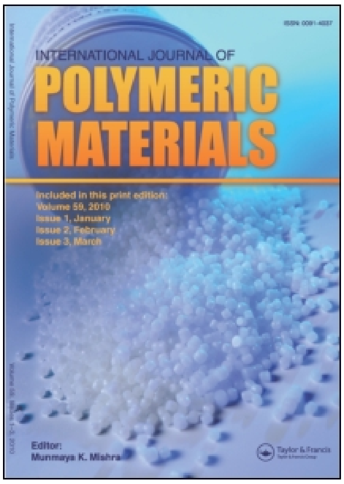

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C. Subramanian[a]; S. Senthilvelan[a]
[a] Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, India

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Effect of Fiber Length on Hysteretic Heating of Discontinuous Fiber-Reinforced Polypropylene

C. Subramanian and S. Senthilvelan
Department of Mechanical Engineering, Indian Institute
of Technology Guwahati, Guwahati, India

Fatigue application of a polymeric material is limited due to its hysteretic heating behavior. In this work, effort has been made to understand the effect of fiber reinforcement and length of the reinforcing fibers on hysteretic heating behavior and its mechanisms. Unreinforced, 20% short glass fiber-reinforced and 20% long glass fiber-reinforced polypropylene materials have been injection-molded and subjected to a finite number of fatigue cycles. The load required for constant deflection and the surface temperature of materials during testing was measured and correlated with the hysteretic heating mechanism. During material deformation, the presence of the reinforced fibers and fiber-matrix interface in the reinforced material contributed more internal friction, and resulted in higher heat generation than unreinforced material. Higher fiber density and the inferior fiber-matrix bonds existing in the short fiber-reinforced material generated higher heat than that of long fiber-reinforced material during testing.

Keywords: fatigue, hysteretic heating, reinforced fiber length, thermoplastic composites

INTRODUCTION

Viscoelastic characteristics of a thermoplastic material generate internal friction during cyclic material deformation. This action involves the accumulation of the generated hysteretic energy during loading cycles, resulting in thermal softening. The presence of reinforcing fibers reduces thermal softening failures at high stresses

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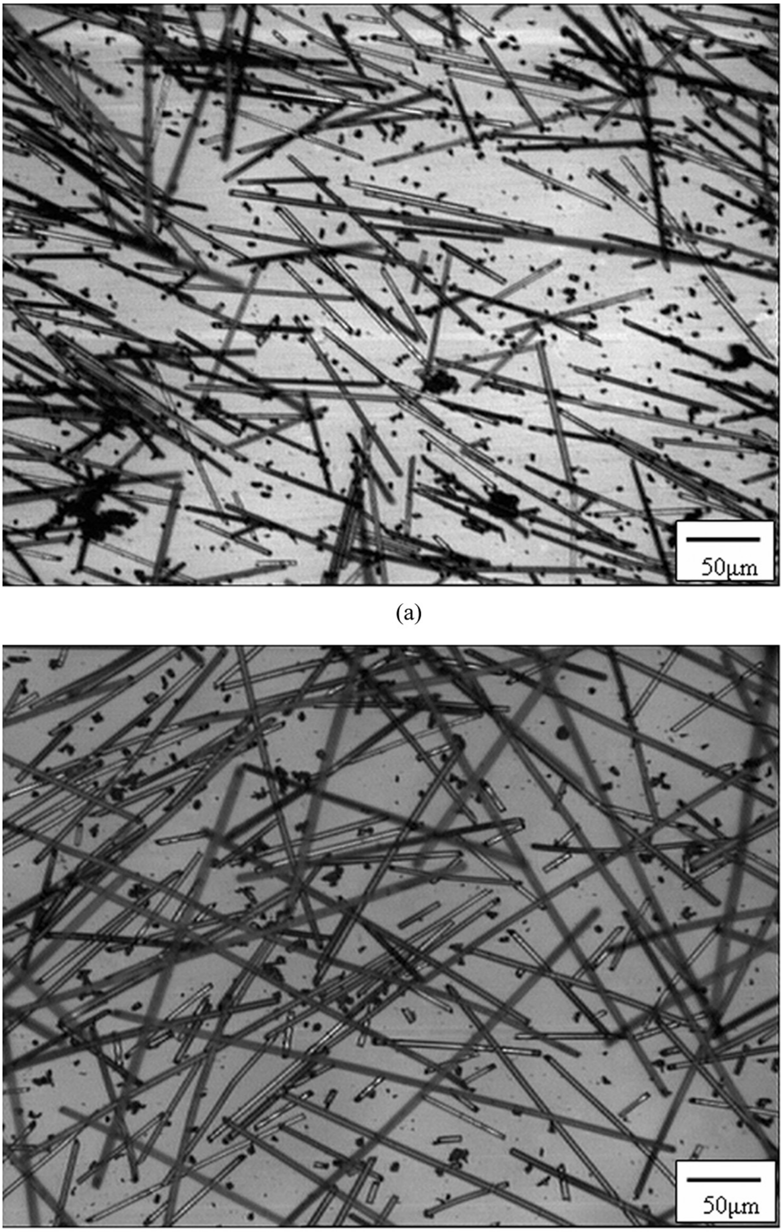
Address correspondence to S. Senthilvelan, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India. E-mail: ssvelan@iitg.ernet.in

