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10.2417/spepro.005623

Choice of extrusion screw for recycling glass-fiber-reinforced liquid crystal polymer

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A smaller extrusion screw produces a recycled product with adequate mechanical and thermal properties for reuse in electronic and electrical applications.

Liquid crystal polymer (LCP) is an exceptional engineering thermoplastic with high chemical and physical stability.[1] Glass-fiber-reinforced LCP (GFLCP) could reduce both the cost and the mechanical anisotropy of LCPs. The material has excellent heat resistance and processability, which make it suitable for use in electrical components. Scraps of GFLPC from 'runner and gate' molding systems and defective products can be processed by micro-injection molding to generate more than 60% by weight recycled GFLPC (RGFLPC). The GFLCP scraps are often irregularly shaped and are, therefore, granulated to a uniform size so that they can be reused in micro-injection molding. However, during extrusion, the reinforcing glass fibers are damaged, adversely affecting the properties of the product. For glass-fiber-reinforced composites to exhibit effective strengthening and stiffening, a critical fiber length (L_c) is required for the stress to reach the fracture stress of the fiber. If the fiber length is $<L_c$, the fiber will not be broken but rather be pulled out from the fracture surface. We have considered the impact of different screw types—see Figure 1—and how this affects the properties of the extruded RGFLPC. We investigated the average glass fiber length ($\overline{L}$) and distribution, as well as the mechanical, thermal, and rheological properties of the extruded RGFLCP.

We named the extruded RGFLPC samples by the abbreviated name of the screw used in preparing it, so that the RGFLCP-S30 sample was prepared by the S30, a single screw with a length-to-diameter ratio of 30. The damage to the glass fibers during extrusion can be characterized by the distribution of the fiber length (see Figure 2). Compared with RGFLCP, the percentage of glass fibers with length $<50\mu$m and 50–100μm significantly increased to 11.2% and 31.9%, respectively, for RGFLCP-S30. For RGFLCP-T30 (prepared by twin screws, each with a length-to-diameter ratio of 30), the percentage of

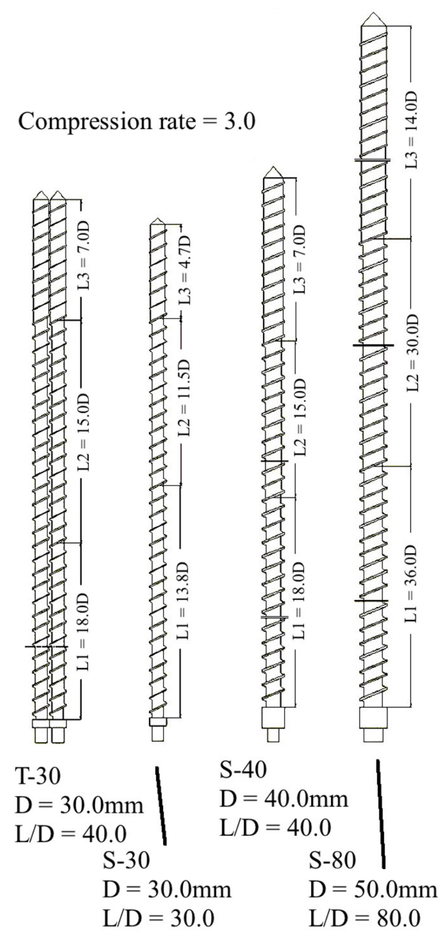

Figure 1. *The structures of the different screws used in this investigation. L1,2,3: Lengths of sections of the screws. D: Diameter. L/D: Length-to-diameter ratio. T-30, S-30, S-40, S-80: Abbreviated names for the different screws, where S means single and T means twin, and the two-digit number gives the ratio of the total length to the diameter.*

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glass fibers with length <50μm and 50–100μm increased to 41.8% and 31.2%, respectively. We deduce that the larger strain generated by the T-30 screws causes severe breakage of glass fibers. We conclude the percentage (V_j) of glass fibers whose length was higher than the critical length of RGFLCP-S30 was higher than other extruded products, while RGFLCP-T30 had the lowest V_j.

Plots of $\overline{L}$ and the mechanical properties of RGFLCP and its extruded products in Figure 3 show that $\overline{L}$ of the extruded samples decreased as the screw length and shear tension increased. $\overline{L}$ in RGFLCP-S30 reduced to 186.4μm, which was an 8.4% decrease. Compared with $\overline{L}$ in RGFLCP, $\overline{L}$ was 50.2% lower in RGFLCP-T30. From these $\overline{L}$ values, we conclude that the greatest glass fiber damage occurred with T-30 screw.

