Tensile, rheological and morphological characterizations of multi-walled carbon nanotube/polypropylene composites prepared by microinjection and compression molding

Gulstan S. Ezat[1*], Adrian L. Kelly[2], Mansour Youseffi [3], Phil D. Coates [2]

[1] Department of Physics, College of Science, University of Sulaimani, Qlyasan Road, Sulaimani 4600, Iraq
[2] Polymer IRC, Faculty of Engineering and Informatics, University of Bradford, Bradford, BD7 1DP, UK
[3] Faculty of Engineering and Informatics, University of Bradford, Bradford, BD7 1DP, UK

Abstract

Polypropylene (PP) reinforced with 2 and 4wt% of multi-walled carbon nanotubes (MWNT) were melt-blended in twin screw extruder and then molded by compression or micromolding process. The impact of injection speed on the surface morphology, rheological and tensile characteristics was investigated by using a scanning electron microscope, parallel plate rheometry, and tensiometry. Results showed that the tensile properties of micro-molded specimens were remarkably higher than the compression molded sheets. Compared to compression molded sheets, micromolded specimens demonstrated up to 40% and 244% higher tensile stiffness and yield strength, respectively, most likely due to the alignment of polymer chain segments in the flow direction induced during the micromolding process. It was observed that the fast filling speed caused a drop in the tensile properties of the nanocomposites and polymer. Rheological examination revealed that the presence of a rheological percolation network in the nanocomposites produced by micromolding and the fast injection speed was beneficial for establishing the percolated network. Morphological examination revealed that the size of nanotube agglomerations that appeared in micromolded specimens was up to 5 times smaller than in compression molded sheets and the agglomeration size decreased with the increase of the injection speed.

*Corresponding author: Gulstan S. Ezat
Department of Physics /College of Science/University of Sulaimani/ Sulaimani/ Iraq
E-mail address: Gulstan.ezat@univsul.edu.iq

KEYWORDS

Polypropylene, nanocomposites, microinjection molding, injection speed, compression molding.

1. INTRODUCTION

Micromolding is known as one of the most precise fabrication tools to make micro-featured plastic shapes for utilizations in microelectronics, medical, and micro-electromechanical systems (Fassi an Shipley, 2017; Surace at el., 2012). It is the minimize form of the conventional injection molding (IM) techniques that have the potential of producing micro-sized parts using small amounts of materials. During micromolding process, high injection pressure and extreme shear rates are employed at a short filling time, which produces micro components of higher surface quality and better dimensional accuracy than the macro components produced by IM (Giboz et al., 2012).

Among commodity plastics, polypropylene plays an important role in the plastic industry owing to its high durability, good thermal, chemical stability, and easy processability. As a result of expanding industry, the demand for new applications needs further modification in the functionality of plastics in terms of mechanical electrical, and thermal characteristics (Maddah, 2016).

Carbon nanotube/polypropylene nanocomposites are favorable materials with advanced mechanical and electrical characteristics for making macro-scale components in both electronics and medical sectors (Gulrez et al., 2014). One of the main technical issues in the preparation of polypropylene nanocomposites is the agglomeration of carbon nanotubes in the polymer matrix. Carbon nanotubes tend to form bundles because of the huge surface energy which is associated with the high length to diameter ratio of the nano-sized tubes and the strong intermolecular forces that hold individual tubes together. Breaking up nanotube agglomeration can be difficult, particularly, when it is mixed with non-polar polypropylene (Du et al., 2007; Ezat et al., 2011, Ezat et al., 2019).

Processing the carbon nanotube polymer composites by micromolding (μM) is preferred as a large-scale production of micro-products using only a few grams of expensive carbon nanotubes. The intensive thermomechanical history experienced by micromolding component results in significant variations in polymer chain orientation under shear and extension flows which produce complex microstructures that can be controlled by processing conditions. Investigations on the microstructures of microinjection molded polypropylene have found similar skin-core features as in macro parts. A skin-shell layer consisting of highly aligned polymer chain segments and a spherulitic core layer with random orientations of polymer chains were observed in both parts. On the other hand, due to the large thermal gradient across the small specimen, the thickness of shell layers and the degree of crystallinity in micro molded parts were found to be greater than in the macro parts (Chu et al., 2007; Liu et al., 2012; Whiteside, 2004). This kind of skin–core microstructure present during micromolding process depends highly upon the processing parameters and can significantly influence the mechanical behavior of the micro-parts. Among different parameters, injection speed is known as the most dominant parameter that has a vital role in the morphology and properties of micromolded parts (Kamal et al., 2010; Wang et al., 2019). The variation of injection speed in the nanocomposites can control the stretching of polymer chains in the flow direction, consequently helps the nanotube agglomerations to redistribute and align within the specimen.

To date, several types of research have been reported on the properties of micromolded nanocomposites (Abbasi et al., 2011; Lee et al., 2020; Pagano et al., 2018; Zhou et al., 2016; Zhou et al., 2017; Zhou et al., 2018; Zhou et al., 2019) while much fewer researches have been conducted on the correlation-ship between injection speed in micromolding and physical characteristics of carbon nanotube-polymer composites (Zhou et al., 2016; Zhou et al., 2017). Investigations have mainly concentrated on the morphology development and electrical conductance of the nanocomposites and almost no research has been published about the influence of the injection speed on the stiffness and strength of micromolded nanocomposites.

In this study, the properties of MWNT/PP composites prepared by compression and micromolding processes are investigated. The correlation between speed of injection, tensile, rheological and, morphological properties of micromolded MWNT/PP composites are presented and compared to the compression molded counterparts.

