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ORIGINAL PAPER

Nano, micro and multiscale filler-reinforced functionalized polypropylene composites: FTIR characterization and mechanical study

Nanoth Rasana[1,2*] and Karingamanna Jayanarayanan[1,2]

[1]Department of Chemical Engineering and Materials Science, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India
[2]Centre of Excellence in Advanced Materials and Green Technologies, Amrita Vishwa Vidyapeetham, Coimbatore, India

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ABSTRACT

Nano, micro and hybrid filler-reinforced polypropylene (PP) composites were prepared via melt compounding technique using a twin screw extruder. The nano scale MWCNTs and micro scale glass fibers were used as reinforcements. In addition to the individual effect of nano and micro scale reinforcements in virgin PP, the dual effect of multiscale (MWCNT/glass fiber) fillers was also elucidated. Morphological images revealed the effectiveness of dispersion of the fillers in the matrix and it was observed that the functionalized composites showed increased filler dispersion. The static mechanical properties of the non-functionalized and functionalized samples were compared and the hybrid composite with 2 wt.% MWCNTs showed the highest tensile strength without modulus reduction. The strong bonding between carboxyl-treated MWCNTs and maleic anhydride-grafted PP was well revealed in the FTIR spectra. In hybrid composites, the effect of silane-treated glass fibers was revealed and the siloxane linkages occurred between the glass fiber surface and silanol groups were confirmed by the FTIR spectra. **Polyolefins J (2022) 9: 33-43**

Keywords: MWCNTs; multiscale; FTIR; functionalization; hybrid composites.

INTRODUCTION

Nowadays conventional composites are replaced with superior novel nano and multiscale composites which have specific characteristics and multifunctional properties [1-2]. Amongst the nano and multiscale composites, multiscale composites have gained wide attention of researches since these kinds of advanced materials could integrate the properties of nanoscale, microscale fillers and macroscale fibers [3-5]. Multiscale composites have advanced applications in various sectors owing to their exceptional mechanical, optical and electrical properties, uniform distribution of dual scale fillers in the base matrix and the high aspect ratio of nanofillers [6-7]. To achieve optimum performance of multiscale composites, it is important to select appropriate

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[*] Corresponding Author - E-mail: n_rasana@cb.amrita.edu, rasana9@gmail.com

reinforcements and processing techniques and ensure proper dispersion of fillers in the matrix [8]. Another important property of multiscale composites is their ability to withstand high impact loads and good energy absorbing capability, and so their acceptance in modern vehicle structures and structural materials are very significant [9]. It is also reported that the incorporation of multiscale fillers has enhanced the ductility of the composites with regard to the brittle fracture experienced by multiscale scale composites without sacrificing the mechanical properties of the composites. In addition to the load bearing capability, in the case of multiscale composites, since dual scale fillers are used as reinforcements, the amount of micro filler added could be reduced and light weight components could be manufactured without reduction in mechanical properties [9-10].

Multiscale composites, especially with the incorporation of MWCNTs, have been found to provide enhanced mechanical properties and improved electrical and thermal conductivities [11]. Multiscale filler reinforced composites could be manufactured by incorporating dual scale fillers in the composites or by modifying the resin matrix and filler reinforcements. Qui et al. [12] prepared epoxy/CNT/glass fiber multiscale composites and observed that with 1 wt.% of functionalized CNTs tensile strength and modulus enhanced by 16% and 27%, respectively. They dispersed surface modified CNTs in resin matrix and pre-impregnated the unidirectional glass fiber performs. Pedrazolli et al. [13] reported the hybridization of polypropylene matrix with glass fiber and nanosilica/graphene nano platelets. They noticed that the agglomerates of nanosilica in PP matrix could be avoided and dispersion can be enhanced with the addition of PP-*g*-MA. The homogeneous dispersion of graphite nanoplatelets was also observed in the PP-*g*-MA compatibilized matrix in the TEM micrographs. In addition, the smaller crystal size of PP reinforced graphite nanoplatelets composites in the presence of MA compatibilizer analyzed by XRD evinced that better dispersion of nanoplatelets has occurred in the presence PP-*g*-MA, conforming with their TEM observations. It is also observed that the presence of PP-*g*-MA does not improve the tensile properties of an unfilled matrix but in the presence of nanofillers/short glass fibers tensile properties have improved which shows the possible effect of PP-*g*-MA on the interface between the filler and the matrix. It was reported that at graphene nanoplatelets content of 5 wt.% and glass fiber content of 20 wt.% and in the presence of 5 wt.% PP-*g*-MA, hybrid multiscale composite has exhibited the highest tensile strength and viscoelastic properties. In another work [14], authors suggested that in the multiscale composite system of graphene/carbon fiber/polypropylene, storage modulus enhances with the inclusion of higher content of graphene nanoplatelets. It was observed that nanoplatelets accumulate at the carbon fiber front tow and leads to mechanical reinforcement [14]. Another work on multiscale composites has detailed the effect of aramid fiber treatment and carbon nanotubes on the interfacial shear strength of polypropylene. Aramid fibers were treated with acid solutions and coated with MWCNTs. It was explored that MWCNT deposition on aramid fibers largely enhanced the surface roughness of the fibers which suggests that the interfacial shear strength enhancement is owing to the physicochemical interactions between aramid fibers, CNTs and PP in addition to mechanical interlocking [15]. Another group of researchers found that CVD deposition of carbon nanotubes on microsilica particles in PP has enhanced the elastic modulus, ultimate tensile strength and impact strength of PP composites [16]. The surface functionalization of carbon nanotubes serves to increase the compatibility of nanotubes with the polymer and enhance the mechanical interaction at the fiber/matrix interface. In order to achieve higher degree of nanotube dispersion in base matrix, the attached functional groups on the nanotubes are essential. Enhanced adhesion between the polymer and filler due to function alization will offer more load transfer at the polymer/filler interface, which in turn, improves the mechanical properties [17]. Chemical functionalization (covalent) or physical functionalization (non-covalent) can be performed on graphene or MWCNT fillers to reduce surface tension, thereby reducing the possibility of the aggregate formation and reducing the strong interfacial interaction between the filler and the matrix. Chemical functionalization could improve multi functionality of filler by attaching functional groups such as –COOH, –OH and –NH_2 on carbon arrangements [18-20]. Karsili et al. [21] reported the functionalization of nanotubes with silane molecules and identified the characteristic absorption peak related to silicone group on CNT spectra after the surface treatment of CNT with silane.

