Improvement in Mechanical Properties of Aluminum Polypropylene Composite Fiber

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Abstract: Aluminum particles (Al) were added to polypropylene (PP) in the presence of poly ethylene glycol (PEG) and *polypropylene-graft-maleic anhydride* to produce composites. The composites were then melt-spun into a mono filament and tested for tensile properties, diameter evenness and morphology. Melt rheological properties of Al/PP composites were studied in linear viscoelastic response regions. It was observed that level of dispersion of aluminum particles within a polypropylene composite fiber could be improved by incorporating polyethylene glycol. The improvement of dispersion led to an improvement in the fibers mechanical properties through a reduction of the coefficient of variation of fiber diameter.

Keywords: Mechanical property, Composite fiber, Metal-filled polymer composite, Dispersion, Rheology

Introduction

Due to the rapid evolution of small and light electronic devices there has been a requirement to develop light weight materials for electromagnetic radiation (EMR) shielding. EMR from one electronic device can interfere with the operation of another electronic device [1,2]. This phenomenon is called electromagnetic interference (EMI). EMI can be reduced or avoided by shielding one or more of the electronic devices.

There are two general approaches to achieve light weight materials for EMR shielding; one is achieved by incorporating conductive filler (metal particles, metal-coated glass, or carbon fibers) into a polymer matrix [3-7] and the other is coating a light weight structure with conductive materials [8,9]. The metallic coating of plastic is well established, however it requires the manufacturer to undertake a secondary process and purchase extensive capital equipment to EMR shield an electronic casing component. The manufacture of the same casing component from a metal filled polymer composite provides a one step process to produce an EMR shielded product.

Metal-filled polymer composites have been of interest for electrical conductivity, heat conduction as well as electromagnetic interference shielding due to their light weight and ease of formability [10-17]. They can have electrical characteristics close to metals while their mechanical properties and processing behaviors are like plastics [1,18-20]. Further improvement of the property of metal-filled polymer composites can be achieved by introducing sub micron or nano scale metal particles into the polymer matrix [21,22].

One of the major issues in the manufacture of particle filled polymer composites is poor particle dispersion and particle aggregation. The dispersion of particles in the polymer matrix can have a considerable effect on the mechanical properties of the composites either in filament, film or solid forms. A homogenous dispersion can be achieved by surface modification of particles which in turn brings significant improvement in mechanical properties [23-25].

Most research has focused on the preparation and characterization of metal-filled polymer composites in form of plaques, sheets and films [26-33]. There have been limited publications on the extrusion into fibers of this class of polymer composites. The control of dispersion is an important and critical issue in processing composite fibers. The level of particle dispersion within the polymer matrix of composite fibers dictates the success of a composite fiber. Compatibilizer such as polypropylene-graft-maleic anhydride (PP-g-MA) has been found to be very effective to induce dispersion of fillers within PP matrix and in promoting interfacial adhesion [34-37]. The purpose of this study is to improve the processability and mechanical properties of Aluminum polypropylene composite fibers by the addition of polyethylene glycol (PEG) and polypropylene-graft-maleic anhydride (PP-g-MA).

Experimental

Materials and Preparation of PP/Al Composite Fibers

Al/PP composites at different filler contents, 1.0, 5.0 and 10.0 wt%, were prepared by ultrasonic dispersion. Aluminum flakes with the average size of 2 μm (Blitz Duval) and polyethylene glycol (PEG) with a molecular weight (Mw) of 20,000 g/mole (Sigma-Aldrich) were added to acetone. The mixture was agitated in an ultrasonic bath for 10 minutes at a sweeping frequency between 30-40 kHz. Moplen PP 183 (Basell Australia) was added to the mixture. The mixture was then agitated for a further 10 minutes. The resulting

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mixture was left under a fume hood to allow the acetone to evaporate off. Drying was then completed in a vacuum oven at 85 °C for 2.5 hours. Same preparation procedure was used to prepare Al/PP blends containing PP-g-MA (Arqema, Mw=50,000 g/moles) with the same concentration as PEG.

