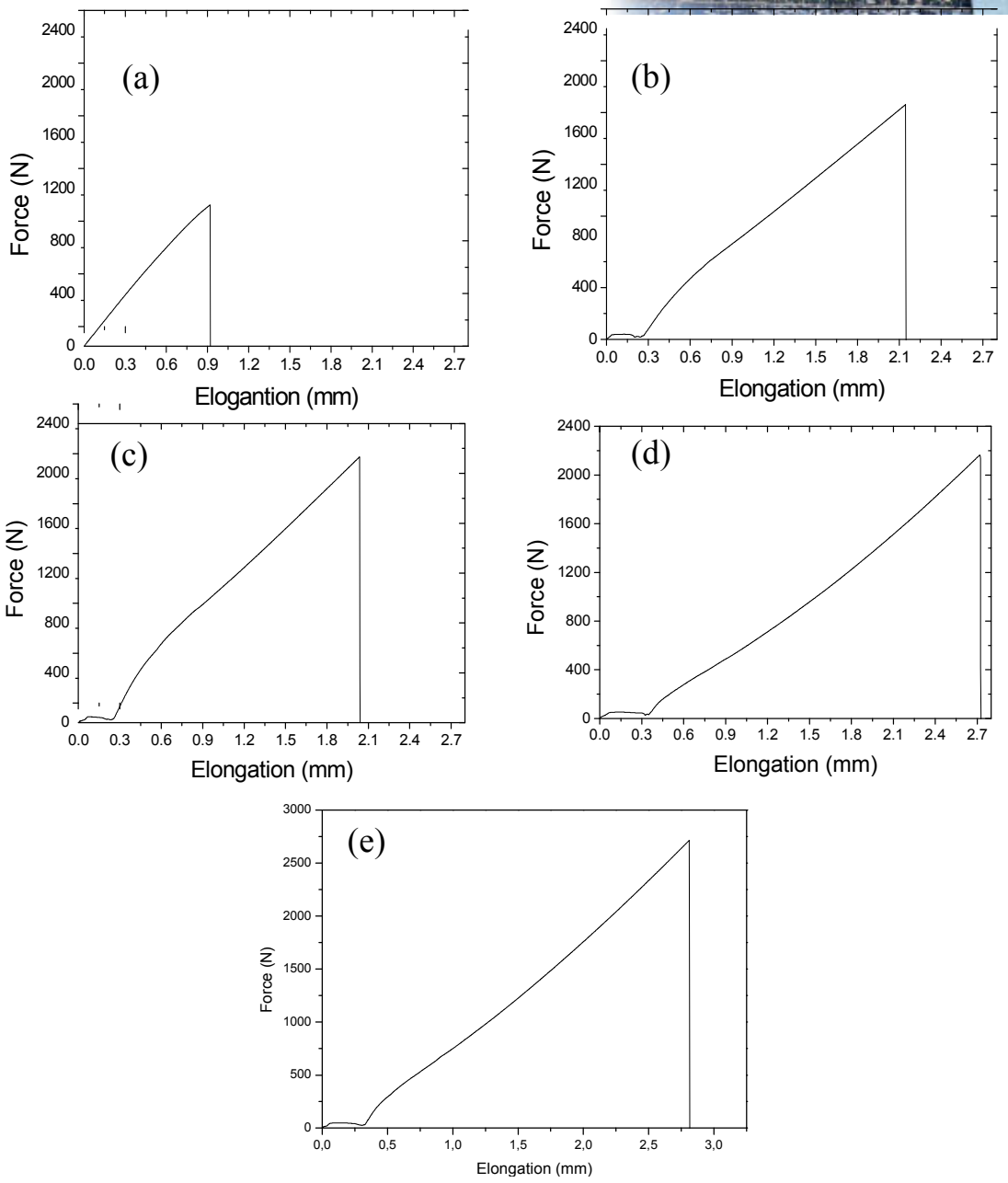

Figure 3. Typical force vs. elongation tensile curves: (a) 0%, (b) 10%, (c) 20%, (d) 30% and (e) 40% of volume fraction of the thinner curaua fiber reinforcing polyester composites.

Figure 4 illustrates the visual aspect of representative ruptured tensile specimens corresponding to each volume fraction of curaua fiber considered for composite reinforcement. An increase non-uniform rupture can be noticed at the fractured tips of composites with more than 10% of curaua fibers. For higher amounts of curaua fibers, such as 40%, the rupture tends to predominate in the longitudinal direction. This will be discussed further with the fracture analysis.