The current work is focused to correlate the morphology with mechanical properties of nano, micro and hybrid multiscale composites. It was revealed from FTIR spectra that better interfacial adhesion could be achieved owing to the inter component interactions developed between the compatibilizer, fillers and the matrix. These bonding mechanisms were confirmed in the presence of treated multiscale fillers in the base matrix using FTIR spectroscopy and correlated with the tensile properties and morphology of the specimens. In addition, the increase in mechanical properties after compatibilization of nano, micro and hybrid samples was elucidated and compared with non-functionalized samples. FTIR studies on multiscale (nano and micro filler (MWCNT/glass fiber) coexist in a base matrix) filler reinforced composites and the comparison of tensile properties of non-functionalized and the functionalized/surface treated synergized nano and micro fillers in a base matrix have not been reported earlier in the literature.

EXPERIMENTAL

Materials

Polypropylene granules (Grade: H200MA) procured from Reliance Industries, India with a melting temperature of 167.7°C and a melt flow rate (230°C/2.16 kg) of 20g/10min were used as the matrix polymer. The density of polymer used is 0.90 g/cm^3. Multiwalled carbon nanotubes functionalized with 1.5 wt.% of -COOH groups with an outer diameter of 20-30nm and an average length of 10-20µm were used as nano scale fillers, and procured from United Nanotech Innovations Private Ltd, India. The specific surface area of MWCNTs was 210m^2/g and nanotube purity was greater than 97%. Micro scale glass fibers with an average length of 3mm and a diameter of 14µm are used as micro reinforcements and compatibilizer PP-*g*-MAH was procured from local suppliers at Tamilnadu, India. 3-Aminopropyl triethoxy silane was procured from Thomson's India Scientific Company, Tamilnadu, India. A two-step approach was implemented to melt nano, micro and hybrid multiscale composites compound. A small laboratory scale kneading machine (temperature of the barrel 190°C and the rotor blade speed of 60 rpm) was used to compound the masterbatches of nanofiller (MWCNT) in PP. The masterbatches of nanofiller was then further added with PP granules in the twin screw extruder to prepare nanocomposites. Micro composites reinforced with glass fibers were also compounded in the twin screw extruder. In the case of hybrid composites at first masterbatches of MWCNTs were prepared using a kneading machine and these masterbatch granules were further mixed with correct proportions of glass fiber and PP granules in a counter rotating twin screw extruder. The length to diameter ratio of extruder screw was 30 and the temperature of the heating zones of the extruder was varied from 160 to 210°C. The screw speed was maintained as 100 rpm. The extrudate pulled out at the die zone of the extruder was cooled in a water bath and injection molded according to ASTM D638 standard. The processing temperature was set between 180 and 210°C with a mold temperature at 50°C. The sample nomenclature is represented in Table 1. Specimen names 'N','G' and 'H' represent nano, micro and hybrid composites, respectively. Nanocomposites were prepared with the MWCNT content of 1, 3 and 5 wt.% (N1, N3 and N5). Hybrid composites were prepared with MWCNT content varying from 0.5 to 5 wt.% (H0.5, H1,H2, H3 and H5) along with 20 wt% of glass fiber. 'G' represents micro composite with micro filler, and with a glass fiber content of 20 wt.%. Non-functionalized nano and hybrid composites are composites in which CNTs are treated with -COOH groups and non-functionalized micro and hybrid composites are composites in which micro scale glass fibers are untreated with silane coupling agent. Functionalized nano, micro and hybrid composites represent composites in which PP-*g*-MAH is added, MWCNTs are treated with –COOH groups, and glass fibers are treated with silane coupling agent.