2. EXPERIMENTAL

2.1 Materials

Polypropylene homopolymer with melt flow index (MFI) 3.0 g/10 min (100-GA03; Ineos, Hampshire, UK.) was used in this study. Multi-walled carbon nanotubes with an average length of 10-30µm, the outside diameter of 20-40nm, and the inside diameter of 5-10nm were purchased from Cheap Tubes Inc. (USA). The nanotubes were used directly as they were supplied by the manufacturers. For optimization purposes, polypropylene pellets were ground into fine powders of about 100 µm at the Polymer Processing Research Centre in Queen's University, Belfast.

2.2 Nanocomposite preparation and molding

The PP powder was mechanically premixed with 2 and 4wt% of nanotubes, then the dry blends were melt-mixed in a (Prism-TSE-16-TC, UK) twin-screw extruder at a screw speed of 100 rev/min. A screw feeder designed at Bradford University was used to feed the dry mixture. The temperature profile was set at 180, 200, and 210°C from the feeder section to the die section. The obtained blend was chopped after cooling in a water bath and subjected to compression and micromolding processes.

A dumbbell shape micro tensile bars with dimensions of 6mm×0.5mm×0.25mm were produced using a Microsystem (Battenfeld 50, Germany). A volume of 201mm^3 of the chopped blends was used at a clamping force of 60KN and constant holding pressure of 100MPa. The mold and barrel temperatures were 45 and 210°C, respectively. To evaluate the influence of injection speed on the performance of the nanocomposites, the injection was carried out at three speeds (100, 200, and 300mm/s). For comparison, unfilled polypropylene (PP) was processed under the same conditions. The resulting samples were nominated as x%MWNTy, where x represents the weight fraction of nanotubes (wt.%) and y refers to the injection speed. Hence 2%MWNT-100 represents PP composites containing 2wt% nanotubes produced by micromolding at 100mm/s.

To compare the nanocomposite properties before and after microinjection molding, compression molded (CM) sheets were also prepared using a heated press (Moore Ltd., UK) at the temperature of 230°C and pressure of 300MPa for three minutes. The molten composites were quenched in cold water, a dumbbell shape specimens with dimensions of 33mm×6mm×1.2mm were cut from the sheets and used for tensile test.

2.3 Measurement of tensile characteristics

Tensile analyzes of micromolded and compression molded specimens were studied by using a Bose ElectroForce 3220 dynamic mechanical analyzer and an Instron 5564 tensometer, respectively. The tensile test of micro and macro tensile bars was carried out according to ASTM

E-2309 and BS EN ISO 527-1, respectively, at a deformation rate of 5mm/min. To ensure accuracy in the measurements the value of standard errors and mean value of five specimens were calculated from each blend.

2.4 Rheological analysis

Dynamic rheological behavior of the micromolded and compression molded nanocomposites was investigated by using Anton Paar (MCR 501) parallel plate rotational rheometer. The tensile bars were placed between the rheometer plates and the molten material was trimmed off to achieve a smooth surface with 0.5 mm gap. The test was conducted at 200^{o}C in the frequency range of 0.01 to 100 rad/s. For all measurements, the shear strain was kept at 5% within the linear viscoelastic region of the material.

2.5 Morphological characterization

The morphology of micro tensile bars and compression molded sheets were characterized using a Quanta scanning electron microscope (ESEM, FEI Quanta 400) with an operating voltage of 20 kV. Before examinations, the specimen was fractured in liquid nitrogen and then followed gold sputtering to prevent electron charging.

3. RESULTS AND DISCUSSION

3.1 Tensile properties

Figure 1 shows the tensile modulus of polypropylene containing 2 and 4wt% MWNT for compression and micromolded specimens produced at various injection speeds. It can be observed that the tensile modulus of compression and micromolded specimens produced at 100 mm/s followed by a similar trend, the modulus of both specimens was increased with the incorporation of carbon nanofillers. This may suggest that the nanotube dispersion in micro tensile bars was identical to the compression molded sheets. The enhancement of PP stiffness by incorporation of carbon nanotubes is due to the reinforcement effect of the filler as well as the modification of polymer crystallinity by the nanotubes. The highest value of tensile modulus was observed for the micro tensile bars processes at 100mm/s, which was up to 40% higher than the compression molded sheets. This is possibly related to the presence of a large fraction of highly oriented polymer molecules in the micromolded specimens which resulted in the enhancement of the material stiffness (Giboz et al. 2010; Liu et al., 2012; Kamal et al., 2010). Another possible reason for the higher value of stiffness of the micromolded specimens is due to the rise of crystallinity level and increase of nucleation density in these specimens (Zhao et al., 2020). Figure 1, also demonstrates that the use of fast injection speed had a negative impact on the modulus of filled and unfilled polymers, particularly at a 4% loading. The decrease in the modulus of unfilled polypropylene at high injection speed has also been observed by others (Wang et al., 2019) who explained that the decrease in polymer chain orientation due to the effect of shear-heating resulted in the distortion of crystal structure within the specimen.

It is demonstrated in Figure 2, that the micro tensile bars exhibited a 244% higher value of yield stress than the compression molded sheets. The yield strength of both types of specimens appeared to be unaffected by nanotube concentrations. This finding is in agreement with other studies (Zhou et al., 2019), where the incorporation of carbon nanotubes had a negligible effect on the strength of the polymer, suggesting a poor interface between the nanotubes and the matrix. Moreover, similar to the tensile modulus displayed in Figure 1, increasing injection speed had a negative influence on the yield strength of polypropylene and the nanocomposite. A 14% drop in tensile strength of high-density polyethylene by an increase of injection speed from 15 to 120mm/s have also been reported by others (Bociąga, 2001) during conventional injection molding; this was attributed to the formation of bubbles in the products because of incomplete removal of air from the impression due to the shortness of the injection time. Another possible reason for the reduction in tensile properties of polypropylene and the nanocomposites at high injection speed can be referred to as the rise of temperature in the gates and degradation of polymers under elevated shear rates at fast injection speed.

