
Compression Moulding of Thermoplastic Nanocomposites Filled With MWCNT

Fabrizio Quadrini^{1,*}, Denise Bellisario¹, Loredana Santo¹, Felicia Stan², and Fetecau Catalin²

¹University of Rome "Tor Vergata", Department of Industrial Engineering, Via del Politecnico 1, 00133 Rome, Italy

²Universitatea Dunarea de Jos din Galati, Faculty of Mechanical Engineering, Str. Domnească 111, 800201 Galați, Romania

Received: 25 August 2016, Accepted: 10 November 2016

SUMMARY

Multi-walled carbon-nanotubes (MWCNTs) were melt-mixed with three different thermoplastic matrices (polypropylene, PP, polycarbonate, PC, and thermoplastic polyurethane, TPU) to produce nanocomposites with three different filler contents (1, 3, and 5 wt.%). Initial nanocomposite blends (in the shape of pellets) were tested under differential scanning calorimetry to evaluate the effect of the melt mixing stage. Nanocomposite samples were produced by compression moulding in a laboratory-scale system, and were tested with quasi-static (bending, indentation), and dynamic mechanical tests as well as with friction tests. The results showed the effect of the filler content on the mechanical and functional properties of the nanocomposites. Compression moulding appeared to be a valuable solution to manufacture thermoplastic nanocomposites when injection moulding leads to loss of performance. MWCNT-filled thermoplastics could be used also for structural and functional uses despite, the present predominance of electrical applications.

Keywords: Thermoplastic matrix composite, Compression moulding, Nanocomposite, MWCNT

1. INTRODUCTION

Thermoplastic polymer composites are very attractive for industrial applications due to the opportunity of tailoring their properties with special fillers. In this field, nanocomposites are very promising, thanks to the reduced amount of fillers and the resulting improvement in structural and functional performance. Polymer nanocomposites are a new class of reinforced polymers in which at least one dimension of the reinforcing phase is in the nanometre range. It is thought that nanocomposites can provide novel functionality in the area of bulk polymeric components. However, difficulties in nano-filler exfoliation (i.e. in its dispersion into the matrix), high processing times,

and need of defining and optimising a proper mixing/processing technology are still problems to solve. Recently, Djoudi *et al.* have proposed a FE simulation for twin screw mixing of nanocomposites¹. Front cover of the mixer was replaced by a transparent one to directly observe the mixing process, and to measure the temperature by an infrared camera. Experiments have been used for the validation of the numerical model which could be used to optimise nanocomposite processing. In such cases, *in-situ* polymerization can be preferred: Wu *et al.* have prepared carbon nanotube/waterborne polyurethane composites by means of an emulsification process². They discuss great improvements of mechanical performances by the addition of nano-filler up to 3 wt.%.

Many components of industrial interest, such as gears, cams, bearings and seals, are typically produced by injection moulding of thermoplastic matrix composites. In fact, the ease and economics of manufacturing complex parts by injection moulding are well recognised. Thermoplastic nanocomposites should be injection moulded as well. Since MWCNT (multi-walled carbon nanotube) is a well-known nano-filler for composite production, many scientific studies have focused on injection moulding of thermoplastic nanocomposites filled with MWCNT.

In their study on injection moulding of polystyrene (PS) matrix composites filled with CNT, Enomoto *et al.* evaluated their mechanical and electrical properties which were discussed in comparison with composites with conventional carbon fillers³. As a result, the resistivity for nanocomposites was significantly lower than that of conventional

*Corresponding author, fabrizio.quadrini@uniroma2.it

©Smithers Information Ltd., 2017

composites, whereas the elastic modulus slightly increased. A negative effect was found in the reduced strength of this new class of materials. Anyway also the electrical behaviour is difficult to optimise. Li *et al.* filled MWCNT into polyethylene terephthalate (PET) matrix and MWCNT/PET composite was prepared by injection moulding⁴. After injection moulding, the electrical conductivity of injection moulded samples decreased sharply because of the orientation of CNT due to the strong shearing forces.

Nanocomposites are characterised by low volume contents of fillers but the evaluation of the optimal volume content is a complex task. Thiébaud *et al.* studied the mechanical properties of MWCNT/polypropylene (PP) composites⁵. Four grades were chosen (from 1 to 8 wt.%) but the researchers just observed a strong dependence of the Young's modulus and the rupture strain on the CNT content. In a wider study, Rios *et al.* evaluated the effects of the injection-moulding parameters on the electrical, mechanical, and thermal properties of several CNT filled composites⁶. High-density polyethylene (HDPE), polyamide 6 (PA6), polyamide 66 (PA66), polybutylene terephthalate (PBT), and polycarbonate (PC) were selected as matrices. The nanocomposites reached a percolation threshold within CNT concentrations of 2-5 wt.%; however, the mechanical properties of the host polymers were affected. In order to improve the electrical conductivity of a CNT/PP composite, Yang *et al.* also suggested applying vibration during the injection-moulding⁷. Results showed that electrical conductivity of samples prepared by vibration injection moulding was far higher than the case of samples prepared by conventional injection moulding. The effect of the vibration on the mechanical performance of the composites was not analysed. In fact, the recent review of Tiusanen *et al.* clearly shows that electrical properties are mainly

discussed in scientific studies about CNT filled thermoplastic composites⁸. As a further confirmation, one of the latest studies deals with the evaluation of the volume resistivity of CNT/PC nanocomposites produced with different injection moulding temperatures⁹. Nevertheless there is a strong potential in using CNT filled nanocomposites in tribological and structural applications.

