Synergistic augmentation of polypropylene composites by hybrid morphology polyaniline particles for antistatic packaging applications

Yasir Qayyum Gill, Hira Ehsan, Muhammad Shafiq Irfan, Farhan Saeed and Abdul Shakoor

1 Department of Polymer and Process Engineering, University of Engineering and Technology, Lahore, Pakistan
2 Department of Mechanical Engineering, University of Engineering and Technology, Peshawar, Pakistan
3 Author to whom any correspondence should be addressed.
E-mail: ygill@uet.edu.pk, hirapolymer@gmail.com, shafiqirfan@uet.edu.pk, f.saeed@uet.edu.pk and shakoor@uetpeshawar.edu.pk

Keywords: hybrid, polypropylene, antistatic, packaging, conductive

Abstract
In current study polyaniline filled polypropylene (PP/PAni) conductive composites were prepared by a novel premixing technique followed by melt mixing. The PP/PAni composites were also compatibilized by addition of polypropylene grafted maleic anhydride. Polyaniline was prepared by using ammonium per sulphate and ferric chloride as single oxidants. Effects of oxidizing agents (of polyaniline) on composites were studied by morphological, electrical and mechanical properties on composites. FTIR analysis was also carried out to study the nature of interactions and possible bonding between polyaniline and polypropylene matrix. Thermal analysis was carried out to study the thermal stability of composites. Morphological analysis revealed that the proposed premixing technique was quite successful in depositing polyaniline to polypropylene matrix. This analysis was also supported by the results of electrical conductivity where formation of conductive pathways were observed by addition of polyaniline thus converting insulating nature of polypropylene to a semiconducting one.

1. Introduction

Electrically conductive polymer composites are class of polymers that contain conductive fillers dispersed within the polymer matrix [1]. Conductive polymer composites have gained much attention during last decades due to their wide range of applications. Due to low density, ease of processability, corrosion resistant nature and tunable electric properties these electrically conductive polymers are widely used as antistatic media, self-regulated heating materials, sensors, energy storing devices and design of electro-optical devices [2–4]. Polypropylene, polyethylene, ultra-high molecular weight polyethylene, polystyrene, polyamides etc have been extensively used for fabrication of electrically conducting polymer composites [5]. In order to impart conductivity, these polymers are filled with conductive polymers. A conducting polymer is an organic polymer that has the ability to behave as a semiconductor or a conductor. Polyaniline, polypyrroles, polythiophenes and polyphenylene vinylenes are most widely studied conducting polymers in literature [6]. These conducting polymers comprise alternate single and double bonds and hence are also called conjugated molecules [7].

Polyaniline (Emeraldine base) is considered as one of the most useful conducting polymer due to its high environmental and thermal stability, low resistivity, simple doping/dedoping chemistry and ease of manufacturing. It has been widely used in many applications e.g. solar energy conversion devices, rechargeable batteries, electrochemical sensors, capacitors and corrosion protectors [8]. It is slightly different from other conducting polymers i.e. polythiophene and polypyrrole in a way that it possesses three different oxidation states namely leucoemeraldine (fully reduced), emeraldine (partially oxidized) and pernigraniline (fully oxidized). Polyaniline is also unique in a way that by treating with acid or base it can be rapidly converted in salt and base forms [9]. Polyaniline is commonly prepared by polymerizing aniline monomer in acidic medium in the presence of an oxidizer. Properties of polyaniline are dependent on nature of acid, oxidant, reaction medium,
agitation, concentration of monomers and polymerization temperature \[10\]. Different oxidants are used for chemical synthesis of polyaniline. Peroxydisulphates of sodium and ammonium, potassium dichromate, hydrogen peroxide, vanadium oxide, ferric chloride are some common oxidants used for synthesis of polyaniline \[11−13\]. In literature polyaniline is mostly prepared by using ammonium per sulphate as oxidizer because of high conversion and electrode potential. However, ammonium per sulphate is stoichiometrically consumed in the reaction and requires treatment of acidic by-products of oxidant \[14\]. Ferric chloride has also been reported as effective oxidizer for chemical synthesis of polyaniline. However, oxidation potential of ferric chloride is 0.77 V that is lower than the electrode potential of ammonium persulphate. According to Yasuda and Shimizu, this low electrode potential would reduce side reaction during polymerization. Moreover, ferric chloride is soluble in chloroform, ether and other organic solvents so it can also polymerize aniline derivatives while ammonium persulphate has poor solubility in organic solvents \[15\].

