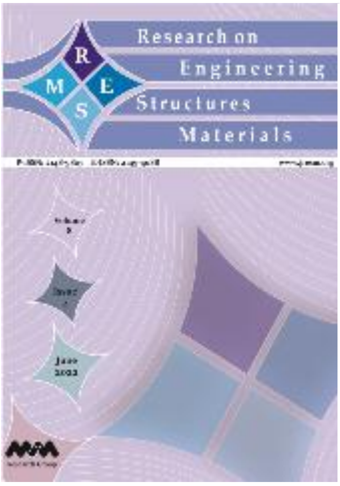
Research on Engineering Structures & Materials
journal homepage: http://www.jresm.org
Research Group



Influence of multi-walled carbon nanotubes on tensile and flexural properties of polyamide 66/short glass fiber composites

Özgür Demircan, Fatma Burcu Uzunoğlu, Naser Rezaei Ansaroudi

Online Publication Date: 15 Aug 2022
URL: http://www.jresm.org/archive/resm2022.443ma0607.html
DOI: http://dx.doi.org/10.17515/resm2022.443ma0607

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Demircan O, Uzunoglu FB, Ansaroudi NR. Influence of multi-walled carbon nanotubes on tensile and flexural properties of polyamide 66/short glass fiber composites. *Res. Eng. Struct. Mater.*, 2022; 8(4): 659-674.

Research on Engineering Structures & Materials

journal homepage: http://www.jresm.org

Research Group

Research Article

Influence of multi-walled carbon nanotubes on tensile and flexural properties of polyamide 66/short glass fiber composites

Özgür Demircan*[1,2,a], Fatma Burcu Uzunoğlu[2,b], Naser Rezaei Ansaroudi[1,c]

[1]*Department of Metallurgical and Material Engineering, Ondokuz Mayıs University, Samsun, Turkey*
[2]*Department of Nanoscience and Nanotechnology, Ondokuz Mayıs University, Samsun, Turkey*

Article Info

Article history:

Received 07 Jun 2022
Revised 27 Jul 2022
Accepted 10 Aug 2022

Keywords:

Composite material; Thermoplastics; Polymer Nanocomposite; Polyamide 66; Glass fiber; Carbon nanotube; Plastic injection moulding

Abstract

In this study, influence of multi-walled carbon nanotubes (MWCNTs) on tensile and flexural behaviour of 15% short glass fiber (SGF) reinforced Polyamide 66 (PA 66/15SGF) and 30% short glass fiber reinforced Polyamide 66 (PA 66/30SGF) is investigated. Test specimens composed of neat PA 66, PA 66/15SGF, PA 66/30SGF and PA 66/30SGF/MWCNTs are produced using plastic injection moulding machine; and their tensile and flexural properties are characterized. The effects of MWCNTs contents on the micro-structure and morphology of the composites were investigated by using a scanning electron microscope (SEM), fourier transform infrared spectroscopy analysis (FTIR) and optical microscopy (OM). Mechanical analyses reveal that neat PA 66 exhibits the lowest elastic modulus, 2.11 GPa, and tensile strength, 60.61 MPa, while the highest tensile modulus, 4.69 GPa, and strength, 87.05 MPa, are exhibited by PA 66/30SGF/MWCNT and PA 66/30SGF, respectively. In other words, with the addition of MWCNT, tensile strength of PA 66/30SGF decreases by 13.4 % whereas the elastic modulus increases by nearly 4.7 %. In addition, flexural test results shows that the integration of MWCNTs improves the flexural strength and flexural modulus of PA 66/30SGF by 1% and 12%, respectively.

1. Introduction

Thermoplastics are commonly used in both commodity and industrial applications covering many industrial fields such as automobile, aeronautic and aviation, defence, sports industry and so forth [1, 2]. Some thermoplastics are considered to be suitable substitutes for metallic materials in industrial applications [3]. However, in spite of their advantages, thermoplastic materials may become deformed during the use or production [4]. In order to avoid these deformations and to increase their mechanical performance, thermoplastics can be filled with microscale or nanoscale reinforcing materials such as carbon fibers (CF), glass fibers (GF), carbon nanotubes (CNTs), nanoclays and so on [5, 6].