Characterization Methods

The morphology of nano, micro and hybrid composites was revealed using scanning and transmission electron microscopy (SEM and TEM) techniques. Thin slices

Table 1. Nomenclature of nano, micro and hybrid composites.

Specimen	Polypropylene content (wt. %)	Nano filler (MWCNT in wt.%)	Micro filler (Glass fiber in wt.%)
PP	100	0	0
N1	99	1	0
N3	97	3	0
N5	95	5	0
G	80	0	20
H0.5	79.5	0.5	20
H1	79	1	20
H2	78	2	20
H3	77	3	20
H5	75	5	20

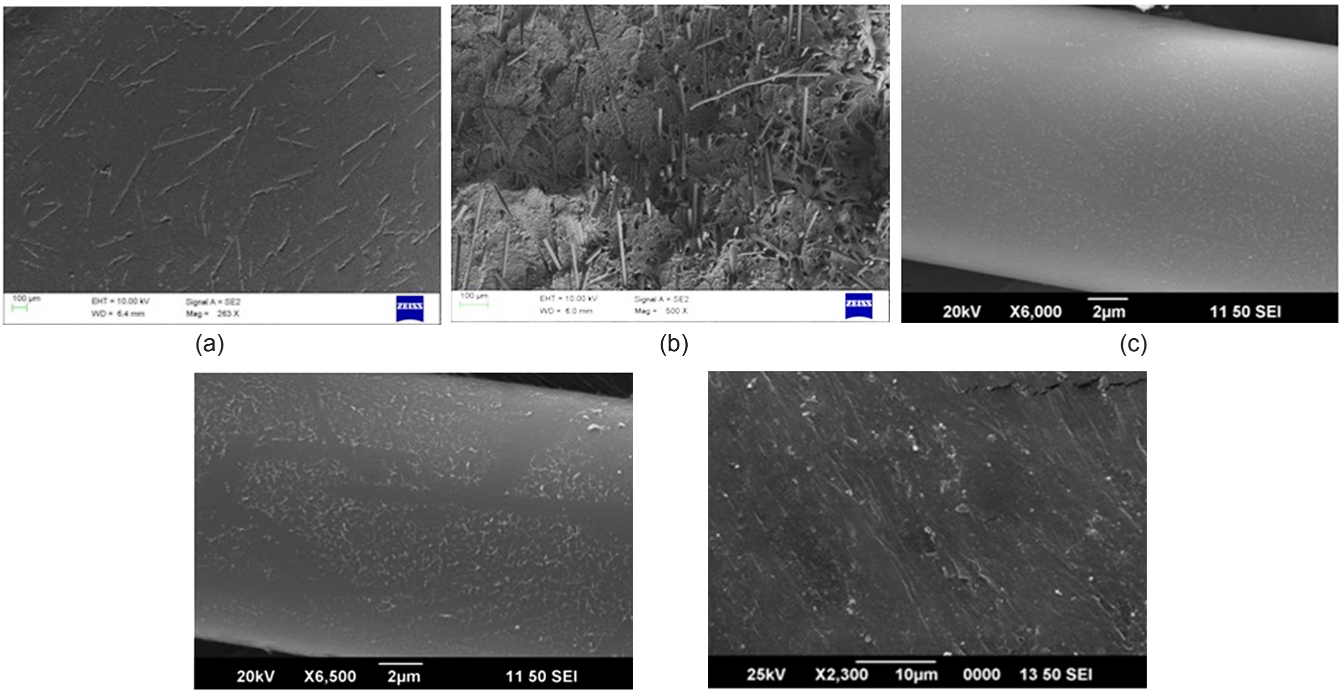
of composites were cut from the injection molded nano and hybrid composites and placed on Cu grid for TEM (JEM 2100 transmission electron microscopy, JEOL, India) analysis. The dispersion of micro fillers was revealed using scanning electron microscopy (JSM-6490LASEM, JEOL, India) analysis. The surface of the composites was first treated with hot xylene to enable the removal of PP layer from the surface to reveal filler distribution. A thin layer of gold-palladium of <3nm was sputtered on the samples to enhance the conductivity and reduce the charge effect on the sample surface. Tensile tests were carried out using a Tinius Olsen universal tensile testing machine as per (ASTM D638) standards with a constant crosshead speed of 50mm/min. Tensile tests were performed on six specimens at room temperature and average tensile values were reported. FTIR analysis (Nicolet iS10 Spectrophotometer, USA) with a resolution of 4 cm^{-1} and the wavenumber ranging from 4000 to 400 cm^{-1} was employed to understand the functionalization of groups on the matrix and fillers and their interaction.