Since 1984 efforts have been made to use these conducting polymers in polymer composites or composites to obtain useful products with tunable properties \[16\]. Polyaniline has been widely used in various polymer matrices to produce conducting polymer composites. Interfacial compatibility between the polymer matrix and polyaniline is a key parameter in determining the mechanical and electrical properties of composites. Due to thermodynamically immiscible nature of two polymers, a two phase system is formed upon their melt mixing. Different polarities and crystal structure of polymers result in incompatibility between the whole system that results in inferior mechanical and electrical properties \[17\]. This issue is commonly resolved by addition of suitable compatibilizers that aid both dispersion and adhesion. Graft copolymers have been reported as effective compatibilizers for polymer composites \[18\]. Due to higher reactivity of anhydride groups, maleic anhydride graft polymers are commonly used as compatibilizer for improving the interfacial adhesion between the two immiscible phases. In maleic anhydride graft polymers, the succinic groups are highly reactive and can easily form covalent bonds with the polymer backbone chain and end groups \[19\].

In the current study PP-grafted-Maleic anhydride (PP-g-MA) compatibilized PP/PAni composites were prepared by melt mixing. Polyaniline was prepared by chemical polymerization method using two oxidizers separately i.e. ammonium per sulphate and ferric chloride. Along with compatibilization, mixture was sonicated prior to melt mixing so that a uniform dispersion can be attained. Effect of two oxidizers on crystal structure, electrical, mechanical and morphological properties of the composites were observed.

2. Experimental

2.1. Chemicals

Hydrochloric Acid (37% Labscan), Aniline (Merck Schuchardt, Germany), Ammonium per sulphate (DaeJung Chemicals, China), Ferric (III) chloride (BDH GPR \[16\]), Distilled water, Polypropylene (Homopolymer, Repol, Reliance Industries Limited, India), Polypropylene-graft- Maleic Anhydride (Grafting rate: 0.8%−1.0%, Melt Flow index: 50–80 g/10 min at 190 °C and 2.16 Kg, Shandong Dawn Polymer Co., Ltd China.) were used in this research. Polypropylene and propylene grafted maleic anhydride were grinded to powder using liquid nitrogen on a laboratory scale rotary mill.

2.2. Synthesis of polyaniline

Polyaniline was prepared by chemical oxidation of aniline monomer in acid medium. 0.6 M solution of aniline in 1 M HCl was prepared. To it 0.7 M solution of oxidant either Ferric (III) chloride (FeCl₃) or Ammonium per sulphate (APS) was added dropwise while stirring in an ice bath (for APS). Stirring was continued for about 3 h. Temperature of ice bath was maintained at 0 to 5 °C (for APS) while for FeCl₃ stirring was done at room temperature. After 3 h solution was filtered using Whatman filter paper and washed repeatedly with 1 M HCl. Residue was collected over filter paper and dried in vacuum oven at 60 °C until a constant mass was obtained. This final product was crushed in mortar and pestle and was stored.

2.3. Preparation of PP/PP-g-MA/PAni composites

Composites with different weight percentages (0.6 wt%−PP/Fe0.6, 1 wt%−PP/Fe1.0, 2 wt%−PP/Fe2.0, 3 wt%−PP/Fe3.0, 5 wt%−PP/Fe5.0 and 10 wt%−PP/Fe1.0) of polyaniline prepared using FeCl₃ were formulated for 50 g samples. In case of APS based PAni specimens (5 wt%−PP/APS 5.0 and 10wt%−PP/APS 10.0) were prepared. The schematic diagram illustrating the pre-mixing and melt mixing steps of composite preparation is shown in figure 1.