Being a thermoplastic, Polyamide 66 (PA 66) is one of the most outstanding materials used as engineering resin owing to its good mechanical, chemical and thermal performance [7, 8]. Apart from neat PA 66, there are various types of polyamides reinforced with materials such as glass fibers. The addition of glass fibers is known to increases the mechanical properties of polyamide-matrix composites [9-17]. The main factors determining the tensile properties of PA 66/GF composites are fiber fracture, diameter, length, orientation and interfacial strength [18-21]. In addition, production parameters such as mold temperature, injection pressure and speed may affect the mechanical properties of the polymer matrix composite materials [22, 23]. Recently, nanomaterials too have been used as reinforcement; and one of the most prominent of them are carbon nanotubes [24-26]. In terms of their forms, CNTs are categorized as single-walled carbon nanotubes (SWCNTs)

**Corresponding author: ozgur.demircan@omu.edu.tr
[a] orcid.org/0000-0001-8235-3966 ; [b] orcid.org/0000-0002-4197-785X; [c] orcid.org/0000-0001-9933-9706
DOI: http://dx.doi.org/10.17515/resm2022.443ma0607

[27] and multi-walled carbon nanotubes (MWCNTs) [28]. The use of MWCNTs as nanofillers is due to their superior mechanical properties such as very high tensile strength varying between 11-63 GPa [29] and Young's modulus, which is approximately 1 TPa [29, 30]. However, polymer matrices have drawn more attention in industrial applications owing to their light weight, easy machinability and production costs [31-34].

A number of theoretical and experimental studies have been carried out to date regarding CNTs/polymer composites [35-48]. Majority of these studies indicate that CNTs are able to improve the mechanical properties of polymer matrix composite systems. Coleman et al. [25], Miyagawa et al. [49] and F.S.A. Khan et al. [48] provided comprehensive reviews on the mechanical reinforcement of polymers by the use CNTs. It is suggested that well-dispersion of nano materials is an important parameter controlling the efficiency of load transfer and hence determining some of the mechanical properties [50]. Therefore, CNT-polymer matrix interaction and crack behaviour of CNTs/polymer composites have been the subjects of several studies [51-56]. Ajayan et al. [57] examined morphology of fractured epoxy/SWNTs composites by SEM and observed SWCNTs stretching across a crack opening in the epoxy resin. Liu et al. [58] investigated the morphology and mechanical properties of MWCNTs-reinforced Polyamide 6(PA 6) composites. The authors reported a 26% reduction in tensile strength, which was explained by the brittleness of polymer matrix after the addition MWCNTs. Ferreira et al. [59] explored that addition of CNTs significantly improves the tensile strength and elastic modulus of PA 6/CNTs composites. Chopra et al. [60] studied PA 6/MWCNTs nanocomposites and reported that the presence of MWCNTs increases the tensile strength of Polyamide 6 by nearly 12%. Similarly, Kartel et al. [61] studied the tensile properties of PA 6/CNTs composites and reported that the tensile strength of the composite exhibits non-linear dependence behaviour by the addition of CNTs up to 0.5 wt.%. The mechanical tests performed by them showed that the PA 6 matrix composites incorporating 0.25 wt. % CNTs exhibit the highest tensile strength.

Although a great number of studies on CNTs/polymer composites are available in literature, there are not sufficient amount of studies focusing on the composites reinforced with the combination of short fibers and nanofillers [62, 63]. Therefore, the full potential of nanofillers and the properties of their combinations with other reinforcement materials, such as glass fibers, have not fully become known yet. This paper aims to introduce the tensile and flexural properties of MWCNTs-integrated Polyamide 66/short glass fiber nanocomposites so that the results obtained from this study can be used in designing new thermoplastic composites with MWCNTs.

2. Experimental

2.1. Composite Constituents

Neat PA 66, 15 wt. % short fiber glass reinforced PA 66 (PA 66/15SGF) and 30 wt. % short fiber reinforced PA 66 (PA 66/30SGF) granules (Mat Polymer, Istanbul/Turkey) were used as polymer materials in composite. MWCNTs, which were obtained from the manufacturer, (Ege Nanotek Kimya Sanayi, Izmir/Turkey) were used as nano reinforcements in composites (Table 1).