In a previous study, some of the authors deepened the effect of the injection moulding process on the mechanical and tribological properties of thermoplastic nanocomposites¹⁰. Samples were produced by melt mixing in a twin-screw extruder, and subsequent injection moulding of pellets. Three thermoplastic matrices (PA6 and PA66, and polyoxymethylene, POM) were mixed at different weight contents (up to 5 wt.%) with several nano-fillers (silica, alumina, titania and carbon nanotube, CNT). In order to characterise the nanocomposites, differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), tensile, bending, and indentation tests were used as well as pin-on-disk tests in dry and wet sliding conditions. As a result, the effect of the nano-filler on the sliding behaviour of the nanocomposite was observed for each thermoplastic matrix, and was correlated with the other mechanical properties. It was found that the tribological performance of thermoplastics could be enhanced by the addition of a small amount of nano-filler, but the presence of the nano-filler in the polymer bulk may strongly affect material mechanical properties. Particularly, semicrystalline polymers, such as POM, PA6, and PA66, reduce their mechanical performances after loading with nano-fillers because of the reduction in the crystallization degree. Nevertheless, very good results were obtained in tailoring the friction coefficient and in increasing the wear strength, above all for PA66.

It is not obvious that injection moulding is the best moulding process for CNT filled nanocomposites. In this technology, nanocomposite mixtures are typically obtained by melt mixing (in a twin-screw extruder) and final mixtures are subsequently injection moulded. It has been observed that functional properties are often better in nanocomposites after melt mixing rather than after injection moulding. Probably, other moulding technologies could be preferable to increase nanocomposite performances for such applications. A good idea may be using compression moulding, which is typically used for thermosetting materials or highly-filled thermoplastic ones, but it could be used also for thermoplastic nanocomposites. Compression moulding allows the moulding of complex shapes in the case of very high viscosity of the polymeric mixture, due to loading. In the past, compression moulding was used to evaluate the influence on the electrical resistivity and morphology of MWNT/PC composites¹¹. By adjusting compression moulding parameters, it was found that the volume resistivity of PC with 1 wt.% MWCNT composites can be varied over eight orders of magnitude, whereas for 2 wt.% MWCNT, the variation was within one decade. Anyway, also in this study, other structural or functional properties were neglected.

In the present study, the authors evaluated the suitability of using compression moulding for producing thermoplastic nanocomposites filled with MWCNT. Three different matrices (PP, PC, and thermoplastic polyurethane, TPU) have been used, and several tests have been performed to evaluate structural and friction properties of nanocomposites.

2. MATERIALS AND METHODS

2.1 Nanocomposite Production

Materials design for the experimentation is summarised in

Figure 1. Pellets of thermoplastic nanocomposites were prepared by melt-mixing commercial thermoplastic materials and MWCNTs in a twin-screw extruder. Three different kinds of polymers were selected for the experimentation, depending on their intrinsic nature: a semi-crystalline polymer with a glass transition temperature above room temperature (PP), a semi-crystalline polymer with a glass transition temperature under room temperature (i.e. a thermoplastic elastomer, TPU), and an amorphous polymer (PC). Being rigid at room temperature, PC exhibits a glass transition temperature much higher than PP. Selecting these polymers, it has been possible to deepen the effect of MWCNT on polymer mobility. Three different filler contents were chosen (1, 3 and 5 wt.%). It is important to note that, working at fixed weight percentages of fillers, different levels of filling were really obtained in the three matrices. In fact, PC density ranges typically between 1200 and 1220 kg m⁻³ whereas PP ranges between 860 (fully amorphous) and 950 kg m⁻³ (fully crystalline). TPU density is generally higher than 1100 kg m⁻³, and therefore MWCNT/PP nanocomposites were always characterised by lower levels of filler loading than the other two matrices.

Nanocomposite samples were produced by compression moulding with laboratory equipment. Moulding

temperatures were 250, 260 and 290 °C for TPU, PP and PC, respectively. The applied pressure was very low (about 1.25 bar) whereas the moulding time was quite high (20 min). This selection of process parameters was made to maximise agglomeration of pellets with a minimum material flow. In fact, injection moulding generally leads to optimal agglomeration, but polymer flow could be responsible for the reduction of performances for nanocomposites. In order to reduce material flow without affecting pellet agglomeration, moulding temperature and time can be increased in compression moulding. Anyway, moulding pressure had to be reduced to avoid polymer degradation.

One sample at a time was compression moulded, with a nominal size of 50x8 mm². The final thickness depended on the polymer matrix, being about 2.0 mm for PP and 2.6 mm for PC and TPU. The effect of the MWCNT content on the sample thickness for each single matrix was negligible. Two samples were produced for each combination of thermoplastic matrix and MWCNT content. Their weight was measured in order to extract the nanocomposite densities.

2.2 Differential Scanning Calorimetry (DSC)

DSC tests (by DSC 7, Perkin Elmer) were performed on nanocomposite

pellets from 0 °C to 200 °C at 10 °C/min. This temperature range was sufficient to observe all the main thermal changes for PP and PC, whereas the glass transition temperature of TPU was not visible, being much lower than room temperature.

2.3 Dynamic Mechanical Analysis (DMA)

DMA tests (by Netzsch DMA 242 C) were performed on all the nanocomposite samples. Viscoelastic properties were investigated at several frequencies (1, 5, 10 and 20 Hz) in three-point bending mode at room temperature.

2.4 Bending Tests

As DMA tests apply a very low displacement (about 120 μm), specimens are not damaged during testing and can be used for further analyses. Therefore, all the nanocomposite specimens were also tested by conventional quasi-static bending. Tests were carried out by means of a material testing machine (MTS Insight 5) at the rate of 1 mm/min up to a maximum inflection of 3 mm.