RESULTS AND DISCUSSION

Morphological Analysis

SEM and TEM Analysis

The SEM image of micro composite (G) revealed the uniform dispersion of glass fibers in the PP matrix (Figure 1(a)). Even though the glass fibers incorpo rated are in the micron size range, the melt flow processing through the twin screw extruder disperses the glass fibers uniformly apart without excessive wear of the glass fibers. Owing to high shear between



(a) (b) (c)

(d) (e)

Figure 1. (a) SEM image of micro composite (G) in which glass fibers are uniformly distributed (b) SEM fractograph of hybrid composite which revealed the dispersion of glass fibers in H3 composite (c) zoomed individual glass fiber (SEM image) in H3 composite (d) SEM image revealing the presence of MWCNTs on the surface of glass fiber in H3 composite (e) SEM image of N3 composite showing the uniform dispersion of glass fibers in the PP matrix.

the screw and the barrel it is possible to reduce the aspect ratio of the glass fibers. The fractured surface of the hybrid composite (H3) was analyzed by SEM, which also showed the uniform distribution of a large number of glass fibers within the matrix (Figure 1(b)). It is disclosed from the micrographs of G and H3 composite that the aspect ratio of glass fibers can be maintained in the polymer, which can be correlated with enhanced mechanical properties reported in section 3.3. It could be noted that in Figure 1(b), MWCNTs could not be noticed along with glass fibers in H3 composite due to large differences in scale of micro and nanoparticle. To understand the dispersion of MWCNTs on and around the surface of glass fibers, an individual micro scale glass fiber in hybrid composite was zoomed at higher magnification, revealing the presence of MWCNTs (Figure 1(c) and (d)). Amongst the nanocomposites at 3 wt.%, a uniform dispersion of MWCNTs (Figure 1(e)) could be observed in the SEM image as white projections.

The TEM images shown in Figures 2(a) and 2(b) explored the dispersion of MWCNTs in the nanocomposite (N3) and Figures 2(c) and 2(d) displayed the dispersion of CNTs in the hybrid (H3) composite. The TEM image of the N3 nanocomposite (Figure 2(a)) conforms to the SEM result of N3 (Figure 1(e)), revealing the uniform distribution of MWCNTs in the PP matrix. At higher content of 5wt% MWCNTs, agglomerations could be clearly visible, which could deteriorate the overall properties of the composites (Figure 2(b)). In the case of TEM images of hybrid composites also, uniform dispersion and distribution was observed for H3 composite, which contains 3 wt.% MWCNT (Figure 2(c) and Figure 2(d)). It could