3.2 Rheological analyzes

Complex viscosity of micro tensile bars and compression molded polypropylene containing 0, 2, and 4wt% carbon nanotubes produced at various injection speeds are shown in Figure 3. From Figure 3 it can be observed that the viscosity of unfilled PP treated by CM and µM were remained steady under low frequencies, indicates the flow behavior of Newtonian fluids. With the incorporation of nanotubes, the viscosity of PP increased and the rate of increase was more apparent for the nanocomposite processed by µM. At 4wt% nanotubes the viscosity of the composites processed by µM deviated from Newtonian behavior and became more dependent upon the frequency, suggesting that the transition from viscoelastic liquid-solid took place in the composites processed by µM due to the development of rheological percolation network.

The rheology of polymer nanocomposites has frequently been utilized to examine the interaction between the CNT and the polymer matrix. The greater values of complex viscosity at low frequencies were attributed to the higher state of nanotube dispersion and interaction within the polymer (Ezat et al., 2012; Han et al., 2009; Zhang et al., 2008). It can be seen from Figure 3 that the increase in injection speed had a more dramatic effect on the complex viscosity of the nanocomposite than the unfilled polymer, indicating that the application of high injection speed decreased the entanglement of nanotubes and enhanced their distribution within the polymer.

The relaxation behavior of the nanocomposites treated by the CM and µM process was studied in a Cole-Cole plot by plotting a graph of imaginary viscosity (η'') versus real viscosity (η'). In the literature, the change in the shape of the Cole-Cole plot from a single arc into double arcs has been used to identify the percolation of the filler and to analyze stress relaxation in the molten composite (Abbasi et al., 2009; Song and Zheng, 2015; Wu et al., 2007).

Figure 4 shows the Cole-Cole plot from which it can be observed that for PP processed by CM and µM the plot exhibited one arc corresponding to the relaxation of the PP matrix. The plot shows that only the nanocomposites with 4wt% MWNT loading processed by µM displayed two arcs. The tail at high viscosity is attributed to the long-term relaxation of the nanotubes. This suggests that due to the better dispersion state of the nanotube in the nanocomposites processed by µM, maximum interaction among the nanoparticles occurred which restrained the long-range motion of the polymer chains and consequently retarded the relaxation process [see SEM analysis].

To further clarify the impact of injection speed on the thermo-rheological behavior of MWNT/PP composites, the phase angle (delta) was plotted versus the absolute value of the complex modulus (G*) following the Van Gurp-Palmen method which is presented in Figure 5. According to the Van Gurp-Palmen method, the drop in the value of phase angle and the presence of plateau at a low modulus corresponds to the formation of the rheological network in the materials (Song and Zheng, 2015). Figure 5, displays that at low complex moduli, the phase angle of PP approached 90^{o}, which represents the flow characteristics of a viscoelastic fluid. The decrease in the value of phase angle to below 45^{o} was only observed at 4wt% of nanotubes for the nanocomposites processed by µM. The application of the faster injection speed leads to a greater shift in the phase angle. These results confirm that the rheological percolation threshold was occurred at 4wt% of nanotube concentrations for the nanocomposites produced by µM and suggests that the increase in filling speed promoted the physical contact between the filler and the polymer (Das and Satapathy, 2014)

3.3 Dispersion of MWNT

Figure 6 illustrates the dispersion states of the fractured surfaces of the nanocomposites processed by compression and micromolding. In order to make a reliable analysis, for each specimen, two images were collected from two different sites of the specimens. Figure 6a,b demonstrates that for the nanocomposite sheets the nanotubes were highly agglomerated, only a few individuals of nanotubes were present within the polymer and most of them formed bundles of diameter larger than 10µm. From Figure 6c,d, it can be observed that dispersion of nanotubes for the micro tensile bars processed at an injection speed of 100mm/s was slightly better than for nanocomposite sheets, i.e. larger number of smaller aggregation can be seen in these composites and the diameter of nanotube agglomerations reduced to about 3-5µm. For the nanocomposites processed at 300mm/s (Figure 6e, f) the majority of nanotubes appeared to be well dispersed individually and the size of nanotube agglomerates was dramatically reduced to less than 2µm. This is consistent with the tensile test results and may indicate that the greater tensile properties of the mico specimens were partly due to the enhancement of nanotube dispersion.

The increase in the degree of nanotube dispersion in the specimens produced at faster injection speeds can be related to the increase of extensional stress and the fast cooling time which caused a rapid freeze of the specimens and prevented the nanotubes from re-agglomerate. Enhancement of nanotube dispersion in polypropylene composites produced by micromolding has also been reported by a previous study (Abbasi et al., 2011) which was attributed to the high shear stress and the small size of the spherulites which developed during micromolding. These results are in agreement with the rheological analyzes, confirm that the fast injection speed applied during the micromolding process facilitates nanotube dispersion, consequently assisted the formation of the rheological percolation network.

4. CONCLUSIONS

The influence of injection speed on the properties of microinjection molded polypropylene filled with 2 and 4wt% of multiwalled carbon nanotubes was investigated. The morphology, tensile and viscoelastic properties of the nanocomposites processed at injection speeds of 100, 200, and 300 mm/s were examined and compared to the properties of nanocomposite counterparts treated by compression molding. Relative to the compression molded sheets, the micro tensile bars exhibited up to 40% and 244% greater value of tensile modulus and yield strength, respectively. This is possibly due to the high degree of orientation of the polymer molecules and carbon nanotubes developed under extreme shear rates during micromolding process. The addition of nanotubes enhanced the modulus and the strength of both types of specimens by the same degree. The modulus and strength of the nanocomposites processed at an injection speed of 100mm/s were higher than those processed at an injection speed of 300mm/s. Rheological characterizations indicated that the relaxation of polypropylene was hindered in the nanocomposites treated by micromolding process due to percolation at 4% nanotube concentration. An increase in injection speed caused a pronounced deviation from the ideal polymeric melt rheology at low frequencies, indicated the enhancement of viscoelastic behavior. Scanning electron microscopy confirmed that the employ of fast injection speed broke the nanotube entanglement and reduced the agglomeration sizes to less than 2µm.