Polypropylene powder along with cross linker PP-g-MA (5% of PP powder) was added in 100 ml of distilled water in a flask. Polyaniline of required concentration was added in 100 ml of distilled water in another flask. Both the mixtures were sonicated for 2 h in a sonication bath (Desen Ultrasonic Cleaner DSA100-GL1). Then both mixtures were combined and again sonicated for 2 h. This mixture was stirred for about 3 h along with
heating. After 3 h the mixture was removed from stirrer and was dried in a drying oven at 90 to 100 °C until fully dried green colored powder (figure 2) was obtained. This powder was further thermally processed using twin screw mixer at 200 °C and 40 rpm for about 8 to 10 min. In this way a solid mass of polypropylene coated polyaniline was obtained. This solid mass was converted to thin sheets of thickness 1 mm via compression molding. About 35 grams of solid mass was placed in between hot plates of compression molding machine at 200 °C and pressure of about 200 bar was applied for 10 min. After 10 min heating was closed, and sheet was allowed to cool properly under constant pressure.

2.4. Characterization
Optical micrograph for polypropylene coated polyaniline powder was taken by Olympus STM-6 measuring microscope. FTIR/ATR analysis was carried out to study the interaction between compatibilizer, polymer matrix and the filler. FTIR/ATR spectra were recorded by JASCO FT-IR 4100 with 32 scans. For polypropylene and polyaniline powder, specimen was mixed with KBr and pressed in pellet making assembly to form a pellet. This pellet was then characterized by FTIR. For composites, ATR analysis was carried out directly on molded specimen. SEM micrographs were taken by JEOL JSM 5910 SEM at 15KV intensity in secondary mode. All specimens were sputter coated with gold prior to testing for SEM analysis. XRD spectra was recorded by PANalytical X Pert PRO X-ray diffractometer with Cu radiation of wavelength 1.54 Å to study the crystallinity of composites. Tensile strength and modulus of compatibilized PP/PAni composites was studied by a universal testing machine (TIRA Test 2810) according to ASTM D 638. Thermogravimetric analysis was carried out using Shimadzu TGA-50 in air with a heating rate of 5 °C min⁻¹ and temperature ranging between 100 °C–600 °C. Electrical conductivity of molded composites was calculated by four probe method. Molded specimen of 2.5*2.5*0.1 (cm) were subjected to electric current by two outside probes having probe spacing of 0.28 cm by using a DC precision power source Keithley, Model 6220 and the resulting voltage across the two inside probes was measured by voltmeter Keithley, Model 2182. Electrical resistivity was measured by following equation

\[ \rho = \frac{\pi}{\ln 2} \left( \frac{V}{I} \right) F_1 F_2 \]  

Where F₁ and F₂ are finite thickness and length correction factors. Here, F₁ and F₂ are 0.9999 and 0.875 respectively [20].
3. Results and discussion

3.1. Optical microscopy
Optical micrograph of PP/Fe3 specimen at 40x (figure 3(a)) and 400x (figure 3(b)) magnification is shown in figure 3. Uniformity of green color on polypropylene granules indicates uniform dispersion and distribution of polyaniline in polypropylene matrix. This uniformity of dispersion shows that pre-mixing technique was quite successful in adhering polyaniline to polypropylene particles. This uniformity is also evident from SEM micrographs where uniform dispersion and formation of conducting paths are visible that lead to enhancement in conductivity and mechanical properties.
3.2. FTIR/ATR