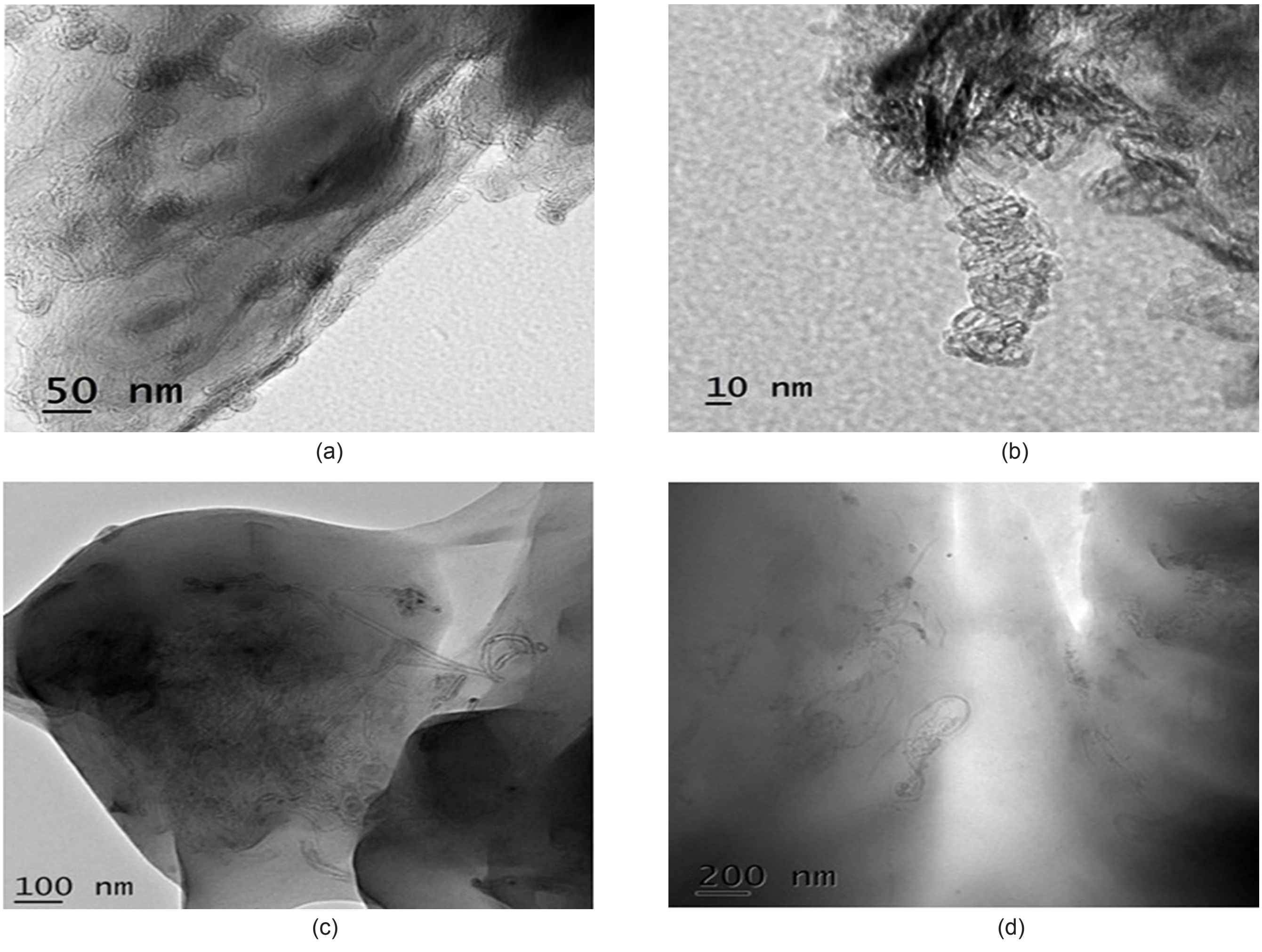


Figure 2. (a) TEM image of N3 composite which shows the uniform distribution of MWCNTs in PP (b) TEM image of N5 composite indicating agglomerates in MWCNT content of above 5 wt.% (c) and (d) TEM image of hybrid composite showing the dispersion of MWCNTs in the PP matrix.

be observed from the TEM images of both nano and hybrid composites that the aspect ratio of the MWCNTs was not affected much, and the long curly nanotubes became more entangled and dispersed to a greater extent in the base matrix, which could be correlated to the tensile properties.

FTIR

FTIR studies were employed to understand the formation of functional groups on the matrix, fillers and their interaction. In order to increase the polarity of polypropylene, it could be grafted with maleic anhydride and hence its affinity with other polar materials could be enhanced. The anhydride groups are highly reactive and form covalent bonds to polar polymer backbones and end groups (Figure 3). Figure 4(a) shows the characteristic FTIR peaks of the virgin PP and PP-*g*-MAH. The grafting reaction of polypropylene with maleic anhydride was performed in the melt via free radical mechanism using benzoyl peroxide as the initiator.

The peaks which correspond to CH stretch are 2950cm^{-1}, 2918 cm^{-1} and 2836 cm^{-1} and the peaks corresponding to CH_2 deformation and symmetric CH_3 deformation are 1456 and 1376 cm^{-1}, respectively. The FTIR spectra of PP-g-MAH show the absorption band at 1720 cm^{-1} which indicates the presence of the initiator (benzoyl peroxide) used during functionalization. The absorption band near 1780 cm^{-1} represents the presence of grafted anhydride [22].

MWCNTs were treated by a mixture of H_2SO_4 and HNO_3 to introduce the carboxyl group on to their surface. The FTIR spectra of acid-treated MWCNTs are shown in Figure 4(b). The peak at 1640 cm^{-1} corresponds to C=O and the peak at 1102 cm^{-1} is in correspondence with C-O stretching, indicating the presence of carboxyl group [23]. The functionalized MWCNTs present an additional broad strong peak at 3417 cm^{-1} which is assigned to the vibration of –OH peaks [23-24]. This shows that carboxyl acid groups are attached on to the surface of MWCNTs. The characteristic peaks and the