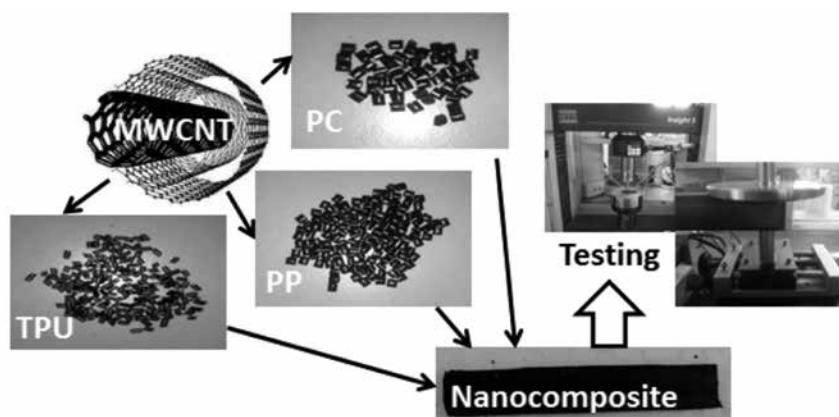
2.4.1 Indentation Tests

Indentation tests were performed by means of the same material testing machine which was equipped with a WC indenter, having a tip diameter of 2 mm. Indentation tests on polymers allow to evaluate local mechanical performances¹². The test rate was 0.5 mm/min and the pre-load 2 N. In order to make a comparison between samples, the indentation pressure at the penetration depth of 0.5 mm was extracted: 2 tests were performed on each specimen after bending test. Indentations were made near the ends which were not affected by mechanical bending.

2.5 Friction Tests

Tribological properties of nanocomposites were evaluated by

Figure 1. Material design for thermoplastic nanocomposites



using a reciprocating-type ball-on-flat tribometer (CSM Instruments) with a counter-body spherical pin (6 mm in diameter) made of 100Cr6 (manufacturer nominal hardness: HV=7 GPa). Sliding tests were performed in room conditions without lubricant in a zone near the ends of the samples previously tested under bending and indentation. Tests were performed with a vertical load of 1 N, a sliding speed of 0.0566 m/s, an amplitude of 6 mm and a total sliding distance of 25 m. The friction coefficient was monitored during the tests and used to make a comparison among different samples and mixing conditions.

3. EXPERIMENTAL RESULTS

Densities for all the nanocomposites are reported in **Figure 2** in terms of average between two samples. As expected, by increasing the MWCNT content, the density increases as well because of the higher density of the MWCNT (about 2600 kg m^{-3}) in comparison with all the polymeric matrices.

Results from DSC analyses are shown in **Figures 3, 4 and 5** for nanocomposites with PP, PC and TPU matrix, respectively. Each graph shows a comparison between 3 different scans, one for each MWCNT content. Experimental curves have been vertically shifted to optimise this comparison.

All the results from DMA tests are reported in **Figure 6**. From a single multi-frequency scan, 5 values (one for each frequency) for the storage modulus and other 5 values for the loss factor can be extracted. As DMA tests were carried out on two different specimens for each combination of polymeric matrix and MWCNT content, two curves of storage modulus and loss factor are reported for the same combination. This way, it is possible to observe that the repeatability of results is acceptable, i.e. data scattering is

Figure 2. Average density for all the nanocomposite samples

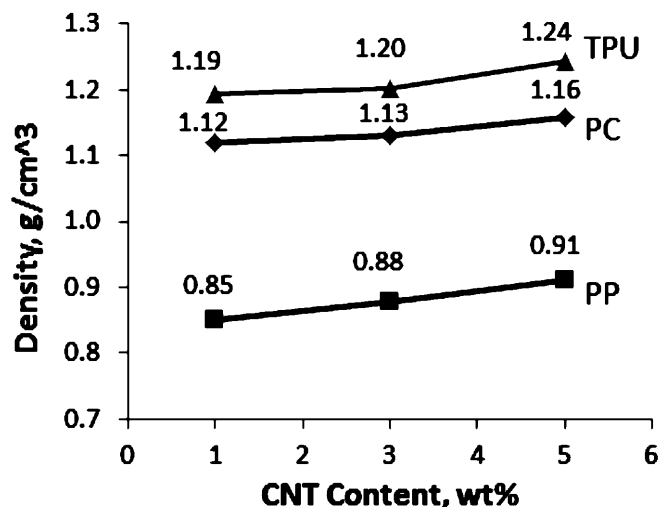


Figure 3. DSC scans of MWCNT/PP nanocomposite pellets

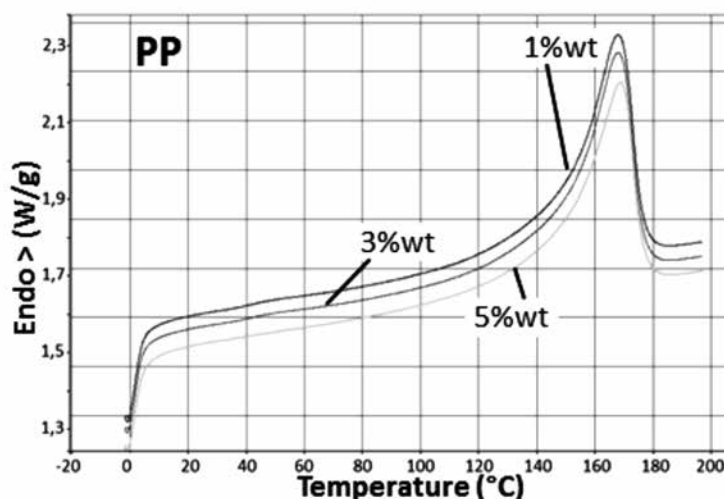
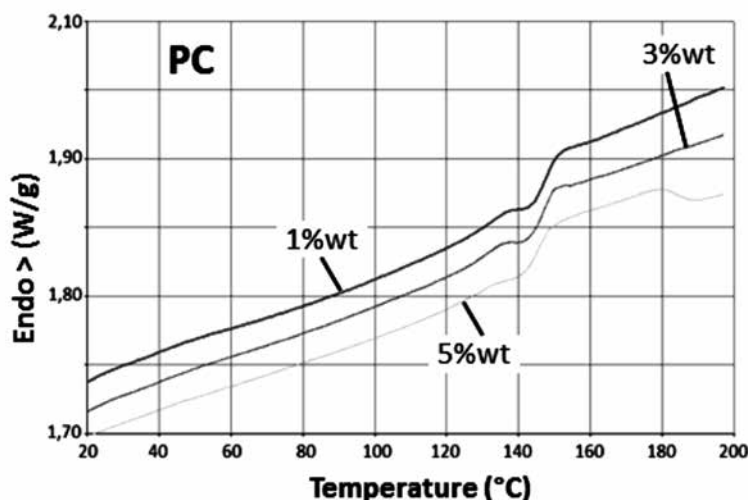