FTIR/ATR spectra of polypropylene, polyaniline and compatibilized PP/PAni composites were studied and are shown in figure 4. Absorption peaks for polypropylene were observed near 2917 cm\(^{-1}\), 1454 cm\(^{-1}\) and 1374 cm\(^{-1}\) representing C–H stretch, CH\(_2\) and CH\(_3\) deformation respectively. Band near 1033 cm\(^{-1}\) represents isotactic polypropylene bend. Similarly polyaniline was characterized by a broad band near 3400 cm\(^{-1}\) indicating N–H stretching vibrations of aromatic amine, bands near 1600 cm\(^{-1}\) and 1500 cm\(^{-1}\) correspond to benzene and quinone ring deformation, absorption peak near 1200 cm\(^{-1}\) is assigned to stretching vibration of C–N group of secondary aromatic amine. Peaks near 1100 cm\(^{-1}\) and 800 cm\(^{-1}\) indicates C–H in-plane bending and C-H aromatic out of plane bending modes respectively. When respective amounts (0.6, 1, 2, 3, 5 and 10 wt.%) of polyaniline was added to polypropylene matrix, absorption peaks of polyaniline were observed in ATR spectra of composites. These peaks represent the incorporation of polyaniline in polymer matrix. Along with the peaks of polyaniline an additional peak near 1720 cm\(^{-1}\) was observed in ATR spectra of compatibilized composites. This peak is attributed to the carbonyl group that arises due to the addition of compatibilizer i.e. Polypropylene grafted maleic anhydride in composites. Intensity of this carbonyl peak at 1720 cm\(^{-1}\) varies slightly due to slight difference in its concentration. Relatively weak intensity of carbonyl group in composites with 5 and 10 wt% of polyaniline is due to the overlapping of carbonyl peak with its nearby polyaniline peak near 1600 cm\(^{-1}\) and also due to slightly low content of compatibilizer. As stated in literature that carbonyl group from an anhydride shows two partly overlapped bands in the region of 1830–1740 cm\(^{-1}\). However, this observation is not supported by our findings as only one peak of carbonyl is observed in all spectra. From this observation it can be concluded that it is due to the chemical changes caused by melt conditions and the added components. Formation of imide group due to reaction of terminal amine groups of polyaniline and anhydride of compatibilizer is negligible as no signal of imide formation has been observed near 1770 cm\(^{-1}\). So, it can be concluded that due to the presence of carbonyl group physical interactions are generated within the matrix. However, no evidence of interaction between polyaniline and polypropylene grafted maleic anhydride have been observed. But the position of all the peaks was observed to be the same as that of their pure components. From this observation it can be concluded that physical networking is created between polyaniline and polypropylene matrix.

3.3. Morphological analysis

Liquid nitrogen assisted fractured surfaces of PP/PAni composites were analyzed by SEM at x5000 to reveal their morphology. SEM micrographs of PP/PAni composites filled with 3, 5 and 10 wt% of PANi were observed and are shown in figures 5(a)–(d). Figures 5(a), (b) are the micrographs for PP/Fe0.6 and PP/Fe1 while figures 5(c) and (d) contains PP filled with 5 and 10 wt.% PAni respectively x5000. From these figures it can be observed that uniform dispersion and distribution is achieved in PP composites filled with 5 wt% PAni. As the concentration of polyaniline increases to 10 wt% agglomeration of polyaniline starts in polypropylene matrix due to more filler-filler interactions instead of filler matrix interactions. This can be visualized in figure 5(d).

Moreover, these micrographs contain some elongated structures that promote the formation of conducting paths. These conducting paths are formed as a result of shear forces on polyaniline particles during molding as described in results of electrical conductivity. These conducting paths form a net of wires that contribute in...
3.4. X-ray diffraction
Crystal structure of PP/PAni composites was analyzed by XRD. Figure 6 shows the diffraction patterns for compatibilized PP/PAni composites. As mentioned in literature XRD analysis of pure polypropylene reveals strong reflection peaks at 14.28°, 17.14°, 18.92°, 21.40°, and 22.20° [21]. Similarly, polyaniline shows its reflection peaks at 15°, 20° and 25° [22]. Similar peaks were observed in given XRD spectrum for specimen containing different concentrations of polyaniline.

XRD spectra of compatibilized PP/PAni composites show some sharp and well defined peaks which indicate semi-crystalline nature of polyaniline and polypropylene. The semi-crystalline nature of polyaniline can be attributed to repetition of quinoid and benzinoid rings in polyaniline structure. However, as evident from figure 6, crystallinity of sample S6 and S7 is lower as compared to S1, S2, S3, S4 and S5. From this observation it can be stated that crystallinity of polyaniline prepared by using ferric chloride as oxidant is higher as compared to polyaniline prepared by using ammonium persulphate as oxidant. This can be attributed to low oxidation potential of ferric chloride (0.77 V) than ammonium persulphate (1.94 V) which results in formation of slow growing structures [23]. This factor also affects the crystallinity of compatibilized PP/PAni composites as evident from XRD spectra of composites.