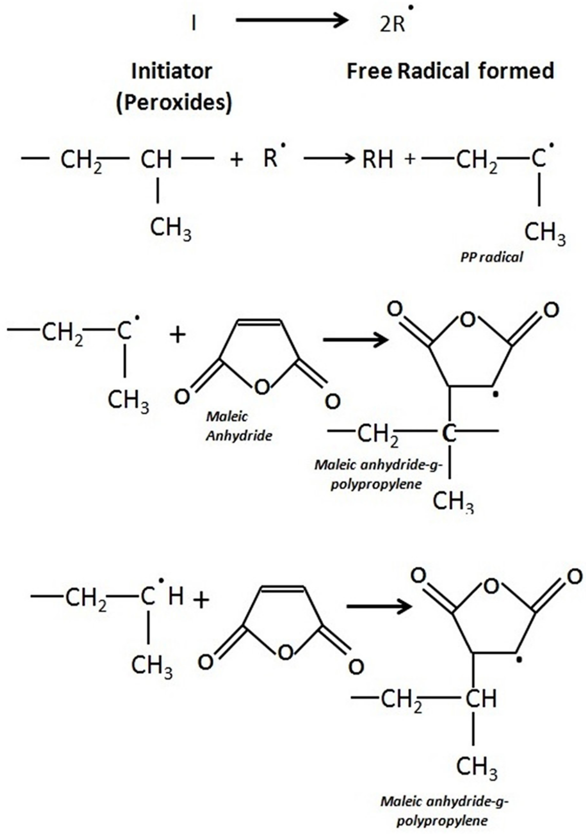
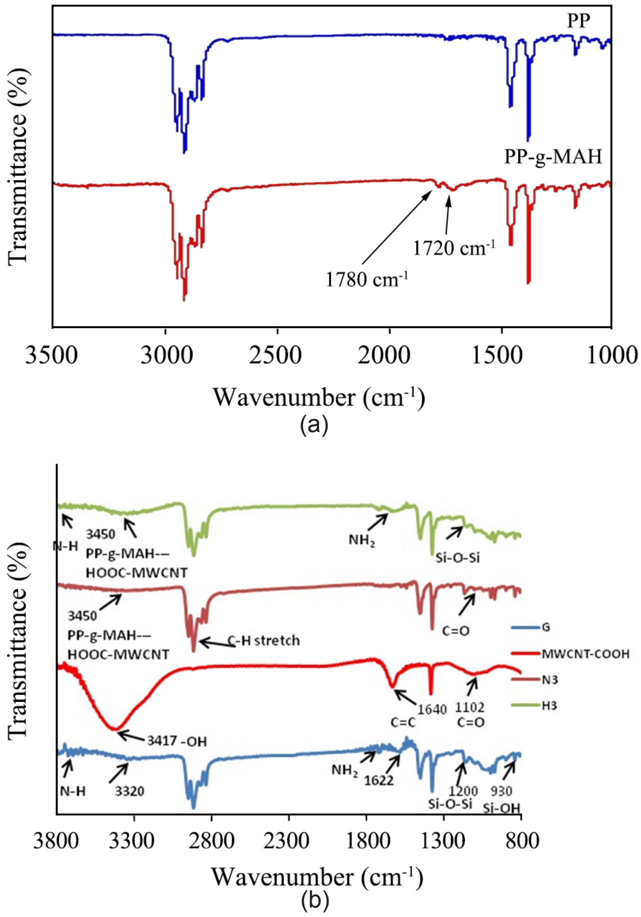


Figure 3. Grafting of polypropylene with maleic anhydride compatibilizer.



(a)

(b)

Figure 4. (a) FTIR spectra of neat PP and PP grafted with maleic anhydride compatibilizer. (b) FTIR spectra of carboxyl-treated MWCNTs, micro, nano and hybrid composites.

corresponding functional groups and bonds obtained from FTIR spectra are presented in Table 2.

The FTIR spectra of N3 composite clearly represent the reaction occurred between –COOH-treated MWCNTs and PP-*g*-MAH. The broadened peak at 3450 cm^{-1} clearly represents the interaction occurred between the acid-treated MWCNTs and maleic anhydride grafted polypropylene [24]. The compatibilizer was used to promote the carbon nanotube dispersion and good adhesion between nanotubes and the PP matrix was obtained by the wrapping of PP-*g*-MAH on MWCNTs. The nano scale dispersion of MWCNTs in the PP matrix is achieved by strong bonding between hydroxyl groups of multiwalled nanotubes and maleic anhydride group of PP-*g*-MAH. All the characteristic –CH stretch in the PP matrix could also be observed in the N3 matrix. The peak corresponding to C=O stretch in -COOH acid could also be observed in the N3 composite. The characteristic bands of isotactic polypropylene are also visible at 998, 974 and at 842 cm^{-1}.

Glass fiber was treated with 3-aminopropyl triexthoxy silane as silane coupling agent. The silane coupling agent is primarily responsible for the enhanced adhesion between the glass fiber and the matrix [25-27]. The organo silanes could initiate the coupling reaction between the inorganic glass fiber surface and the organic matrix since they contain silica and organo functional group capable of forming bond with glass fiber and the polypropylene matrix [28]. Glass fibers were dipped in hydrolyzed silane solution for 30 minutes and dried at 1100°C followed by drying at room temperature and in an oven for 24 hours. The FTIR analysis showed the presence of silicone-based groups attached on the glass fiber surface. The organo silanes could bond to each other by the condensation of the hydrolyzed alkoxy groups (silanol groups) and to the silanol groups on the glass fiber surface [22].

The silanol group formed during the hydrolysis reacts with the glass fiber surface. Due to this interaction silane networks are formed and fixed to glass fiber through siloxane (-Si-O-Si-) linkages. The FTIR spectra of G composite (polypropylene/glass fiber micro composite) show the absorption bands at 3320 cm^{-1} which represents the combinations of vibrations of Si-OH or H_2O. All the characteristic peaks assigned to -CH stretch of polypropylene matrix and Si-CH_3 stretch appeared in the spectra of G composite. The silanol group formation at 1200 cm^{-1} is assigned to the possible siloxane linkage formed.