and frequencies [1]. Rittel [2] investigated the heat generation of polymethylmethacrylate (PMMA) and polycarbonate (PC) under cyclic compressive loading. Both test materials exhibited a significant influence of frequency and applied stress on the heat generation. Rittel et al. [3] examined the hysteretic thermal response of modified PMMA at high stress level, and chain mobility is identified as a contributing parameter. Rittel and Rabin [4] developed a numerical model for thermal analysis of PC and PMMA materials subjected to cyclic compressive loading, and compared with measured temperature. Moisa et al. [5] investigated the heat generation in two amorphous materials under cyclic compression conditions. From this work, correlation between the molecular structure of a polymer and thermomechanical behavior under cyclic loading was established. Kultural and Eryurek [6] investigated the fatigue behavior of calcium carbonate-filled polypropylene material. In this work, the influence of loading frequency and percentage of calcium carbonate on the material temperature rise was observed. Bellenger et al. [7] investigated the bending fatigue performance of glass fiber-reinforced polyamide 66 and measured specimen temperature using an infrared camcorder. Many works [2–7] have attempted to understand the influence of stress magnitude and frequency on hysteretic heating behavior under cyclic loading of various engineering polymers. However, no work has been reported to understand the influence of fiber reinforcement and the length of fiber reinforcement on the internal heat generation of a thermoplastic material. The present work attempts to achieve this task by investigating the performance of short and long fiber-reinforced material subjected to a finite number of fatigue cycles.

TEST MATERIALS AND METHODOLOGY

Unreinforced, 20% long glass fiber and 20% short glass fiber-reinforced polypropylene (PP) materials have been considered to understand the hysteretic heating behavior of discontinuous thermoplastic composites. Test materials were injection-molded into tensile test specimens pertaining to the ASTM D 638 standard for static and fatigue performance evaluation. Test specimens were subjected to a finite number (7200) of fatigue cycles using a servohydraulic fatigue testing machine, Instron 8801, at 1 Hz, $R = 0$ with constant displacement of 1 mm. The load which is required for the 1 mm deflection under cyclic sinusoidal loading was measured for the chosen test materials. During testing, the test specimen temperature was measured



(a)

(b)

FIGURE 1 Separated fibers from test specimens (a) short fiber-reinforced PP and (b) long fiber-reinforced PP.

using a noncontact infrared temperature sensor (Raytek MID, ±0.1°C accuracy). The temperature increase under cyclic load was observed for all three test materials. Tensile tests were carried out and fractured surfaces were investigated to quantify the fiber matrix interface strength. Tensile tests were performed at atmospheric condition (23°C and 50% humidity) using an Instron 8801 testing machine at a constant crosshead speed of 1 mm/min. Injection-molded test specimens were burned in a muffle furnace at 600°C, and the extracted fibers were observed under optical microscope to confirm the final reinforced fiber length in the test specimens (Figure 1). The length of the extracted fibers is measured using a Zeiss microscope (KS 300) with an image analysis system. The average fiber length in long fiber-reinforced PP and short fiber-reinforced PP was found to be 1.35 and 0.28 mm, respectively.