A lab-scale Maxwell mixing extruder (SDL Atlas) was used for melt blending and extruding the composite fibers. The machine settings used for blending were 170 °C rotor temperature, 180 °C die temperature, 0.10 mm head space and a rotor speed of 50 rpm. The blended polymer pellets were spun at 190 °C rotor temperature, 210 °C die temperature, 0.10 mm head space and a rotor speed of 50 rpm. The fiber was collected on a bobbin at 34 m/min wind up speed. The collected fiber was then post drawn by passing fiber through an oven set at 130 °C. The oven length was 58 cm and the applied draw ratio was 1.2:1.

Characterization

Prior to testing, samples were conditioned for 24 hours according to AS 200/1995. Tensile tests were performed in accordance with the ASTM method D3822-96 (Standard Test Method for Tensile Properties of Single Textile Fibers) using a SIFAN 2 (BSC Electronics) single fiber tensile tester. The gauge length was set at 25 mm for each test. At least twenty single fibers were measured for each batch of composite fibers. The mean diameter, CV of diameter, tenacity and elongation at break were determined. Morphological characterization of the longitudinal composite filament samples was conducted using an Olympus standard bright field reflected light optical microscope. Images were obtained using a digital camera attached to the microscope. Rheological properties in molten state of all composite samples were determined by dynamic mechanical measurements in disk form (diameter 25 mm; thickness 1 mm). Storage modulus (G'), loss modulus (G") and dynamic viscosity (η) were measured as a function of frequency at 230 °C using a strain-controlled rheometer (ARES, TA Instruments).

Results and Discussion

The complex viscosities (μ) at 230 °C for PP and its Al composites with PEG and PP-g-MA as a function of frequency is presented in Figure 1. The complex viscosities decreased with the increase of frequency, indicating a non-newtonian behavior and pseudoplastic characteristics of Al/PP composites. Incorporation of Al particles into PP matrix slightly increased the complex viscosity compared to that of pure PP. When introducing PEG, homogeneous dispersion of Al particles within the PP matrix and/or physical interactions between the Al and the matrix increase remarkably. This results in the increase of the complex viscosities of the composites as shown by Figure 1. The addition of aluminum increased the viscosity of the polymer at low shear rates. The higher the loading of aluminum, the higher the increase in
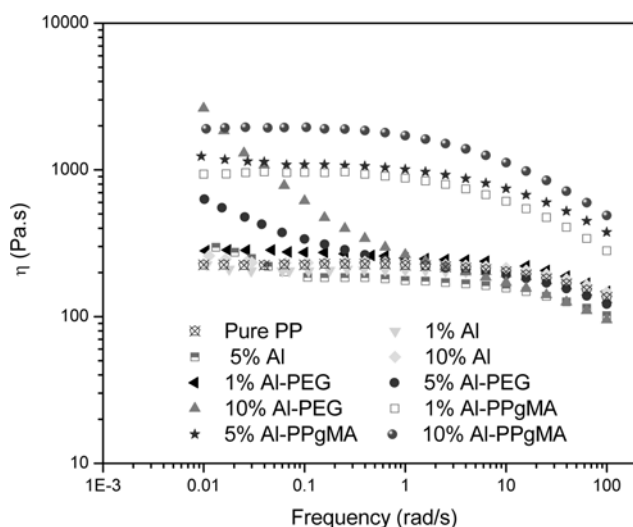

Figure 1. The complex viscosity versus frequency for pure PP and composite fibers.

viscosity. The addition of polyethylene glycol caused a significant increase in viscosity at low shear rates. The higher the loading of aluminum, the higher the increase in viscosity. This behavior can be explained by particle interactions, leading to high viscosity at low shear rates; but at high shear rates the viscous stresses predominate over particle interactions and the viscosity is less. This may be because when the Al content is high, the particles tend to agglomerate into a network structure which is readily destroyed by shear. The viscosity of the composite will then be determined largely by the polymer matrix at high shear rates; but at low shear rates the composite viscosity is more influenced by the strength of bonding in the network structure. Composites that contained PP-g-MA have higher viscosities than those that contained PEG. This could partly be due to the higher molecular weight of PP-g-MA. The enhancement of viscosity is most significant in the high frequency region which may suggest a change from liquid-like behavior to solid-like behavior at high frequencies [38].