We noticed that the mechanical properties deteriorated a little after extrusion, although those of RGFLCP-S30 were acceptable. Reductions in the notched impact, tensile, and flexural strengths of RGFLCP-S30 were 4.5%, 8.2%, and 3.7%, respectively. The notched

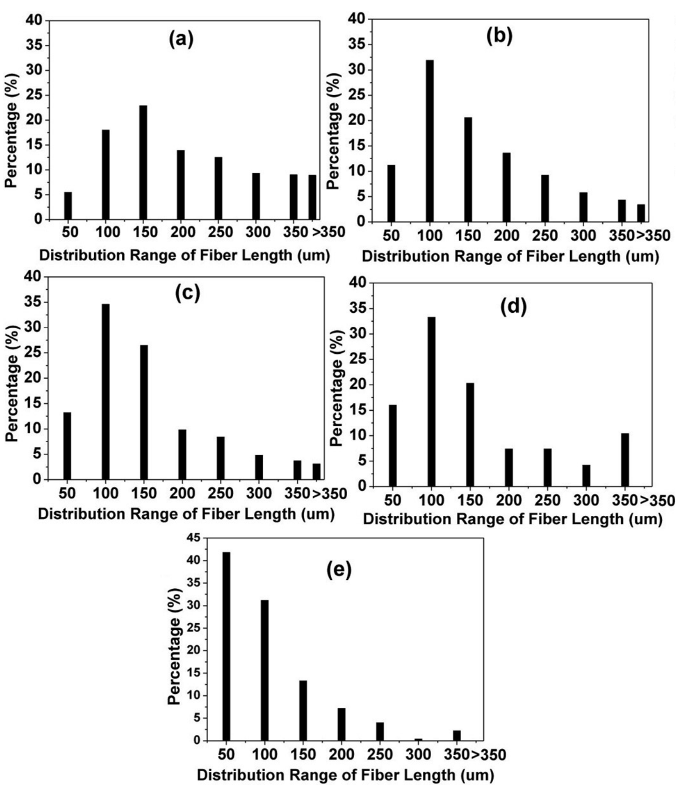

Figure 2. The glass fiber length distribution of recycled glass-fiber-reinforced liquid crystal polymer (RGFLCP) and extruded samples, where the final characters indicate the screw used during the extrusion. (a) RGFLCP, (b) RGFLCP-S30, (c) RGFLCP-S40, (d) RGFLCP-S80, and (e) RGFLCP-T30.

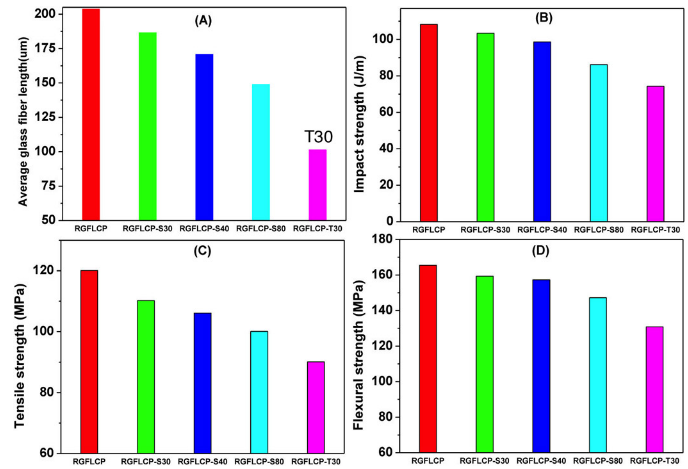

***Figure 3.** (A) Average glass fiber length ($\overline{L}$), (B) impact strength, (C) tensile strength, and (D) flexural strength of RGFLCP and its extruded products. Red: RGFLCP. Green: RGFLCP-S30. Blue: RGFLCP-S40. Cyan: RGFLCP-S80. Pink: RGFLCP-T30.*

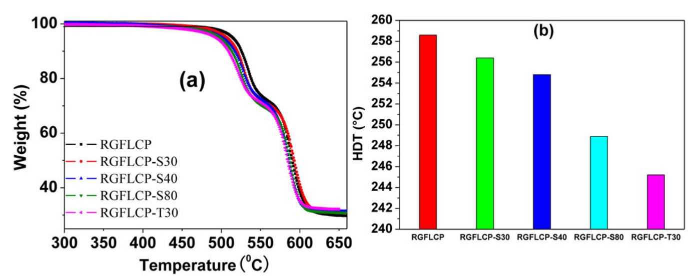

***Figure 4.** Thermal properties of RGFLCP and its extruded samples. (a) Thermogravimetric curves. (b) Heat deflection temperature (HDT).*

impact, tensile, and flexural strengths of RGFLCP-T30 decreased to 74.3J/m, 90.1MPa, and 130.9MPa, respectively. As shear strain increases, both $\overline{L}$ and V_j of the extruded products decrease, and these changes in turn lead to the poorer mechanical properties of RGFLCP-T30.[2]