REFERENCES

Abbasi S., Derdouri A., Carreau P. and Moan M. “Rheological Properties and Percolation in Suspensions of Multiwalled Carbon Nanotubes in Polycarbonate”, Rheol. Acta., 48, 943-959 (2009).

Abbasi S., Derdouri A. and Carreau P.J. “Properties of Microinjection Molding of Polymer Multiwalled Carbon Nanotube Conducting Composites”, Polym. Eng. Sci., 51, 992-1003 (2011).

Bociąga E. “Effect of Mould Temperature and Injection Speed on Selected Properties of Polyethylene Mouldings”, Int. Polym. Sci., 28, 96-102 (2001).

Chu J., Hrymak A. and Kamal M.R. "Microstructural Characteristics of Micro-Injection Molded Thermoplastics", ANTEC. Papers, 1985-1989 (2007).

Das D., Satapathy B. K. “Microstructure-Rheological Percolation-Mechanical Properties Correlation of Melt-Processed Polypropylene-Multiwall Carbon Nanotube Nanocomposites: Influence of Matrix Tacticity Combination”, Mater. Chem. Phys., 147, 127-140 (2014).

Du J-H., Bai J., and Cheng H-M. “The Present Status and Key Problems of Carbon Nanotube Based Polymer Composites”, EXPRESS Polym. Lett., 1, 253-273 (2007).

Ezat G.S., Kelly A. L., Mitchell S. C., Youseffi M. and Coates P.D. “Influence of Maleic Anhydride Compatibiliser On Properties Of Polypropylene/Multiwalled Carbon Nanotube Composites”, Plast. Rubber Compos., 40, 438-448 (2011), DOI: 10.1179/1743289810Y.0000000043.

Ezat, G. S., Kelly, A. L., Mitchell, S. C., Youseffi, M., and Coates, P. D. (2012), “Effect of maleic anhydride grafted polypropylene compatibilizer on the morphology and properties of polypropylene/multiwalled carbon nanotube composite”, Polym. Compos., 33, 1376-1386 (2012), DOI: 10.1002/pc.22264.

Ezat G.S., Kelly A. L., Youseffi M. and Coates P.D. “Effect of Screw Configuration on The Dispersion and Properties of Polypropylene/Multiwalled Carbon Nanotube Composite”, Polym. Compos., 40, 4196-4204 (2019), DOI: 10.1002/pc.25280

Fassi I., Shipley D. Micro-manufacturing technologies and their applications: a theoretical and practical guide, 1st Edition, Springer Publishers: Cham (2017).

Giboz J, Copponnex T. and Mélé P. "Microinjection Molding of Thermoplasticpolymers: Morphological Comparison With Conventional Injection Molding", J Micromech Microeng., 19, 1-12 (2009).

Giboz J., Vite M., Bec S., Loubet J.L., Copponnex and T., Mélé P. "Comparison of the Local Mechanical Properties of a Microinjection Moulded Part with a Classical One through Nanoindentation Tests", 4M. Papers, 17-19 (2010).

Gulrez, S. K., Ali Mohsin, M. E., Shaikh, H., Anis, A., Pulose, A. M., Yadav, M. K., and Al-Zahrani S.M. "A Review on Electrically Conductive Polypropylene and Polyethylene". Polym. Compos., 5, 900-914 (2014).

Han M.S., Lee Y.K., and Kim W.N., "Effect of Multi-Walled Carbon Nanotube Dispersion on The Electrical, Morphological And Rheological Properties of Polycarbonate/Multi-Walled Carbon Nanotube Composites", Macromol. Res.,17, 1863-1869 (2009).

Kamal M. R., Chu J., Derdouri S. and Hrymak A. "Morphology of Microinjection Moulded Polyoxymethylene" Plast. Rubber Compos., 39, 332-341 (2010).

Lee J. H., Park S. H., Kim S. H and Ito H. "Replication and Surface Properties Of Micro Injection Molded PLA/MWCNT Nanocomposites", Polym Test. 83, 1-8 (2020).

Liu F., Guo C., Wu X., Qian X., Liu H. and Zhang J. "Morphological Comparison of Isotactic Polypropylene Parts Prepared By Micro-Injection Molding and Conventional Injection Molding", Polym. Adv. Technol., 23, 686-694 (2012).

Maddah H. A. "Polypropylene as a Promising Plastic: A Review", Am. J. Polym. Sci., 6, 1-11 (2016).

Pagano C., Surace R., Bellantone V., Baldi F. and Fassi I. "Mechanical Characterisation and Replication Quality Analysis of Micro-Injected Parts Made of Carbon Nanotube/Polyoxymethylene Nanocomposites", J Comp Mat., 52, 1-13 (2018).

Song Y., and Zheng Q., "Linear Rheology of Nanofilled Polymers", J. Rheol., 59, 155-191 (2015).

Surace R., Trotta G., Bellantone V.and Fassi I. "Chapter 4 The Micro Injection Moulding Process for Polymeric Components Manufacturing" in New Technologies - Trends, Innovations and Research, Intech Publishers, Rijeka, p.65-90 (2012).

Wang L., Zhang Y., Jiang L., Yang X., Zhou Y., Wang X., Li Q., Shen C., and Turng LS. "Effect of Injection Speed on The Mechanical Properties of Isotactic Polypropylene Micro Injection Molded Parts Based on A Nanoindentation Test", J. Appl. Polym.Sci., 136, 1-8 (2019).

Whiteside, B.R., Martyn, M.T., Coates, P.D., Greenway, G., Allen, P. and Hornsby, P. "Micromoulding: Process Measurements, Product Morphology and Properties. Plast. Rubber Compos.,33, 1-11 (2004), DOI:10.1179/146580104225018346.