The storage modulus (G') and loss modulus (G") of the Al/PP composites at 230 °C as a function of frequency are shown in Figure 2. It is apparent than Al does not have a significant effect on the rheological behavior of PP matrix particularly at high frequency, even at a loading level as high as 10 wt%. However, the storage modulus and loss modulus of the Al/PP that contained either PEG or PP-g-MA were significantly improved compared to the PP matrix, particularly at low frequency. At high frequencies, the effect of PEG on the rheological behavior is relatively weak compared to PP-g-MA as shown in Figure 2. This may suggest that the presence of PEG does not significantly influence the short-range dynamics of the PP chains rather has substantial influence on large-scale polymer chain relaxation.
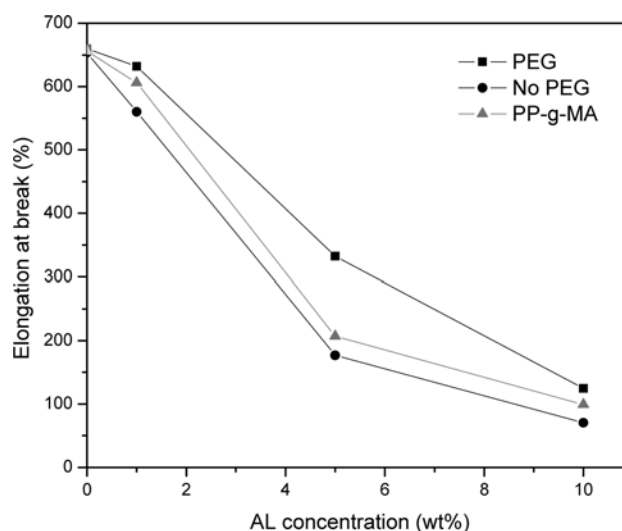
Tensile strength and strain values of both the neat PP and
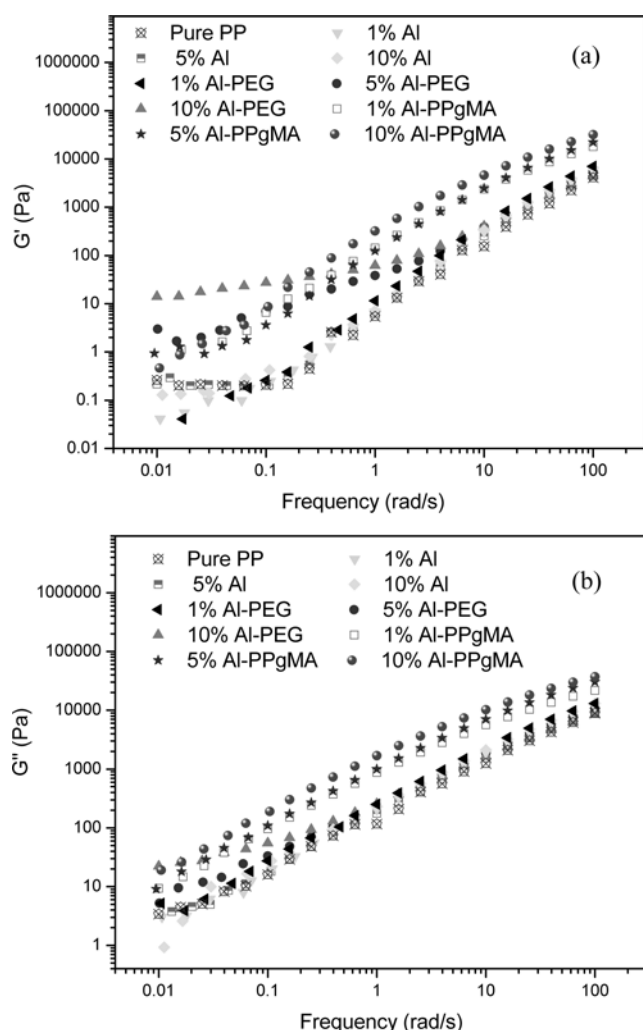
Figure 2. The frequency dependence of (a) storage modulus and (b) loss modulus of Al/PP composite fibers at 230 °C.
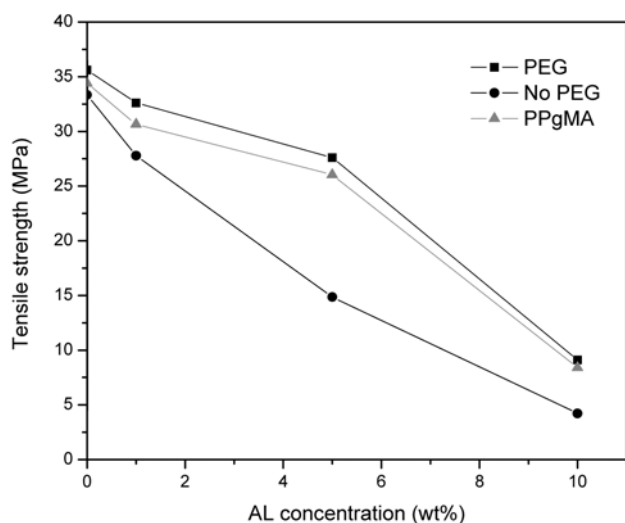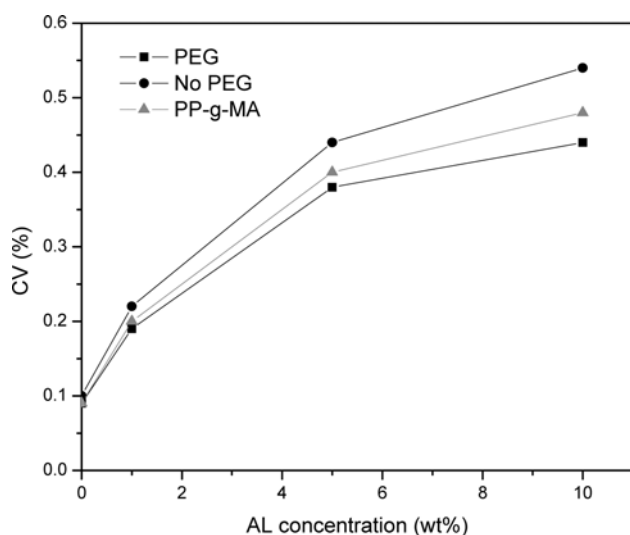