RESULTS AND DISCUSSION

During cyclic loading, some part of the mechanical work was spent on irreversible molecular processes leading to microscopic deformations such as, crazes, shear bands, voids and micro cracks, and the other part of the mechanical work evolved as heat. Thermoplastic materials generate heat as a function of applied load, frequency, sample thickness and number of cycles. This generated heat could exceed the amount of heat transferred to the surroundings because of poor conductivity of the material, resulting in heating and rise in specimen temperature. In general, fatigue tests are carried out to evaluate the endurance strength of a material. In this study, the heat generated during cyclic loading was measured and correlated with the hysteretic heating behavior of a material. Figure 2 shows the measured surface temperature of test materials during fatigue testing. The rise of unreinforced PP (UPP) temperature is due to the hysteretic heating behavior of the polypropylene matrix material and the measured surface temperature is less than reinforced PP. In the case of reinforced PP, the presence of reinforced fibers and fiber matrix interface causes more internal friction, resulting in increased heat generation. Short fiber-reinforced PP (SFPP) exhibited higher temperatures than that of the long fiber-reinforced PP (LFPP) due to the higher internal collision because of the larger number of fiber ends. Figure 3 shows the schematic of short and long fiber-reinforced thermoplastic material for a fixed volume fraction of reinforcement. For a given volume of material, short fiber-reinforced material has more fiber ends than long fiber-reinforced material. Hence, when the short fiber-reinforced

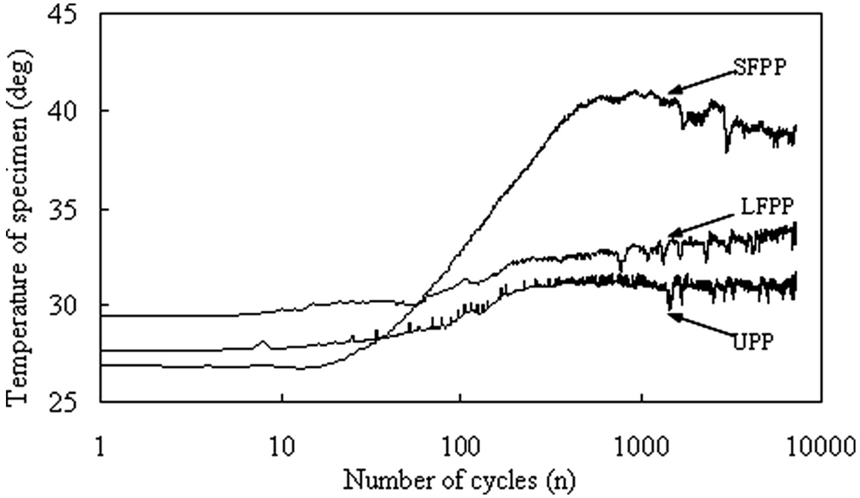


FIGURE 2 Measured temperatures of unreinforced and reinforced polypropylene specimens.

materials are subjected to cyclic loading, the presence of more fiber ends causes more internal friction, resulting in higher heat generation. Kultural and Eryurek [6] also reported a similar behavior, wherein higher material temperature is observed when the percentage of calcium carbonate filler in polypropylene is higher under fatigue testing. Figure 4 shows the load required for maintaining 1 mm deflection of test materials under fatigue loading. Due to the rise in material temperature and material visco-elastic behavior, the load required for a fixed amount of deflection decreases as the cycle progresses. Load drop in both the unreinforced and reinforced test material also revealed the material internal friction during cyclic loading. This load drop is observed to be higher in reinforced material than unreinforced material, confirming the role of reinforcing fibers in internal friction. Among the reinforced materials, the short fiber one exhibited higher load drop than the long fiber one. This behavior is due to the higher material temperature as well as weaker fiber-matrix bonds in the short fiber-reinforced material. Fractured surface of test material after static tensile test was observed to quantify fiber matrix bonding strength (Figure 5). Fiber pullout failures were predominant in the short fiber-reinforced PP (Figure 5a), whereas no such failures were found in the long fiber-reinforced PP material (Figure 5b). Due to the reduced reinforced fiber length, short fiber-reinforced PP exhibited a poorer bond strength between fiber and matrix than long