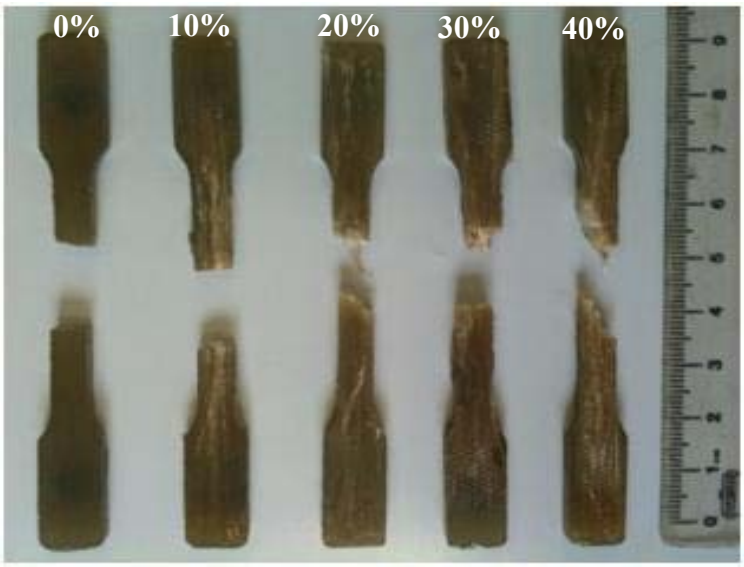

Figure 4. Tensile ruptured specimens for each volume fraction of curaua fiber incorporated into the polyester matrix.

For each curaua volume fraction the corresponding average composites tensile mechanical properties were calculated. Table 1 shows the average value and corresponding standard deviation for the tensile strength (ultimate stress), elastic modulus and total tensile strain for the different composites investigated.

Table 1. Tensile properties for the curaua fiber reinforced polyester composites.

Volume Fraction of Thinner Curaua Fiber (vol. %)	*Tensile Strength (MPa)*	*Elastic Modulus (GPa)*	*Total Tensile Strain (%)*
0	40.84± 5.50	0.97 ± 0.23	0.97 ± 0323
10	61.78 ± 7.90	1.96 ± 0.38	2.82 ± 0.77
20	71.31 ± 7.11	1.93 ± 0.29	4.15 ± 0.51
30	86.94 ± 11.06	2.28 ± 0.31	3.91 ± 0.78
40	103.22 ± 14.03	1,31 ± 0.26	6,90 ± 1,36

In this table it should be noted that the tensile strength continuously increase with the volume fraction of thinner curaua fibers. The total tensile strain initially increases but, within the standard deviation, apparently remains constant up to 30% and then increases for the 40% of curaua fiber composites.

Based on the results in Table 1, Fig. 5 presents the curves of tensile strength (a) and elastic modulus (b) variation with the volume fraction of thinner curaua fibers. In these curves, one may visually sees a significant increase in the tensile strength with the amount of curaua fibers. Within the error bars, corresponding to the standard deviation, the curve in Fig. 4(a) fits into a straight line. For the tensile strength (σ), the best correlation with the volume fraction of curaua fibers (V) can be translated by the following equation:

$$\sigma \text{ (MPa)} = 1.7 \text{ V (\%)} + 42 \quad (1)$$

Whereas for the elastic modulus, a maximum occurs at 30% of curaua fibers followed by a sensible decrease in stiffness.

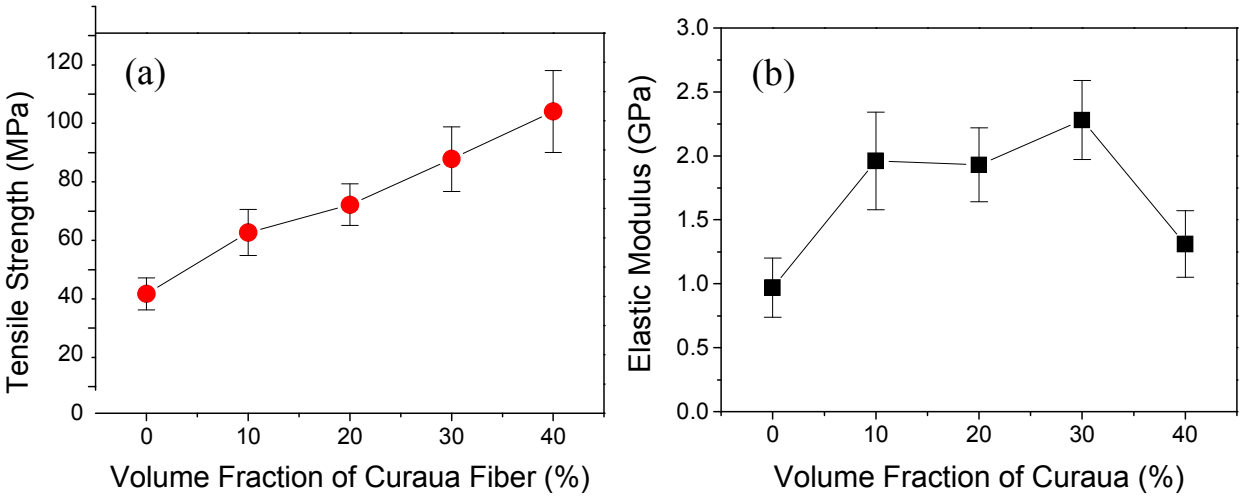

Figure 5. Variation of the tensile strength (a) and elastic modulus (b) with the volume fraction of thinner curaua fibers reinforcing polyester composites.