Figure 4. DSC scans of MWCNT/PC nanocomposite pellets



not higher than differences between nanocomposites. In detail, **Figure 6a** and **6b** show storage modulus and loss factor of PP based composites, respectively. **Figure 6c** and **6d** refer to PC, and **Figure 6e** and **6f** to TPU.

In order to summarise all the DMA results in a single graph, **Figure 7** shows the relationship between the storage modulus and the loss factor for all the tested samples and frequencies, in the case of PP and PC matrix composites. TPU data are not

Figure 5. DSC scans of MWCNT/TPU nanocomposite pellets

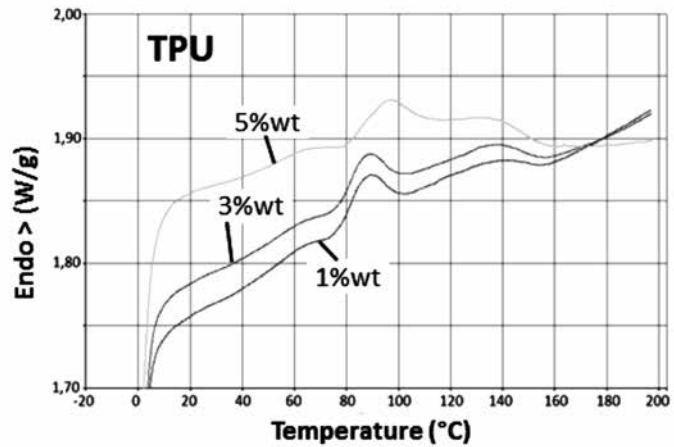
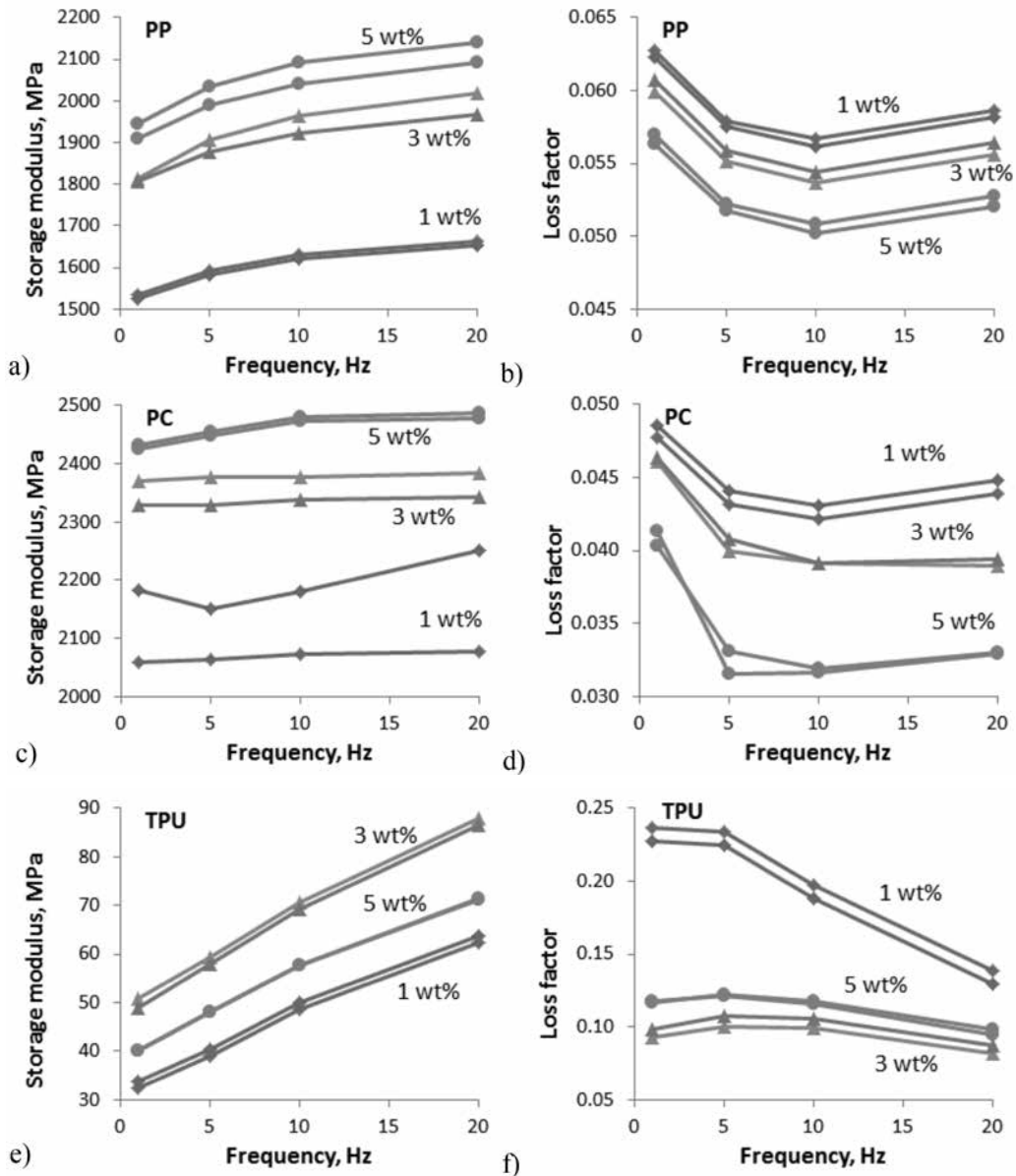


Figure 6. Storage modulus and loss factor from multi-frequency DMA tests for PP (a,b), PC (c,d), and TPU (e,f) based nanocomposites at room temperature (25 °C)



added because of the very low values measured for the storage modulus, and the very high values for the loss factor. Being rigid materials, PP and PC matrix composites are easy to compare.