Wu D., Wu L., Sun Y. and Zhang M., "Rheological Properties and Crystallization Behavior of Multi-Walled Carbon Nanotube/Poly(E-Caprolactone) Composites", J Polym Sci Pol Phys., 45, 3137-3147 (2007).

Zhang Q., Fang F., Zhao X., Li Y., Zhu M. and Chen D., "Use of Dynamic Rheological Behavior to Estimate The Dispersion of Carbon Nanotubes in Carbon Nanotube/Polymer Composites", J . Phys. Chem. B, 112, 12606–12611 (2008).

Zhao Z., Zhang X., Yang Q., Ai T., Jia S. and Zhou S. "Crystallization and Microstructure Evolution of Microinjection Molded Isotactic Polypropylene with the Assistance of Poly(Ethylene Terephthalate)", Polymers., 12, 1-15 (2020).

Zhou S., Hrymak A. N., and Kamal M. R. "Electrical and Morphological Properties of Microinjection Molded Polystyrene/Multiwalled Carbon Nanotubes Nanocomposites", Polym. Eng. Sci., 1182-1190 (2016).

Zhou S., Hrymak A. N., and Kamal M. R. "Electrical and Morphological Properties of Microinjection Molded Polypropylene/Carbon Nanocomposites", J. Appl. Polym.Sci., 43, 1-9 (2017).

Zhou S., Hrymak A. N., and Kamal M. R. "Microinjection Molding of Polypropylene/Multi-Walled Carbon Nanotube Nanocomposites: The Influence of Process Parameters", Polym. Eng. Sci., 58, E226-E234 (2018).

Zhou S., Hrymak A. N., and Kamal M. R. "Electrical, Thermal, And Mechanical Properties of Polypropylene/Multiwalled Carbon Nanotube Micromoldings", Polym. Compos., 41, 1507-1520 (2019).

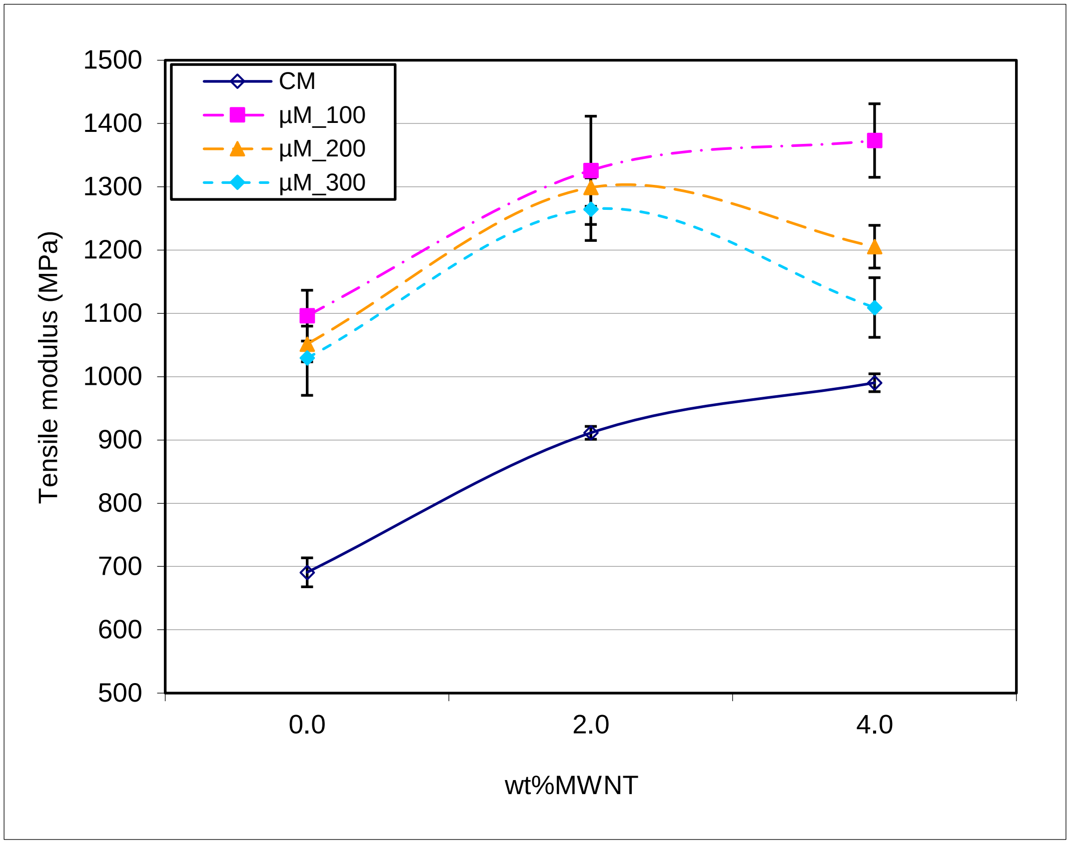

Figure 1 Tensile modulus of MWNT/PP composites with respect to nanotube concentrations for compression molded (CM) sheets and micromoulded (µm) specimens produced at different injection speeds