3.5. Tensile properties
Figure 7 shows the tensile stress and tensile modulus of PP/PAni-FeCl₃ composites along with their standard deviation values in the form of error bars. It was observed that tensile strength and tensile modulus increased prominently upto 2 phr PAni loading and then became almost constant. About 14% and 61% increase in tensile strength and tensile modulus was observed as the concentration of polyaniline in composites was increased from 0 to 2%. Values of tensile strength and tensile modulus at 2 phr were 33.62 MPa and 1.69 GPa respectively. At higher concentration of greater than 2 phr very slight increase (almost negligible) in mechanical properties was observed. Tensile strength increased from 33.62 MPa (2 phr) to 34.13 MPa (10 phr) and modulus was increased from 1.69 GPa (2 phr) to 1.8 GPa (10 phr) for composites prepared by using ferric chloride as oxidant.

Figure 5. SEM micrograph for PP/PAni composites (a) PP/Fe3, (b) PP/Fe5, (c) PP/Fe10, and (d) PP/APS10.
For composites synthesized by using ammonium per sulphate as oxidant tensile strength decreased from 32.86 MPa (5 phr) to 32.01 MPa (10 phr) and tensile modulus from 1.69 GPa (5 phr) to 1.67 GPa (10 phr). Overall it can be concluded that addition of polyaniline does not have a significant effect on mechanical properties of composites. Along with concentration mechanical properties remained unaffected by the type of oxidant used for preparing polyaniline. Slight decrease in mechanical properties at higher loadings of polyaniline can be attributed due to increase in inhomogeneity and non-uniform distribution of filler within the matrix as

Figure 6. XRD spectra for PP/PAni-FeCl₃ and PP/PAni-APS composites.

Figure 7. Tensile strength and tensile modulus for PP/PAni-FeCl₃ composites.
concentration of polyaniline increases. This nonuniformity of distribution can also be visualized by SEM micrographs where agglomeration of polyaniline particles in polypropylene matrix is observed at higher concentrations of the filler.

3.6. Thermogravimetric analysis
Thermogravimetric analysis for compatibilized polypropylene/polyaniline composites was carried out to study their thermal stability and is shown in figure 8. Test was performed within the temperature range of 100 °C–600 °C. Addition of polyaniline in polypropylene matrix increased the thermal stability of polypropylene as revealed by DrTGA thermograms shown in figure. All composites possess a single step degradation process as shown by a single decomposition peak in derivatogram [24].

According to figure 8 the decomposition temperature of compatibilized PP/PAni composites increased continuously as a result of increase in concentration of polyaniline. Decomposition temperature increased from 417 °C (unfilled) to 437 °C (10 phr) for composites prepared by using polyaniline that contain ferric chloride as oxidant. This behavior can be attributed to high decomposition temperature of polyaniline which causes the degradation to occur at high temperature. For composites prepared by using polyaniline containing ammonium per sulphate as oxidant decomposition temperature is 12 °C higher when compared with composite with ferric chloride as oxidant at same concentration (10 phr of polyaniline).