Bending curves for all the nanocomposite samples are shown in **Figure 8**. Also in this case, a good repeatability of the results is present. Curves for PP and TPU matrix are reported in **Figure 8a** whereas curves for PC are shown in **Figure 8b** so as to make clearer the comparison between different MWCNT contents.

For the same reason, only one curve is shown for each filler content in the case of PC matrix nanocomposites (**Figure 8b**). From the bending curves, the flexural modulus has been extracted and is reported in **Figure 9** in terms of average value for each combination of polymeric matrix and filler content.

Figure 10 shows a typical indentation curve. In the initial part of the curve, a small non-linearity is present because of imperfect contact between the indenter tip and the sample. Subsequently, a pseudo-elastic range is visible as it is

characterised by a linear trend. That is not an elastic region, as the material already flows under the indentation load. By increasing the indentation load, a work-hardening-like stage appears: this stage approaches a plateau at high indentation depths. In order to make a comparison between the indentation curves, the indentation pressure at a fixed depth (0.5 mm) has been considered and the values are reported in **Figure 11**. In the case of indentation, two tests were performed for each sample, and therefore 4 values were available for each composite. Average values of all the indentation pressures for each nanocomposite are shown in **Figure 11** together with the error range which is never greater than 3% of the mean value. It was found that there was a very small difference between two indentations on the same sample, and between indentations on two samples with the same combination of polymeric matrix and MWCNT content.

In conclusion, **Figure 12** shows the friction curves for all the composite samples, with the already discussed good repeatability. In fact, two curves are shown for each combination of matrix and filler content, but in several cases, these two curves are perfectly superimposed. In a typical friction curve, the friction coefficient initially increases by increasing the sliding distance because of changes in the contact between the ball and

Figure 7. Relationship between storage modulus and loss factor for all the tested PP and PC based composites, and for all the oscillating frequencies at room temperature (25 °C)

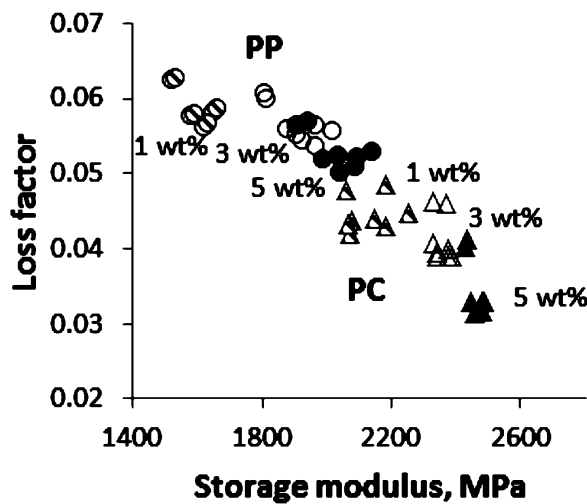


Figure 8. Bending curves for all the PP, TPU (a) and PC (b) based composites

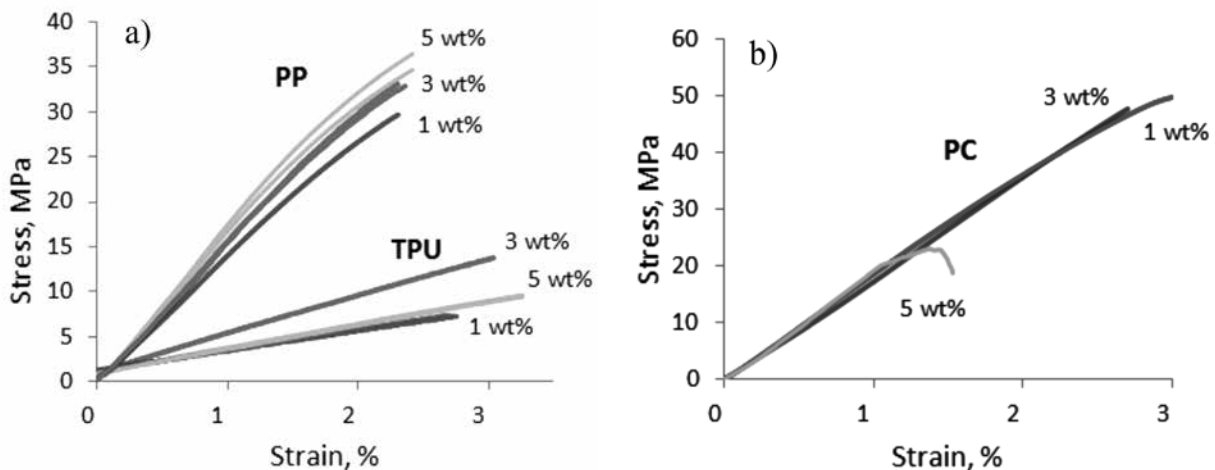


Figure 9. Average flexural modulus for all the nanocomposites

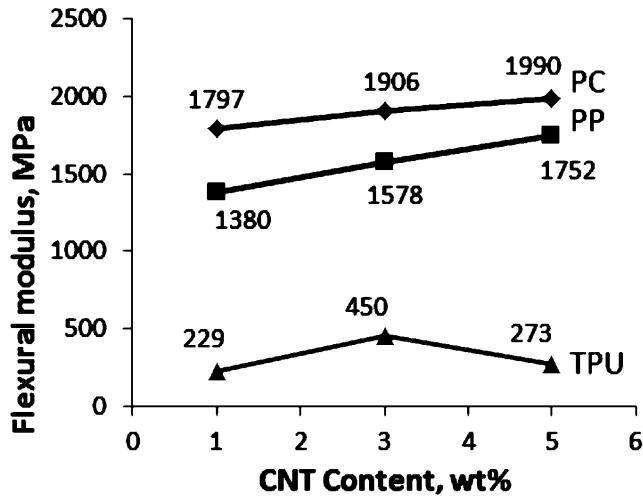


Figure 10. Example of an indentation curve and description of the main occurrences