Figure 3. Tensile strength of Al/PP composite fibers with PEG and PP-g-MA.


Figure 4. Elongation at break of Al/PP composite fibers with PEG and PP-g-MA.

Al/PP composite fibers are plotted in Figure 3 and Figure 4, respectively. The tensile strength and strain of the neat PP fibers were 33.34 MPa and 653.58 %, respectively. Presence of PEG and PP-g-MA slightly increased the tensile strength and strain of neat PP fibers. All Al/PP composite fibers have lower tensile strength and strain compared to neat PP fibers and these properties deteriorated further with increasing amount of Al particles. This decrease happened much quickly for fibers not blended with PEG and PP-g-MA. PEG is more effective than PP-g-MA for imparting tensile strength and elongation at break for all Al concentrations. Higher tensile strength and elongation at break for samples that contained PEG and PP-g-MA are the result of improved Al particle dispersion within the composite. Poor particle dispersion within the polymer leads to agglomerations of Al particles. The agglomeration tends to occur in areas with a high Al to polymer ratio. The higher the Al content the poorer the mechanical properties. The weakest link theory proposed by Peirce [39] suggests that a material will fail at its weakest point. As high agglomeration points in Al particle fibers have lower mechanical properties than the rest of the fiber the fiber will fail at the point of high agglomeration.

To confirm the effect of improved Al particle dispersion by the addition of PEG and PP-g-MA the fiber diameter profile was measured using a SIFAN 2 instrument. Figure 5 shows a plot of the coefficient of variation in fiber diameter (CV %) versus Al blend concentration for both blending systems. As can be seen, variation in fiber diameter increased by incorporating Al particles, however, fiber evenness was improved at all Al blend ratios for composite fibers that contained PEG and PP-g-MA compared to their neat PP fiber counterparts. Presence of PEG led to 20 % improvement in evenness of composite fibers containing 10 wt% compared to its neat composite fiber counterpart.

**Figure 5.** Evennness of Al/PP composite fibers with PEG and PP-g-MA.
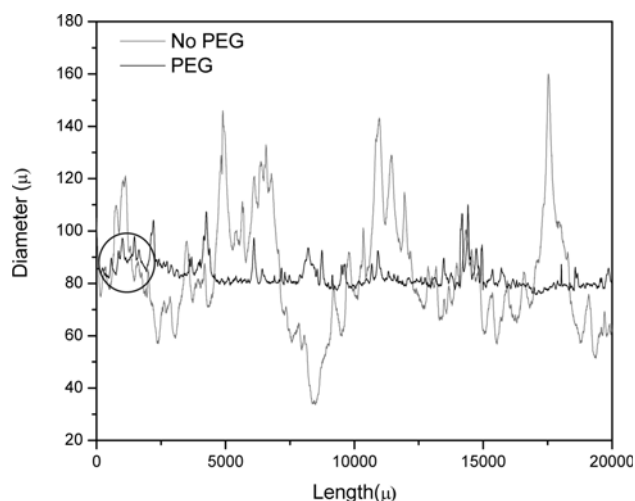
Figure 6. Diameter variation of 10 %wt Al/PP composite fibers.