Figure 4(a) reveals that measures of thermal stability (such as the decomposition temperatures of 1% and 5% mass loss, $T_{-1\%}$ and $T_{-5\%}$, respectively) of the extruded products are lower than those of RGFLCP, suggesting that the extrusion process reduces thermal stability. Compared with RGFLCP-S30, RGFLCP-T30 showed lower decomposition temperatures, perhaps because the both single and twin screws shear the LCP molecular chain, reducing its molecular weight and increasing its carboxyl endgroup content.[3]

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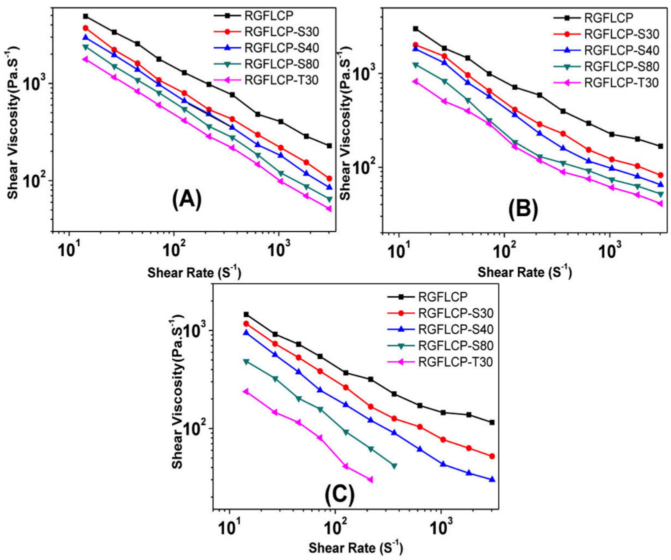

Figure 5. Rheological behavior of RGFLCP and its extruded samples: (A) 320°C, (B) 330°C, and (C) 340°C.

RGFLCP-S30 achieved a rather high heat deflection temperature (HDT) of 256.4°C with only 2.2°C reduction in comparison to RGFLCP (see Figure 4). The HDT of RGFLCP-S80 and RGFLCP-T30 were 248.9°C and 245.2°C, respectively. As shear strain increases, the extruder will break the molecular chain of LCP and the glass fibers, reducing the interaction between these components (such as the cross-linked effect) and increasing the free molecular motion of LCP while reducing its HDT.[4] Nevertheless, at 256.4°C, the HDT of RGFLCP-S30 is sufficient for it to be used in surface-mount packaging technology. This method for constructing electronic circuits, in which the components are mounted directly onto the surface of printed circuit boards, provides smaller components with higher circuit densities, a higher degree of automation, lower labor cost, and much higher production rates.

As the length of glass fibers is reduced, fiber orientation and fiber-matrix interaction become challenging to control,[5] which in turn influences the rheological properties of RGFLCP. At the same temperature and shear rate, RGFLCP-S30 revealed higher shear viscosity than the other extruded RGFLCP samples (see Figure 5). The shear viscosity of RGFLCP-T30 was the lowest of all the samples. Furthermore, the shear viscosity of RGFLCP-T30 was more sensitive to temperature than that of other samples. The results demonstrate granulation has the advantages of reducing shear viscosity and improving the flow properties of RGFLCP. As shear strain increases, the RGFLCP samples suffer increasing mechanical shear stress, leading to severe breakage of the glass fibers. Granulating the sample with the S30 screw had the least negative impact on the mechanical and thermal properties compared with the results with other screws. We conclude that the S30 screw is the most practical choice for extrusion to granulate RGFLCP.

In summary, we report a highly economical and practical technique to recycle GFLCP using the S30 screw. With this process, the mechanical and thermal properties of RGFLCP-S30 meet the requirements for use in electronics and electrical applications. Moreover, we are now investigating whether, with its improved flow properties, it may be possible to process RGFLCP-S30 by injection molding, which would help reduce injection defects such as weld lines, short molding, and the emergence of glass fibers on the surface.

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