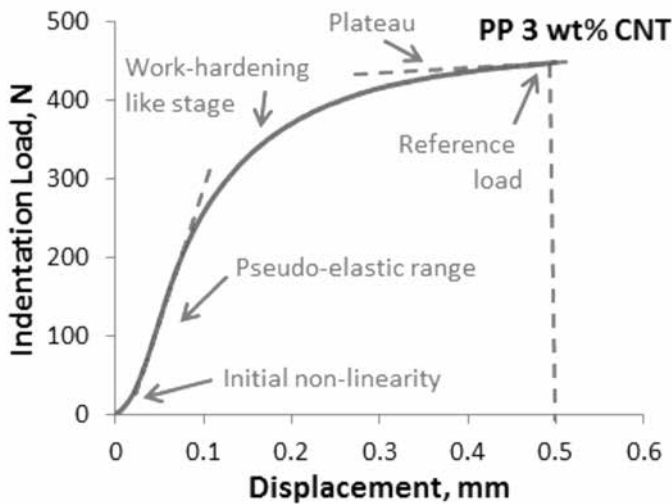
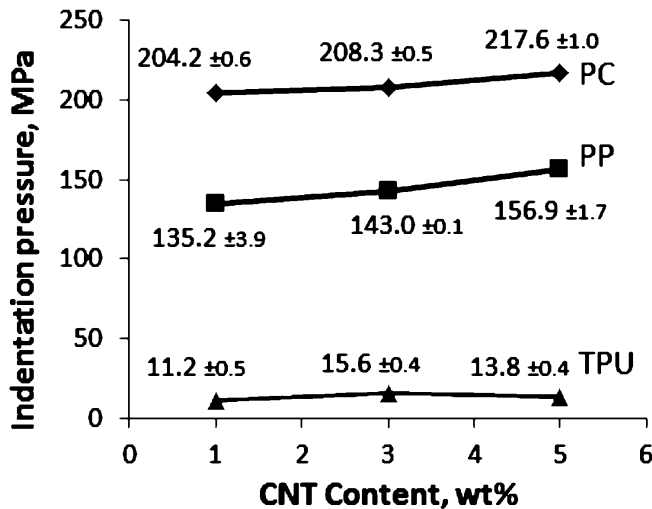


Figure 11. Indentation pressure at the depth of 0.5 mm for all the nanocomposites



the sample. If wear does not occur, the friction coefficient rapidly tends toward a stable plateau. Sometimes, a line with a small slope is present at high sliding distances instead of the plateau because of local deformation of the sample under friction load. Severe wear was not observed in the samples and a friction coefficient was extracted for all of them by averaging the acquired values in the final part of the friction curves. Mean values of the friction coefficients for all the nanocomposites are reported in Figure 13.

4. DISCUSSION

For nanocomposite production, a laboratory procedure has been chosen because of the small size of the samples and the need to apply low pressures for long times. In order to reduce the variability of results coming from the laboratory-scale production, only two samples were produced for each combination of thermoplastic matrix and MWCNT content, and all the tests were made on these samples. The sequence of the tests, from DMA to bending, indentation and friction tests has been selected to avoid the problem that the previous testing phase could affect the following one. Results show that this experimental strategy has been in agreement with expectations. Also for densities, the dispersion range over all the samples was on average 3%, with the highest scattering for TPU. The average values of density for all the nanocomposites show the expected increase with the filler content (Figure 2) even if a linear trend is visible only for PP. For PC and TPU, densities for 1 and 2 wt.% filled composites are similar but considerably lower than 3%wt filled samples. The effect of the filler content on the weight was also confirmed by further analyses.

4.1 Differential Scanning Calorimetry (DSC)

Composite blends were produced by melt mixing which should be the best technology for incorporating nano-

Figure 12. Friction curves for all the nanocomposite samples

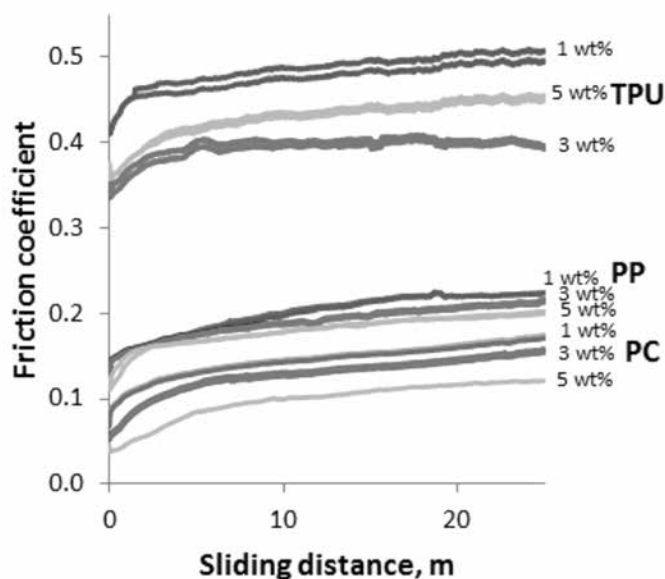
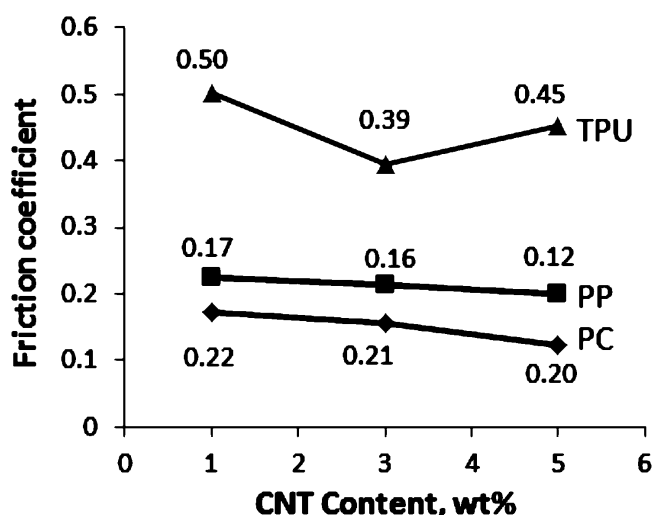