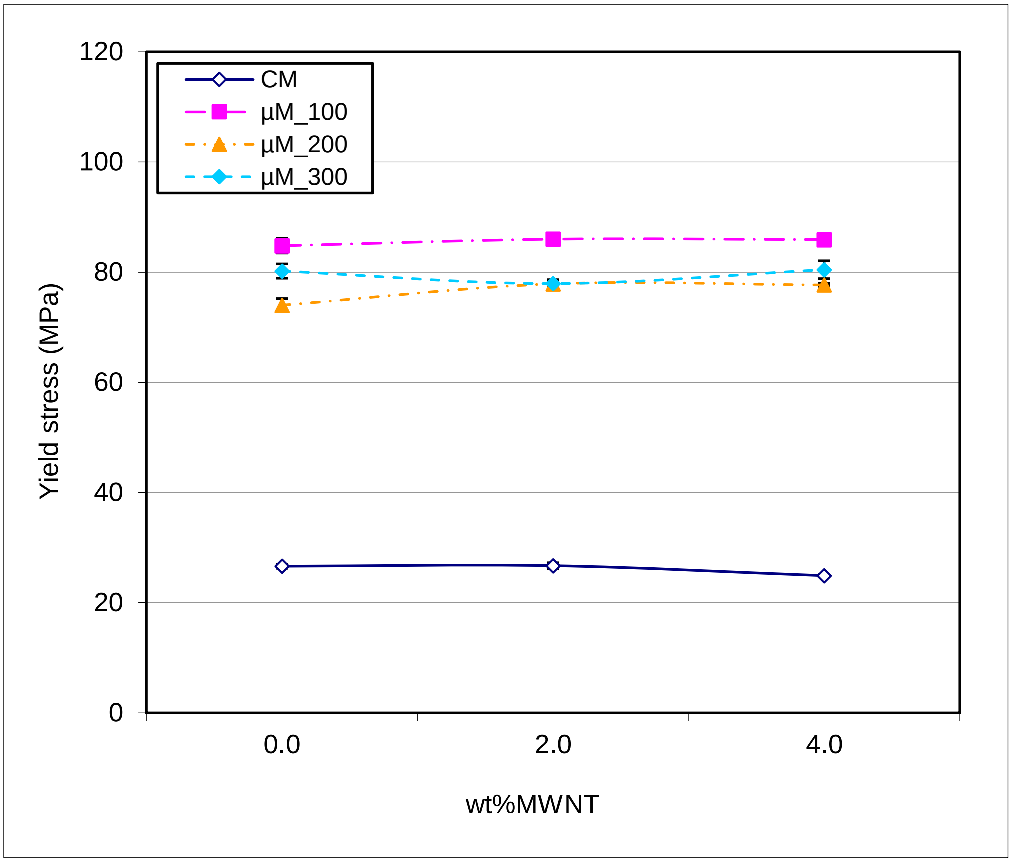

Figure 2 Yield stress of MWNT/PP composites with respect to nanotube concentrations for compression molded (CM) sheets and micromoulded (µm) specimens produced at different injection speeds

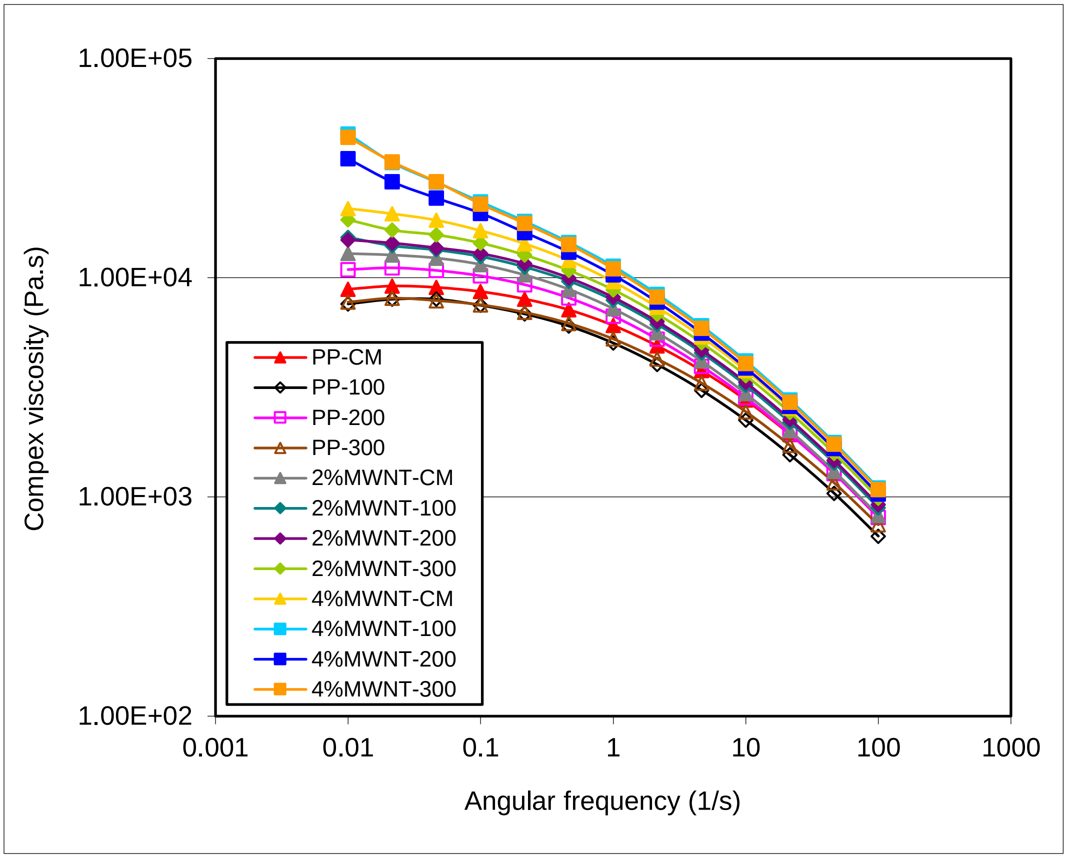

Figure 3 Complex viscosity of MWNT/PP composite as a function of angular frequency for compression moulded (CM) sheets and micromoulded (μm) specimens produced at different injection speeds