To further demonstrate the improved fiber diameter uniformity due to presence of the compatibilizer, the diameter versus length plots of 10 % Al particle filled fibers, with and without PEG, are shown in Figure 6. The fiber without PEG shows a large number of thick points along its length whereas the fiber with PEG is moderately uniform. Optical microscopy of the circled section of Al/PP composite fibers shown in Figure 6 was used to determine the composition of the thick points along the length of the fiber.

Figures 7 and 8 show the optical microscope images of the circled section previously shown in Figure 6. The fiber containing PEG shows a more uniform diameter along its length when compared to the fiber without PEG. The fiber that does not contain PEG shows a series of agglomerated particles around the larger diameter parts of the fiber.
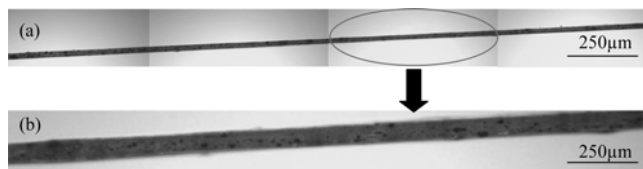
Figure 7. Micrograph of 10 %wt Al/PP composite fiber with PEG.
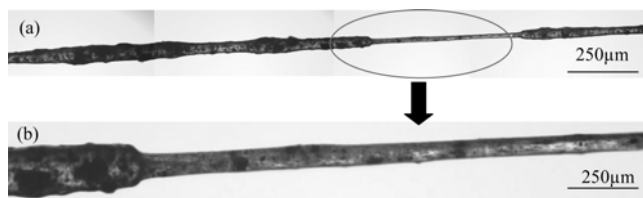
Figure 8. Micrograph of 10 %wt Al/PP composite fiber without PEG.

Figures 7(b) and 8(b) show a higher magnification of the images in Figures 7(a) and 8(a), respectively. The higher magnification highlights the number of agglomerated particles within the fiber that does not contain PEG. Wherever there were large agglomerated particles in the fiber the drawing process was inhibited. When the fiber contained small or no agglomerated particles, a uniform drawing process was achieved. Variation in drawing leads to large variation in fiber diameter and creates weak points along the fiber. Inconsistency in fiber properties (strength and diameter) limits end-use applications of these fibers. Figure 7 also shows that the addition of PEG has not stopped the agglomeration of particles completely however it has reduced the size and the frequency of the agglomerations. Improvement in Al particle dispersion within PP matrix due to presence of PEG led to improved uniformity of Al/PP composite fibers. This suggests that there is a physical interaction in which the PEG coats the surface of Al particles. The compatibility of PEG with PP is far better than the compatibility between PP and Al particles alone. In fact PEG is functioning like a molecular bridge. PP is a non-polar material and Al is strongly polar due to the oxide layer on its surface. There is a hydrophobicity-hydrophilicity balance in PEG that enables it to combine with both the polar Al and the non polar PP. So there is a non-reactive treatment of Al particles by PEG which aids Al dispersion and consequently increases tensile strength and uniformity of resulting Al/PP composite fibers.

Conclusion

This study has shown that PEG and PP-g-MA can be used to attain improved dispersion of aluminium (Al) particles within a polypropylene (PP) matrix, leading to improved uniformity and tensile properties for the extruded Al/PP composite fibers. Better improvement in fiber tensile

properties was achieved with the PEG than with the PP-g-MA. PEG seems to act as a compatibilizer which causes increased dispersion of the Al within the matrix and hence a reduction in agglomeration. The addition of PEG also improves the evenness in diameter of Al/PP composite fibers during drawing. Rheology results also suggest that the presence of PEG does not significantly influence the short-range dynamics of the PP chains but has a substantial influence on large-scale PP chain relaxation.

Acknowledgements

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