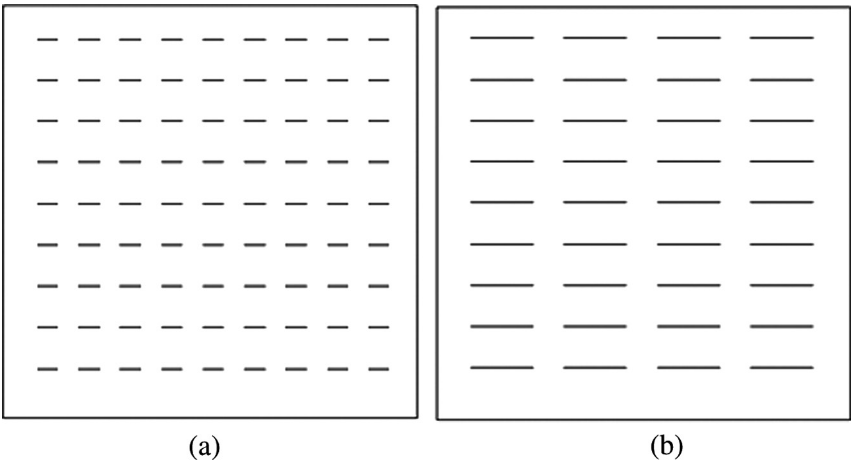


FIGURE 3 Schematic of discontinuous fiber-reinforced thermoplastics for a fixed volume fraction of reinforcement (a) short fiber-reinforced polypropylene and (b) long fiber-reinforced polypropylene.

fiber-reinforced PP material. When the fiber matrix bond is weaker, the load drop was observed to be significantly larger due to the slip between reinforced fiber and matrix.

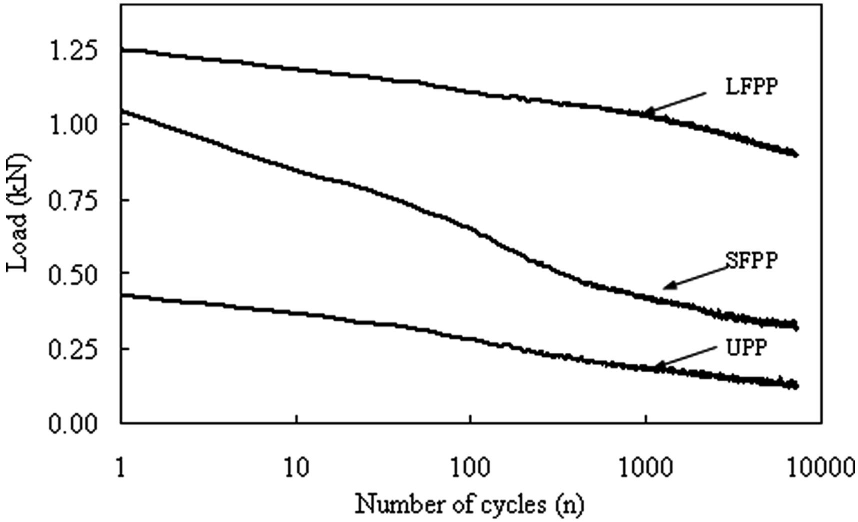


FIGURE 4 Fatigue performances of unreinforced and reinforced polypropylene specimens under constant deflection mode.