Figure 13. Average friction coefficient for all the nanocomposite samples



fillers in already-formed thermoplastic molecules. In fact, due to the polymer flow into the twin-extruder, shear stresses are generated which are particularly efficient in producing nano-particle exfoliation. DSC analysis is able to evaluate the result of this mixing stage directly from the pellets, which cannot be used in other tests because of their small size. **Figure 3** makes a comparison between DSC scans on PP nanocomposites. Changes in the glass transition range (characterised by the small inflection about 40 °C) and in the

melting peak (about 170 °C) seem to be negligible, although typical effects of nano-fillers are the reduction of the glass transition temperature and the melting peak area. It is particularly noticeable that the melting peak extension in the case of the 5 wt.% filled sample is very close to the other two peaks, despite the observed differences in density. A stronger effect is visible in the scan of PC matrix composites (**Figure 4**). PC being an amorphous rigid polymer, only a glass transition is observable at about 150 °C: in fact

the glass transition temperature (i.e. the inflection point) decreases from 147.3 °C to 146.5 °C, and 145.2 °C, going from 1 to 2, and 3%wt. filler content, respectively. The difference between two consecutive contents is small (about 1%) but observable. For TPU, a quantitative comparison is not possible as the main transition (the glass transition) is under the scan range. Anyway the difference in the DSC scan between the 5 wt.% curve and the other two curves is evident from a qualitative point of view (**Figure 5**).

As a general conclusion, a stronger effect of the filler content on the DSC scans was expected, as nano-fillers should reduce the mobility of polymeric molecules. Anyway, further exfoliation can be obtained during pellet processing, and this condition could be optimal for reducing problems during specimen manufacturing. In fact, high exfoliation levels could lead to an excessive increase in the viscosity and a consequent difficulty in filling the mould during the compression moulding stage.

4.2 Dynamic Mechanical Analysis (DMA)

Dealing with molecular mobility, DMA results are surely more suitable for having an evaluation of the interaction between fillers and matrix. In fact, DMA results clearly show the effect of the nano-filler content on the mechanical behaviour of the composite samples (**Figure 6**). For all the samples, the storage modulus increases with the filler content whereas loss factor decreases. Because of the reduced molecular mobility, by increasing the amount of nano-particles, the material stiffness increases as well, and simultaneously, its damping (i.e. the loss factor) is decreased. There is only an inversion which has been observed for the highly-filled TPU nanocomposite (5 wt.%) which behaved better than the 1 wt.% sample but worse than the 3 wt.% one. Evidently, for the adopted

mixing conditions, a filler content about 5 wt.% is associated with a particularly poor exfoliation. This inversion in the effect of the filler content for the TPU matrix has been observed also for the other measured properties.

Generally, far from the transitions, with increasing oscillating frequency, the storage modulus of polymeric materials increases and the related loss factor reduces. This fact was generally observed for all the samples and was particularly evident for PP (Figure 6a, apart from the loss factor value at 20 Hz, Figure 6b). For PC, the effect of the frequency seems to be negligible in the case of 1 and 3 wt.% filled composites (at least for the storage modulus, Figure 6c), whereas for TPU the trend of the storage modulus was almost linear with the frequency (Figure 6e). Data for TPU seem to show a very strong effect of the frequency, but that is due to the elastomeric behaviour of the matrix. In fact, storage modulus values are extremely low (Figure 6e) and loss factor ones extremely high (Figure 6b). As a consequence, quantitative increases of the storage modulus are negligible in comparison with PP and PC.

A good overview of the dynamic behaviour of the rigid nanocomposites (PP and PC matrix) is given by Figure 7 which puts in evidence the expected relationship between storage modulus and loss factor (by increasing the former, the latter decreases). PP and PC matrix composites are characterised by two different adjacent areas on this graph, PC being stiffer than PP. Inside these areas, the effect of the filler content is quite evident: by increasing the MWCNT content, composites become stiffer and damping reduces.

4.3 Bending Tests

In order to have confirmation of the effect of the nano-filler content on the mechanical behaviour of the composites, quasi-static tests were also

performed. The effect of the MWCNT is easily visible from a qualitative point of view by comparison of the bending curves. In the case of PP and TPU, by increasing the filler content, the bending curves shifts up (Figure 8a). For TPU, the inversion of the sample with 5 wt.% filler content can be easily seen. PC samples also showed the expected behaviour with filler content increase, even if it is less appreciable from the graph (Figure 8b). However, on extracting the flexural modulus (Figure 9), the trend is clear. A linear trend is generally visible for all the composites, apart from the datum of the TPU at 5 wt.% of filling. In comparison with the 1 wt.% MWCNT filled samples, the strongest increase in the flexural modulus is observed for TPU (96%) in analogy with DMA results. As PP and PC matrices are stiffer than TPU, lower increases are observed. The increase of the flexural modulus of 3 and 5 wt.% filled composites are 14% and 27% for the PP matrix, and 6% and 11% for the PC matrix. These results seem to be satisfactory in terms of performance increase, particularly for PP matrix composites. In fact, a drawback for the PC composites was related to their brittle behaviour, as PC matrix samples were the only ones that failed under bending test before the maximum inflection of 3 mm. Higher the filler content, lower the strain at break as Figure 8b confirms. Nano-filler exfoliation can lead to material brittleness because of the reduction in molecular mobility. This negative effect is particularly strong in amorphous rigid polymers where an initial brittleness is already present due to their high glass transition temperature.