The FTIR spectra of H3 composite show the presence of Si-OH group (a sharp peak at 930 cm^{-1}) which corresponds to possible formation of silanol group. A strong absorption band at 1100 cm^{-1} is correlated to the formation of siloxane linkage between glass fiber and the silanol groups. The alkoxy group (propyl) of the silane coupling agent is compatible with the polypropylene matrix and hence it generates interaction between the glass fiber and the matrix. The acid-treated MWCNTs present in the hybrid composite are bonded with grafted PP through hydrogen bonding which is assigned to the broad peak (3450cm^{-1}) appeared in the spectra of H3 composite. The PP matrix in turn is compatible with the alkoxy group (propyl group) present in the silane coupling agent attached to the glass fiber surface.

Tensile properties of non-functionalized and functionalized samples

The tensile properties of non-functionalized and func-

Table 2. FTIR characteristic peaks corresponding to matrix, filler, nano, micro and hybrid composites.

IR frequency (cm^{-1})	Functional group
3320	Combinations of vibrations of Si-OH or H_2O
930	Si-OH (Silanol formation)
1200	Si-O-Si bonds in glass fiber (siloxane linkage)
1622	H-OH bonds
3417	-OH stretching
1102	C=O stretching
1640	C=C Aromatic ring stretching
2950,2918,2836	CH stretch, Si-CH_3 stretch
1455,1375	CH_2 deformation, symmetric CH_3 deformation
997,972	Isotactic polypropylene bands
3200-3500	N-H group
1600	NH_2 bending

Table 3. Comparison of tensile properties of non-functionalized and functionalized nano, micro and hybrid composites.

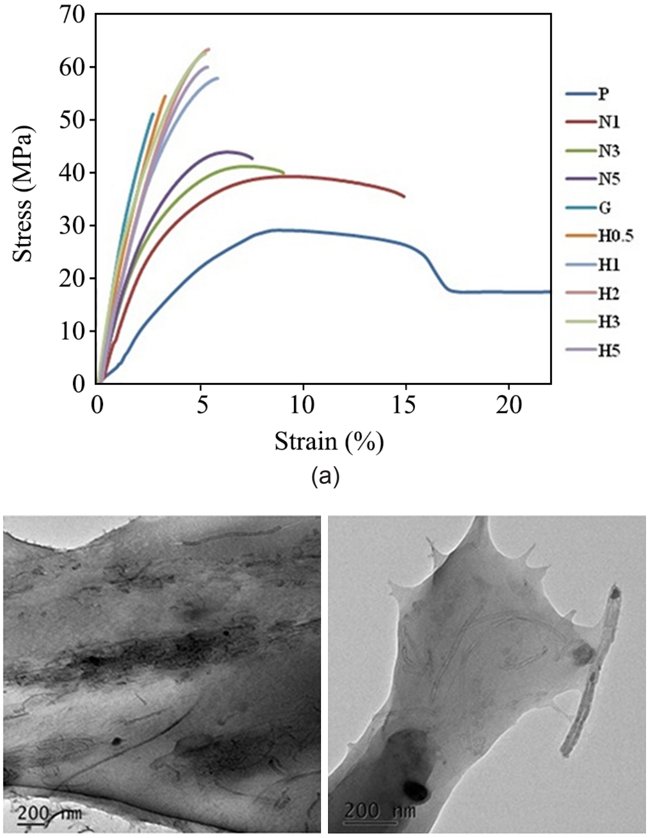
Material	Tensile strength (*BC) MPa	Tensile strength (*AC) MPa	Young's Modulus (*BC) MPa	Young's Modulus (*AC) (MPa)	Elongation-at-break (*BC) (%)	Elongation-at-break (*AC) (%)
PP	29.2 ± 0.5	-----	1100 ± 31	-----	20.0 ± 1.5	------
N1	31.7 ± 0.7	39.2 ± 0.9	1186 ± 52	1506 ± 63	16.2 ± 0.8	14.8 ± 0.7
N3	33.9 ± 0.7	41.2 ± 0.8	1523 ± 59	1825 ± 57	9.0 ±0.4	6.8 ± 0.5
N5	36.0 ± 0.6	43.8 ± 1.1	1587 ± 47	2115 ± 84	7.5 ± 0.2	6.2 ± 0.3
G	41.9 ± 1.2	50.7 ± 1.4	2542 ± 78	3457 ± 76	2.8 ± 0.2	2.7 ± 0.2
H0.5	44.7 ± 0.7	53.3 ± 1.2	2186 ± 42	3424 ± 48	3.0 ± 0.2	3.6 ± 0.3
H1	46.3 ± 0.6	57.7 ± 1.3	2210 ± 55	3305 ± 51	3.4 ± 0.1	5.7 ± 0.2
H2	47.7 ± 0.5	63.2 ± 1.1	2456 ± 92	3424 ± 79	3.7 ± 0.2	5.4 ± 0.1
H3	51.4 ± 1.3	61.5 ± 0.9	2500 ± 68	3580 ± 58	4.9 ± 0.4	4.9 ± 0.2
H5	48.4 ± 0.8	59.0 ± 0.7	2200 ± 71	3200 ± 89	5.5 ± 0.3	5.1 ± 0.1

*BC: Before compatibilization; *AC: After compatibilization

tionalized composites are reported in Table 3 and stress-strain plots and the dispersion of MWCNTs in functionalized composites are shown in Figure 5(a).

