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Friction stir processing of thermoplastic/rubber/nanoclay composites

Mohammad Reza Nakhaei, Amir Mostafapour, and Ghasem Naderi

The effects of pin geometry and process parameters on the mechanical properties of samples fabricated via this novel technique are investigated.

Polypropylene (PP) is a widely used thermoplastic polymer that exhibits several useful properties (e.g., low density, chemical resistance, high thermal stability, low cost, high softening point, good processability, and high strength).[1–3] Moreover, the addition of clay in very small proportions can enhance the mechanical, thermal, and barrier properties of PP dramatically.[4,5] PP and PP/clay composites, however, tend to have poor impact resistance and fracture toughness characteristics at high strain rates and low temperatures. Blending PP with rubbers—such as ethylene-propylene-diene monomer (EPDM)—is therefore becoming a commonly adopted practice to improve the toughness of PP blends, and to increase their applicability within industry.[6,7] The resultant thermoplastic elastomeric materials—such as polyeolefin blends (TPOs)—have broad applications in shipbuilding and automotive industries because of their excellent properties (e.g., elasticity at room temperature and flowability at high temperatures).[8] There are, however, several different methods for the production of PP nanocomposites, and it is important to fully understand how process parameters affect the properties of the final materials.

For instance, the effect of material and processing parameters on the mechanical properties of PP/EPDM/clay nanocomposites prepared by the melt compounding method (i.e., with the use of an extruder and internal mixer) has been investigated previously.[9] The results indicated that an increase in nanoclay concentration (from 0 to 5wt%) gives rise to improved mechanical properties (e.g., increased tensile strength and tensile modulus). At higher nanoclay contents, however, the tensile strength decreased. In addition, friction stir processing (FSP), illustrated in Figure 1, is a novel technique that can be used for the fabrication of composites and nanocomposites (i.e., that include a variety of materials, such as aluminum, magnesium alloys, copper, steel, titanium alloys, and polymers), and for making microstructural modifications.[11,12] To date, however, there have been relatively few reports on the use of FSP for the fabrication of polymeric composites and nanocomposites.[13–15] In particular, there is a lack of available information for the effect of FSP process parameters on the fracture toughness of PP/EPDM/clay nanocomposites.

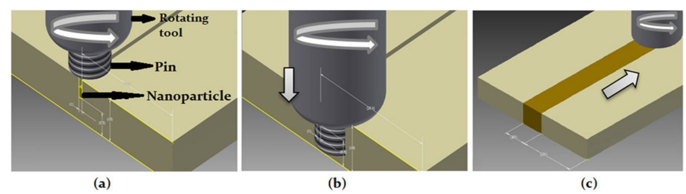

Figure 1. *Schematic illustration of the friction stir processing (FSP) technique. (a) A groove with defined dimensions is machined into a sheet of the base material and nanoparticles are placed in the groove. A non-consumable rotating pin is then (b) plunged into the base material and (c) subsequently moved along the groove. The pin provides complex material movement and plastic deformation within the processing zone, which causes the particles to be dispersed within the base material.*[10]

As part of our ongoing efforts to examine the feasibility of using FSP to fabricate PP/EPDM/clay nanocomposites, in this study our main objective was to investigate the effect of specific process parameters on the fracture characteristics of such materials.[16] In particular, we examined the effect of tool rotational speed (ω), traverse speed (V), shoulder temperature (T), and number of passes (N) on the mechanical properties of a PP/EPDM nanocomposite, containing 5wt% nanoclay, which we fabricated via FSP with the use of a new tool. This tool—which includes a pin, Teflon-coated shoulder, ball bearing, and heating system (see Figure 2)—can be used to fabricate a polymer nanocomposite, of specific size, in the base material.[10]

To produce the PP/EPDM nanocomposite for this study (i.e., with a 5wt% nanoclay concentration), we used our new FSP tool to machine a

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Table 1. Optimum values and ranges for four FSP process parameters, as determined by visual inspection of samples.

Parameters	Range		
	Lower limit	Optimum	Upper limit
Rotational speed (ω), rpm	800	1000	1200
Traverse speed (V), mm/min	30	40	50
Shoulder temperature (T), °C	100	125	150
Number of passes (N)	1	2	3

2mm-wide and 22.5mm-deep groove into the base material and the nanoclay particles were then placed in the groove to a height of 1.2mm.[17] During the FSP for the final nanocomposite, we plunged the rotating pin into the groove until the underside of the shoulder touched the plate surface. We also moved the tool along the groove at a constant speed. We determined the optimum value and appropriate range for the FSP process parameters (see Table 1) through visual inspection of our samples. That is, we required a pin geometry and process parameters that did not have any significant impact on the macrostructure (surface) of the samples. The values we thus chose produced samples without any visible defects, such as degradation and flash defects.[17]

The perturbation plots we present in Figure 3 illustrate the effect of the various process parameters on the tensile strength and impact strength of our TPO nanocomposite samples. From these results it is evident that ω, T, and N have positive effects on the tensile strength, yet negative effects on the impact strength of the samples. We also observe that the tensile strength increases with increased V, up to a specific level. After this point, however, the tensile strength decreases with further V increases. We attribute these changes in the tensile and impact strengths of the nanocomposites to increased levels of nanoparticle dispersion in the sample matrix.[16, 18] In other words, our FSP-fabricated nanocomposites have better mechanical properties than nanocomposites that are fabricated via conventional techniques. The better dispersion of micro- and nanoparticles in the matrix arises because of the higher rotational speed and shear stress in FSP compared with the conventional fabrication approaches.