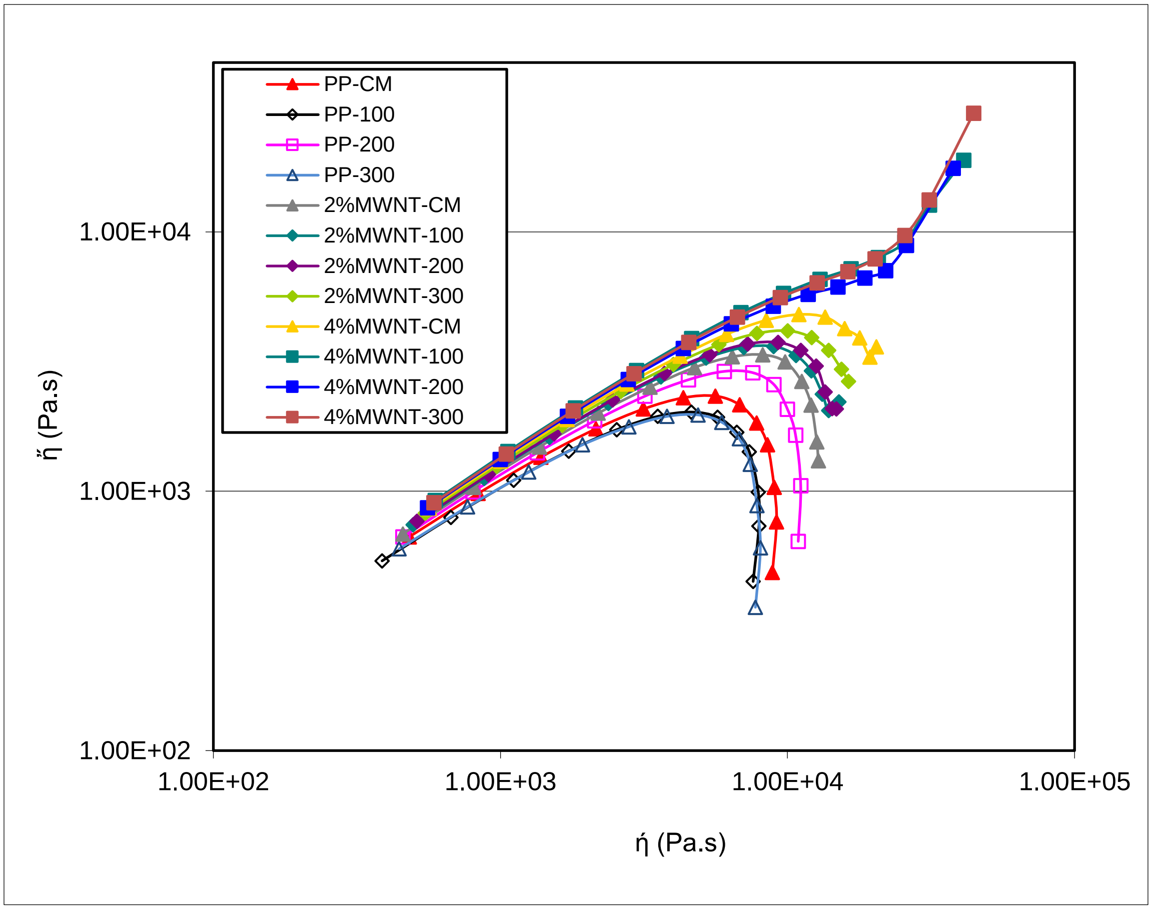

Figure 4 Relationship between imaginary viscosity (ή) and real viscosity (ή) for MWNT/PP composites produced by compression molding (CM) and micromolding (μm) processes at different injection speeds