3.7. Antistatic testing
Effect of oxidizing agents on electrical conductivity of PP/PAni composites is shown in figure 9. An increment in electrical conductivity of PP filled PAni composites was observed using both oxidizers thus converting insulating nature of polypropylene to semiconducting. However electrical conductivity of PP/PAni composites synthesized by using ferric chloride as an oxidant increased upto critical concentration referred as percolation threshold and then dropped. This percolation threshold is that point at which a sharp increase in conductivity is observed due to formation of conductive pathways. Above this percolation limit a decline in conductivity is observed [25, 26]. For composites manufactured by using FeCl₃ as oxidant electrical conductivity was increased from $2.6 \times 10^{-14}$ (for unfilled) to $1.8 \times 10^{-6}$ (5 wt%). This concentration (5 wt. %) was referred as percolation threshold as abrupt increase from $10^{-14}$ to $10^{-6}$ was observed at this concentration. After this concentration slight increase in electrical conductivity was observed as seen in figure 9. For composites fabricated by ammonium per sulphate oxidant electrical conductivity was increased from $2.6 \times 10^{-14}$ (for unfilled) to $8.6 \times 10^{-6}$ (5 wt%). This increase in conductivity can be attributed to formation of conducting pathways as a result of adding polyaniline in polypropylene matrix. These conducting pathways are formed as a result of high shear forces during molding that transform dispersed PAni particles into elongated structures that finally result in formation of conducting network [27]. These elongated structures and conducting pathways can be clearly visualized in SEM micrographs. From above results it can be concluded that nature of oxidant doesn’t have a significant effect on electrical conductivity. For composites fabricated by ammonium per sulphate as oxidant,
electrical conductivity was improved even at higher loadings while for composites fabricated by ferric chloride as oxidant a decrease in electrical conductivity was observed at higher loadings.

4. Conclusion

A modified method for preparing compatibilized polyaniline filled polypropylene composites was introduced in this study which is practical as well as cost efficient. Effect of nature of oxidant and concentration of polyaniline in compatibilized polypropylene matrix was under concern. Effects of these factors were studied on mechanical, electrical and thermal and morphological properties. Polyaniline showed good compatibility with polypropylene even at lower concentration. Optical micrographs showed uniform deposition of polyaniline on polypropylene granules. SEM micrographs also support this observation as interconnected pathways were formed by addition of polyaniline that promote conductivity. Tensile properties increased up to 2 phr polyaniline loading for both types of oxidizing agents and then decreased slightly due to non-homogenous distribution of filler at higher loadings. This aspect was also justified by SEM micrographs where agglomeration is prominent. Thermal analysis revealed the composites to be thermally stable at high temperatures. Electrical conductivity was increased even at high filler loadings. From the results it was concluded that nature of oxidant does not have a significant effect on electrical conductivity and mechanical and morphological properties. However, the proposed technique was successful in depositing polyaniline to polypropylene matrix thus converting the inherent insulating nature of polypropylene to a semiconducting one.

ORCID iDs

Yasir Qayyum Gill  https://orcid.org/0000-0002-1206-6205
Muhammad Shafiq Irfan  https://orcid.org/0000-0002-4202-986X