4.4 Indentation Tests

Indentation tests are very interesting because they provide information about local mechanical performance without affecting the soundness of the samples. Moreover, under indentation, polymeric materials and composites are forced to extensively flow. This way, the

effect of the interaction between fillers and matrices should be maximised. Another advantage is related to the fact that indentation tests are instrumented hardness measurements and, therefore, their results can be correlated with surface performances, as well. In terms of mechanical behaviour, indentation results (Figure 11) confirm observations from bending tests also under severe plastic deformation. PC composites show higher indentation pressures because of the higher stiffness of the matrix in comparison with PP and TPU. Making comparison with the 1 wt.% filled samples, the strongest increase is still observed for 3 wt.% MWCNT/TPU composites (66%). For the TPU matrix, the already discussed loss of performance at 5 wt.% is always present. For PP and PC, increments similar to the flexural modulus can be observed (14 and 39% for PP, 6 and 11% for PC).

4.5 Friction Tests

Friction tests were performed to add information about the functional properties of these kinds of composites, as MWCNTs are generally used to improve the electrical conductivity of polymers. Results from the friction tests are in agreement with all the other results, and so tend to confirm the soundness of the proposed experimentation. Rigid polymers typically show low friction coefficients; this is the reason why the qualitative trend of Figure 12 is the opposite of Figures 8, 9 and 11. The highest friction coefficients were measured for TPU composites. Lower values were measured for PP composites, and subsequently for PC ones. By increasing the filler content, the composite being stiffer, the friction coefficient decreases (apart from the anomaly of 5 wt.% MWCNT/PP composites). Even if the effect of the filler content is visible, from a quantitative point of view, it seems not to be so relevant. MWCNT could be used to provide tailored frictional properties, but probably

strong changes could not be achieved. However, dealing with tribological applications, the production of bulk nanocomposites does not seem to be the best technological solution, because only part of the surface is prone to sliding. If high structural and electrical performance would be necessary, the increase in tribological performances could be a further positive advantage.

5. CONCLUSIONS

Thermoplastic matrix nanocomposites can be effectively produced by compression moulding so as to reduce the loss of performances related to injection moulding. In fact, polymer flow can be reduced in compression moulding, in comparison with injection moulding, as well as related defects (from polymer orientation, to degradation and frozen stresses). However, a small contribute of polymer flow is still present, as it is necessary for material aggregation and further nano-filler exfoliation. Experimental results have shown that nanocomposites produced by compression moulding improve their performance in terms of quasi-static and dynamic mechanical behaviour as well as friction behaviour. Good results have been obtained by using

polymeric matrices with very different intrinsic natures (fully amorphous, elastomeric and semicrystalline). The interaction between these matrices and MWCNTs is surely positive for composite performance in the filler content range from 1 to 5 wt.% (apart the only case of the 5 wt.% MWCNT/TPU composite). The results suggest that this kind of nanocomposite could be used also for other structural and functional applications, apart from electrical ones which are mainly studied in the scientific literature for MWCNT.

ACKNOWLEDGEMENTS

The authors want to acknowledge Dr Jacopo Cugliari for the support in the experimentation and Mr. Gennaro De Vita and Mr. Gianni Palomba for their technical activities.

REFERENCES

1. Djoudi H., Gelin, J.-C. , Barrière, T., *Composites Science and Technology*, **107**, (2015), 169-176.
2. Wu, Z., Wang, H., Xue, M., Tian, X. , Zhou, H., Ye, X., Zheng, K., Cui, Z., *Composites Science and Technology*, **114**, (2015), 50-56.
3. Enomoto K., Yasuhara T., Ohtake, N., Kato K., *JSME International Journal, Series A: Solid Mechanics and Material Engineering*, **46** (3), (2003), 353-358.
4. Li Z., Luo G. , Zhou W., Wei F., *Solid State Phenomena*, **136**, (2008), 51-56.
5. Thiébaud F., Gelin J.C., *International Journal of Material Forming*, **2**, (2009), 149-152.
6. Rios P.F. , Ophir A., Kenig S., Efrati R., Zonder L., Popovitz-Biro R., *Journal of Applied Polymer Science*, **120** (1), (2011), 70-78.
7. Yang L., Liu, F. Xia, H. Qian, X. Shen, K. Zhang, J., *Carbon*, **49** (10), (2011), 3274-3283.
8. Tiusanen J. , Vlasveld D., Vuorinen J., *Composites Science and Technology*, **72** (14), (2012), 1741-1752.
9. Qiu J.H., Zang L.M., Uchiya K., Eiichi S., Wang L.J., *Applied Mechanics and Materials*, **543-547**, (2014), 3878-3881.
10. Guglielmotti A., Lucignano C., Quadrini F., Tagliaferri V., *Journal of Tribology Research*, **1** (1), (2010), 11-19.
11. Kasaliwal G., Gödel A., Pötschke, P., *Journal of Applied Polymer Science*, **112** (6), (2009), 3494-3509.
12. Guglielmotti A., Quadrini F., Squeo E.A., *Polymer Engineering and Science*, **48** (7), (2008), 1279-1288.