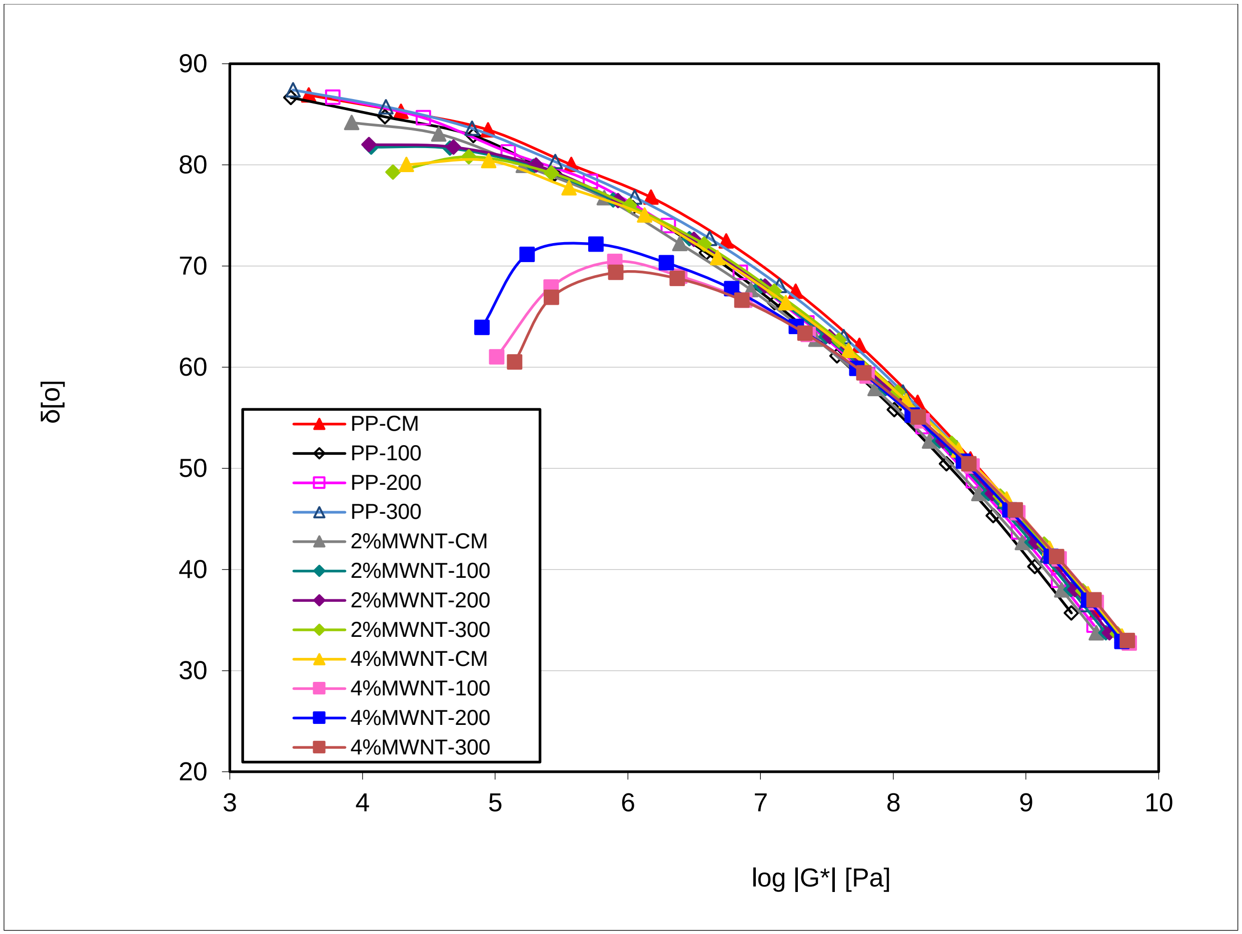

Figure 5 Phase angle (δ) versus logarithmic plot of absolute value of complex modulus |G*| (Van Gurp-Palmen plot) for MWNT/PP composites produced by compression molding (CM) and micromolding (μm) processes at different injection speeds
Produced at injection speeds of 100, 200 and 300mm/s

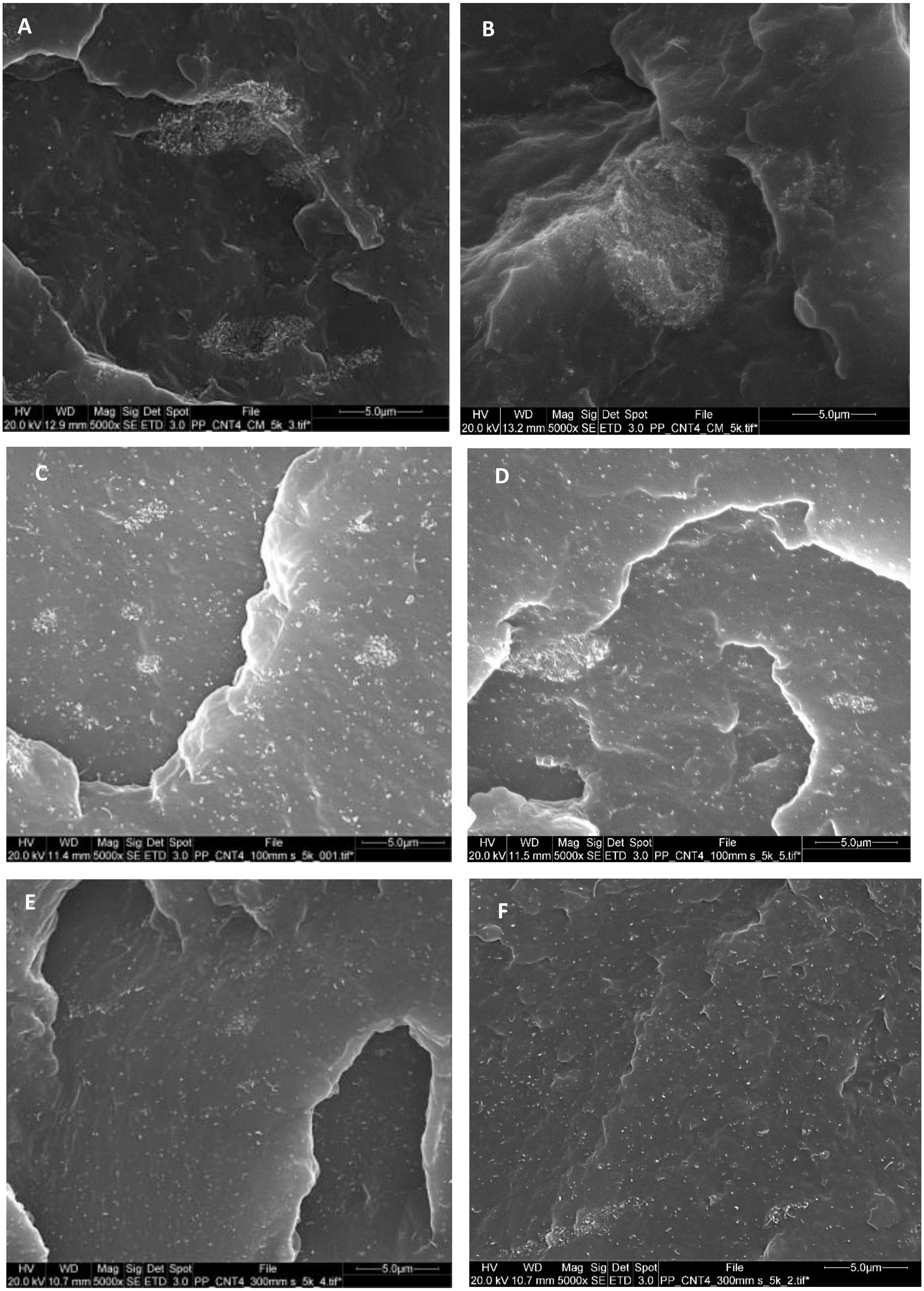

Figure 6 SEM micrographs of MWNT/PP composite containing 4wt% nanotubes for (a,b) compression molded sheets, and micromolded tensile bars produced at injection speed of (c,d) 100mm/s and (e,f) 300mm/s