References

[1] Motaghi A, Hrymak A and Motlagh G H 2015 Electrical conductivity and percolation threshold of hybrid carbon/polymer composites J. Appl. Polym. Sci. 132 1—9
[2] Pang H, Xu L, Yan D and Li Z 2014 Conductive polymer composites with segregated structures Prog. Polym. Sci. 39 1908–33
[3] Yang I Y and Gupta M C 2005 Novel carbon nanotube–polystyrene foam composites for electromagnetic interference shielding Nano Lett. 5 2131–4
[4] Ku-Herrera J J and Avile`s F 2012 Cyclic tension and compression piezoresistivity of carbon nanotube/ vinyl ester composites in the elastic and plastic regimes Carbon 50 2592–8
5 Ding X, Wang J, Zhang S, Wang J and Li S 2016 Carbon black-filled polypropylene as a positive temperature coefficient material: effect of filler treatment and heat treatment Polym. Bull. 73 369–83
6 Jotiram P, Prasad R G S V, Jakka V S, Aparna R S L and Phani A R 2012 Antibacterial activity of nanostructured polyaniline combined with mupirocin Nano. Biomed. Eng. 4 14–9
7 Molapo K M, Ndangulig M P M, Ajayi R F, Mbambisa G, Mailu S M, Njomo N, Masikini M, Baker P and Iwuoha E I 2012 Electronics of conjugated polymers (1): polyaniline Int. J. Electrochem. Sci. 7 11859–75
8 Vivekanandan J, Ponnusamy V, Mahadeswaran A and Vijayanand P S 2011 Synthesis, characterization and conductivity study of polyaniline prepared by chemical oxidative and electrochemical methods Arch. Appl. Sci. Res. 3 147–53
9 Masters J G, Sun Y, MacDiarmid A G and Epstein A J 1991 Polyaniline: allowed oxidation states Synth. Met. 41 715–8
10 Li G, Zhang C, Li Y, Peng H and Chen K 2010 Rapid polymerization initiated by redox initiator for the synthesis of polyaniline nanofibers Polymer 51 1934–9
11 Niziol J, Sniecowski M, Podrza G A and Pielichowski J 2011 Alternative oxidizers in polyaniline synthesis Polym. Bull. 66 761–70
12 Zhang L, Wan M and Wei Y 2006 Nanoscaled polyaniline fibers prepared by ferric chloride as an oxidant Macromol. Rapid Commun. 27 366–71
13 Pang S, Li G and Zhang Z 2005 Synthesis of polyaniline-vanadium oxide nanocomposite nanosheets Macromol. Rapid Commun. 26 1262–5
14 Nestorović G D, Jeremić K B and Jovanović S M 2006 Kinetics of aniline polymerization initiated with iron(III) chloride J. Serb. Chem. Soc. 71 895–904
15 Yasuda A and Shimizu T 1993 Chemical and electrochemical analyses of polyaniline prepared with FeCl3, Synth. Met. 61 239–45
16 Pud A, Ogurtsov N, Korzhenko A and Shapoval G 2003 Some aspects of preparation methods and properties of polyaniline blends and composites with organic polymers Prog. Polym. Sci. 28 1701–53
17 Chongprakobkit S, Opaprapakait M and Chuayjuljit S 2007 Use of PP-g-MA prepared by solution process as compatibilizer in propylene/polyamide 6 blends J. Mater. Sci. 17 9–16
18 Chuayjuljit S, Mooalai S and Potiyaraj P 2005 Use of natural rubber-g-polystyrene as a compatibilizer in casting natural rubber / polystyrene blend films J. Appl. Polym. Sci. 95 826–31
19 Oromiehe A, Ebad D H and Mirbagheri A 2014 Chemical modification of polypolyphenyl by maleic anhydride: melt grafting, characterization and mechanism Int. J. Chem. Eng. Appl. 5 117–22
20 Shehzad M A, Qaiser A A, Javaid A and Saeed F 2015 In situ solution–phase polymerization and chemical vapor deposition of polyaniline on microporous cellulose ester membranes: AFM and electrical conductivity studies Synth. Met. 200 164–71
21 Lin H, Pan Y J, Liu C F, Huang C L, Hisieh C T, Chen C K, Lin Z J and Lou C W 2015 Preparation and compatibility evaluation of polypolyphenyl/high density polyethylene polyblends J. Appl. Polym. Sci. 125 2695–700
22 Bhagwat A D, Sawant S S and Mahajan C M 2016 Facile rapid synthesis of polyaniline (PAni) nanofibers J. Nano.-Electron. Phy. 8 01037 (1-3)
23 Ayad M M, Amer W A and Whdan M 2012 In situ polyaniline film formation using ferric chloride as an oxidant Int. J. Appl. Polym. Sci. 125 6295–700
24 Chen R S, Ab Ghani M H, Ahmad S, Salleh M N and Tarawneh M A 2014 Rice husk flour biocomposites based on recycled high-density polyethylene/polyethylene terephthalate blend: Effect of high filler loading on physical, mechanical and thermal properties J. Compos. Mater. 49 1241–53
25 Sarfraz M, Rehman Z and Ba-Shammakh M 2019 Pursuit of electroconducting thermoplastic vulcanizates: activated charcoal-filled polypolyphenyl/ethylene–propylene–diene monomer blends with upgraded electrical, mechanical and thermal properties Polym. Bull. 76 2005–20
26 Zhang W, Dehghani-Sanjii A A and Blackburn R S 2007 Carbon based conductive polymer composites J. Mater. Sci. 42 3408–18
27 Taiyalus R, Harmia T and Friedrich K 1999 Short fibre reinforced PP/PAni-complex blends and their mechanical and electrical properties Appl. Compos. Mater. 6 167–84