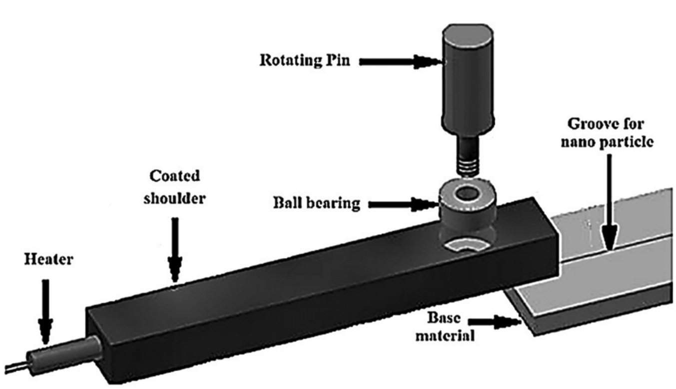

***Figure 2.** Schematic illustration of the new FSP tool used in this study. The tool consists of a pin, Teflon-coated shoulder, ball bearing, and heating system.*

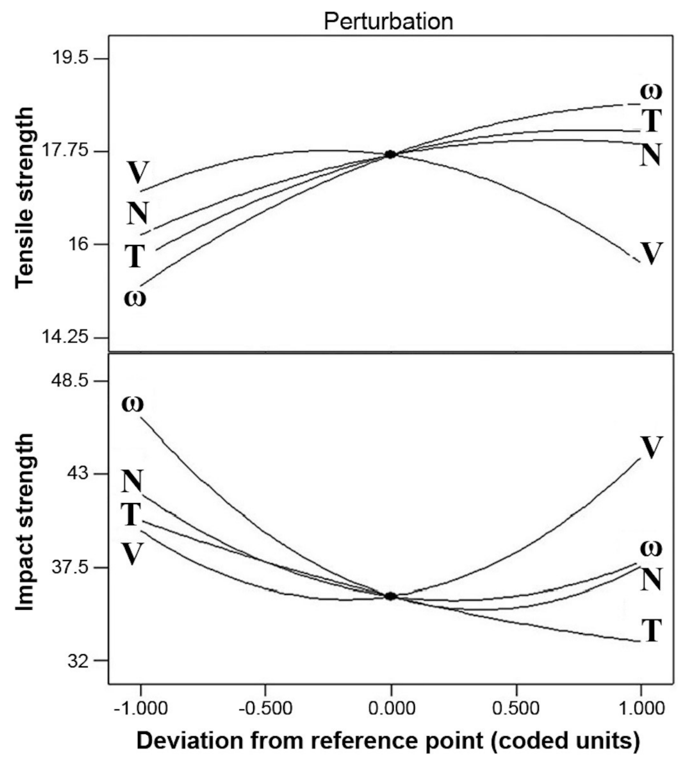

***Figure 3.** Effect of FSP parameters on the mechanical properties of the nanocomposites: (top) tensile strength; and (bottom) impact strength. Results are shown for the effect of (top) V, N, T, and ω on tensile strength and (bottom) ω, N, T, and V on impact strength.*

In our study we also investigated how variations in the pin geometry can influence the mechanical properties of our PP/EPDM/clay FSP-fabricated nanocomposites. The three different geometries—a plain and threaded cylindrical pin, a square pin, and a threaded taper pin—that we examined are illustrated in Table 2. From these three geometries, we achieved the best mixing and dispersion of the nanoclay particles through the processed zone with the cylindrical pin. This is because of the larger contact surface, and the greater amount of stirring and frictional heat that was generated.[16]

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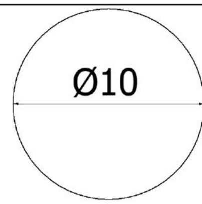
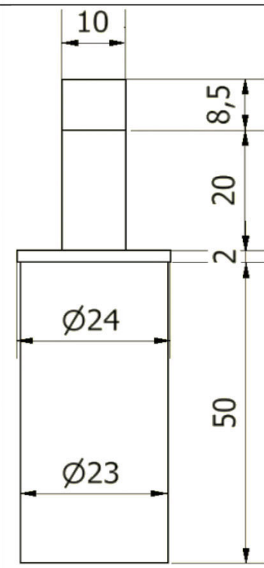
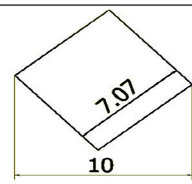
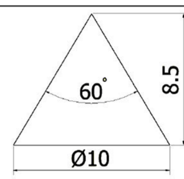
Table 2. *Geometry and dimension of the different threaded pins (used as frictions stir tools in FSP). ϕ: Diameter.*

<table>
<tr><th>Name</th><th>Pin Dimension (mm)</th><th>Dimension(mm)</th><th>Tool shape</th></tr>
<tr><td>Plain and Threaded cylindrical pin</td><td></td><td rowspan="3"></td><td></td></tr>
<tr><td>Square pin</td><td></td><td></td></tr>
<tr><td>Threaded taper pin</td><td></td><td></td></tr>
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In summary, we examined how various FSP process parameters and settings can effect the tensile strength and impact strength of fabricated PP/EPDM/clay nanocomposites. We determined the FSP optimal conditions for our specific nanocomposite (containing 5wt% nanoclay) as a rotational speed of 1200rpm, a traverse speed of 55mm/minute, a shoulder temperature of 137°C, and three passes. Under these conditions we achieved the maximum tensile strength and impact strength values of 17.8MPa and 50.5J/m, respectively. In our future work we will focus on the fabrication (via FSP) of other TPO nancomposites, i.e., that contain different types of nanoparticle. We will continue to investigate the effect of process parameters on the morphology, rheology, and thermal characteristics of these nanocomposites.

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