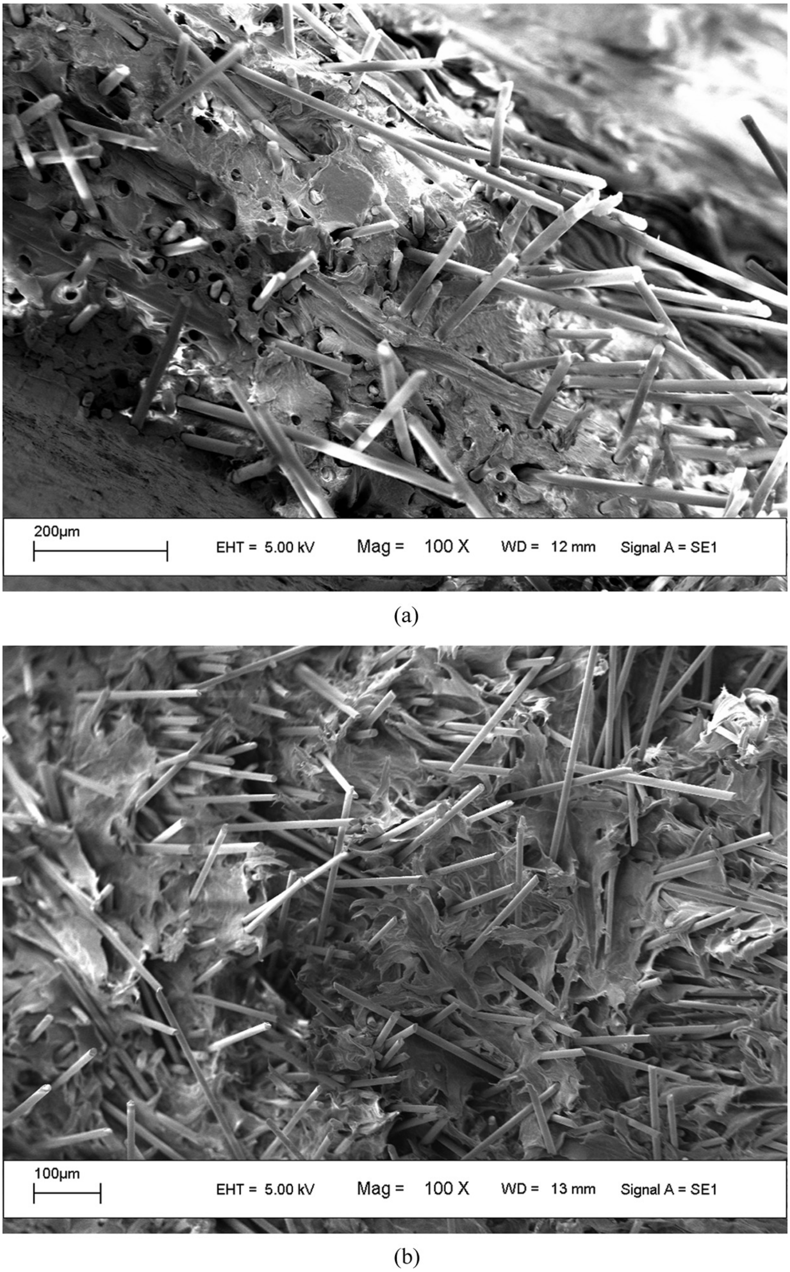


FIGURE 5 Fracture surface of test materials (a) short fiber-reinforced PP and (b) long fiber-reinforced PP.

CONCLUSIONS

The presence of reinforcing fibers within thermoplastic material contributed to the material internal friction under cyclic loading. Fiber end density was also observed to contribute to the material internal friction, resulting in internal heat generation. The following major conclusions have resulted from the present experimental investigation.

- The heat generation due to material internal friction under cyclic loading is indicated by the measured net temperature of the test specimen. Reinforced PP material shows higher temperature than unreinforced PP material, due to the presence of fibers and fiber matrix interfaces. Short fiber-reinforced PP was found to exhibit higher temperatures than long fiber-reinforced PP under cyclic loading, due to the higher fiber end density and inferior fiber matrix bond.
- The load required for a constant amount of deflection under cyclic loading of short fiber-reinforced PP materials was found to be significantly larger than that of long fiber-reinforced PP material, due to the slip between reinforced fibers and matrix. This behavior is due to the inferior fiber matrix bond strength and the higher material temperature of short fiber-reinforced PP material during testing.

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