The stress-strain plot of hybrid composites in which acid-treated MWCNTs and silane-treated glass fibers are incorporated demonstrated a significant increment in tensile strength and modulus values. With the incorporation of silane-treated glass fibers in the PP matrix the tensile strength improved by 21% in comparison with untreated PP/glass fiber micro composite. For nanocomposites, in the presence of PP-*g*-MAH chains and carboxyl-treated MWCNTs, tensile strength and modulus enhanced to their maximum by 62% and 107%, respectively, at 5 wt.% CNTs in the matrix. The strong bonding between the hydroxyl groups of CNTs and the anhydride group of PP chains improved dispersion and tensile properties.

The prominent effect of silane coupling agent and acid-treated MWCNTs could be observed in the H2 composite. The tensile strength of H2 composite enhanced to 63.2 MPa in comparison with 47.7 MPa (ie., for H2 composite in which untreated glass fiber is incorporated), that is about 32.5% and modulus enhanced by 39% (from 2456MPa to 3424MPa). This might be due to the intense adhesion occurred at the interface between glass fiber and the PP matrix. As revealed in the FTIR spectra of hybrid composite, strong siloxane linkages generated could form a complex network between glass fiber and silanol group formed. Furthermore, the alkoxy end of silanol due to its high affinity to polypropylene will wrap around the PP chains and an effective stress transfer is achieved at the interfaces. The brittleness of the composite also reduced with the incorporation of sized glass fiber and without compromising the tensile strength and stiffness. Elongation-at-break also improved. This is a direct indication of the greater amount of energy absorbed



(a)

(b) (c)

Figure 5. (a) Stress-strain plots of functionalized nano, micro and hybrid composites (b) TEM images of H3 composite indicating the uniform dispersion of fillers within the matrix (non-functionalized sample) (c) TEM image of functionalized H3 composite showing improved dispersion (functionalized sample). *The picture in color is available on-line. Please visit: http:\\poj.ippi.ac.ir*

by the composite before failure, and strain-at-break has enhanced by 46% which shows an effectual distribution of interfacial stresses [29, 30].

The TEM images of H3 composite (Figure 5 (b)) revealed uniform dispersion of MWCNTs within the matrix. The improved dispersion of MWCNTs could be observed for the H3 composite in which CNT was functionalized with carboxyl group, glass fibers was treated with silane coupling agent, and polypropylene was grafted with PP-*g*-MAH (Figure 5(c)). This improved dispersion could be further correlated with the enhancement in mechanical properties of functionalized samples.

CONCLUSIONS

Polypropylene-based nano, micro and hybrid multiscale filler-reinforced composites were prepared via melt compounding twin screw extrusion. The micro structure obtained for the composites was correlated with their enhanced mechanical properties and bonding mechanism was revealed using FTIR spectra. FTIR spectra of hybrid composite displayed the characteristic absorption peak for silanol group which depicted the anchoring with glass fiber surface, leading to siloxane linkages. The hydrogen bonding between maleic anhydride and –COOH-grafted CNTs was also revealed from FTIR spectra, which could result in prominent interfacial adhesion. The stress-strain plots of functionalized samples showed a very clear demarcation between the tensile properties of nano, micro and hybrid composites. It can be inferred that the tensile strength obtained by incorporating MWCNT nanofillers into the matrix alone is not very exciting, but retains the polymer ductility. The nano composites can absorb a greater amount of energy with moderate tensile strength. With the incorporation of microscale glass fibers alone in the matrix, the tensile strength improved drastically but a brittle catastrophic failure was observed. For a fixed glass fiber fraction of 20 wt.%, a change in MWCNT content from 0.5 wt.% to 3 wt.% enhanced tensile strength tremendously and maintained reasonable ductility. This signifies the relevance of coexistence of multiscale fillers in the matrix and the properties of composites can be tailored by optimizing the filler content and by the choice of the filler type. Amongst the nanocomposites at 5 wt.% of MWCNTs treated with carboxyl groups, and in the presence of PP-*g*-MAH chains in the PP matrix, the ultimate tensile strength improved by 62% and the modulus by 107%. In the case of hybrid composites, tensile strength enhanced by 117 % and modulus by 123% with regard to neat PP matrix. The synergy of micro and nano fillers in the base matrix can take advantage of the individual properties of the fillers and, along with the compatibilizer, enhance the surface properties that manifest themselves in the mechanical properties. These studies on functionalized PP reinforced composites with nano scale MWCNTs along with micro scale glass fibers (multiscale composite system) demonstrate their application in automotive structural components where light weight characteristics without compromising mechanical properties are vital.

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CONFLICTS OF INTEREST

None declared

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