Results on the flexural properties of commonly available non-selected curaua fibers reinforcing polyester composites [14] depict strength values lower than those shown in Fig 4(a). This is an indication that the selection of the thinnest fibers performed in this work could provide a more effective reinforcement for polyester composites with improved strength.

The fracture analysis of representative tensile ruptured specimens was performed by both macro (visual) and microscopic (SEM) observations. Figure 6 shows the macrostructural aspect of the fracture tips of different composites. In this figure it is relevant to comment that for the pure polyester specimen, 0% fiber, Fig 6(a), the fracture is transversal to the tensile axis, indicating the propagation of a single crack throughout the brittle polyester matrix. However, for composite specimens with 20%, Fig. 6(b) and 40%, Fig. 6(c), part of the fracture surface shows evidence of longitudinal rupture. This longitudinal rupture exhibits signs of fiber separation from the polyester matrix. Apparently, this is a consequence of a fiber/matrix debonding mechanism.

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Figure 6. Fracture tip of tensile-ruptured polyester composites with (a) 0%, (b) 20% and (c) 40% of volume fraction of thinner curaua fibers.

Figure 7 shows typical SEM fractographs of a 30% volume fraction of thinner curaua fiber reinforced polyester composite. With lower magnification, Fig 7(a), the fracture surface display evidence of broken fibers sticking out of the polyester matrix. Apparently, the fibers are well adhered to the matrix, which justifies the significant improvement on the composites strength and stiffness with increasing amount of fibers up to 30%, as shown in Fig. 4.

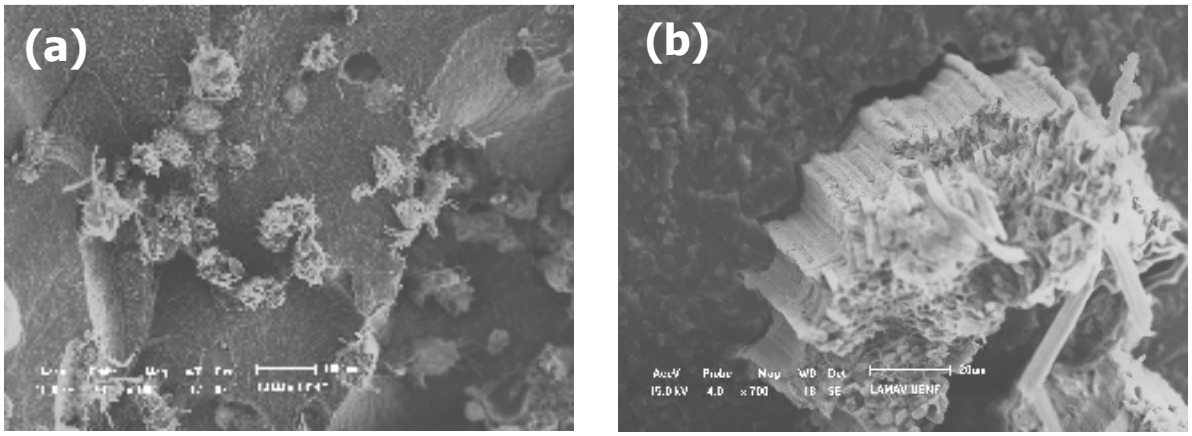

Figure 7. Microstructure of composite with 30% vol. of curaua: (a) 100X and (b) 700X.

However, a few holes in the surface of Fig 7(a) could also indicate a low fiber/matrix interfacial resistance, as indeed happens in lignocellulosic fibers reinforcing polyester matrices [5,6-14]. In this respect, Fig 7(b) with higher magnification shows a crack alongside a curaua fiber beginning to detach it from the polyester matrix. Therefore, although thinner curaua fiber could improve the strength of polyester composites, the weak adhesion between the fiber and the composite matrix is still an important limitation to further increase in the mechanical strength and stiffness. This weak adhesion is probably responsible for the fiber debonding from the polyester matrix, which causes the longitudinal rupture shown in Fig. 6, and the relatively lower stiffness at 40% of volume fraction in Fig. 5(b).

Conclusions

- Selected thinner curaua fibers significantly improve the strength of polyester matrix composites. This improvement corresponds to a linear increase up to 40% in volume of fiber and surpasses the flexural results with similar composites.
- Macro and microscopic analysis indicate that the thinner curaua fibers act as effective reinforcement for the brittle polyester matrix despite the weak fiber/matrix interface. In fact, most fibers are well adhered to the polyester matrix but evidence of fiber pullout from the matrix indicates a relatively low interfacial shear stress. This is an important limitation for further composite improvement.

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