2.2. Fabrication Method

Figure 1 (a) to (h) shows the preparation process of the PA 66/30SGF/MWCNTs composite. The plastic injection machine was used to produce the test specimens. The granules were fed to the machine via a hopper and then pushed towards the nozzle by a rotating screw in the hot resistances. The temperature in the resistances which was nearly 285^{0}C and the rotary motion of the screw facilitated PA 66/SGF granules to melt and adequately mix with MWCNTs. Once this melted mixture reached the nozzle, it was injected into the moulds being hold between two clamps and took its final shape.

Table 1. Properties of MWCNTs

Parameter	Value
Purity (%)	>95 % (CNT) >97 % (C)
Outer diameter (nm)	10-20
Interior diameter (nm)	5-10
Length (μm)	10-30
Surface area (m2/g)	>200
Colour	Black
Ash	Mass < % 1.5
Electrical conductivity (S/cm)	>100
Density (tap) (g/cm3)	0.22
Density (true) (g/cm3)	2.1

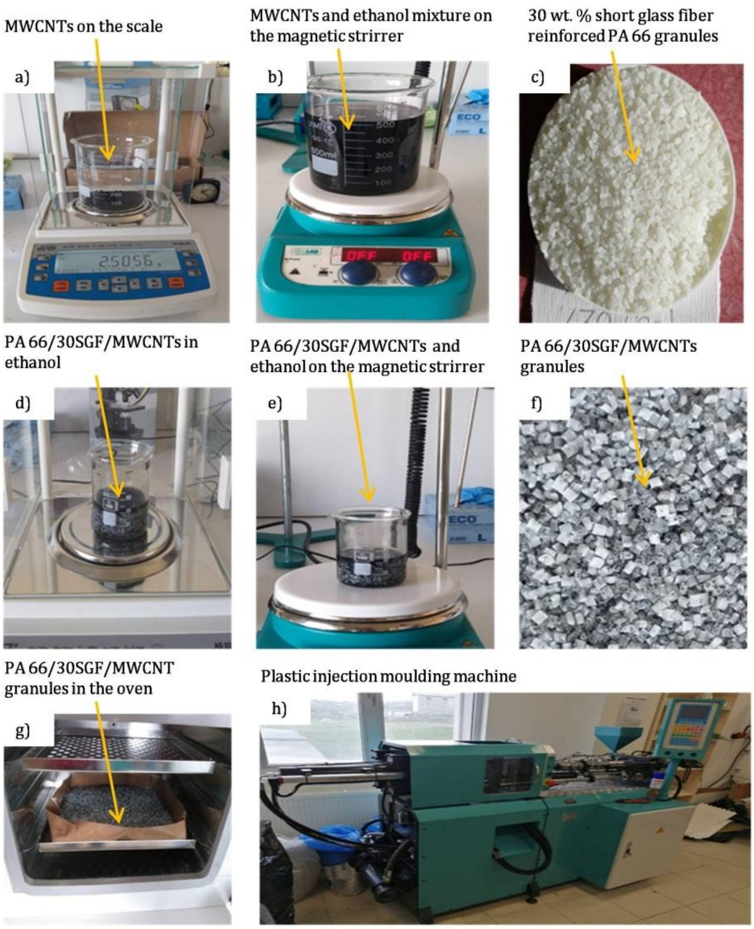


Fig. 1 Preparation process of PA 66/30SGF/MWCNT composite specimens

2.3. Characterization

Four types of specimens in accordance with ISO 527-2 type-1A and ISO 178 standards were produced by plastic injection moulding machine. A JSM-7001 F machine was used to characterize scanning electron microscope (SEM) (Japan) properties. Tensile and flexural properties of the specimens were examined using Instron 5982 100 KN (USA) test machine at room temperature with a crosshead speed of 5mm/min. Mechanical tests and specimens are shown in Figure 2 (a) to (d).

Fig. 2 Mechanical tests and specimens: (a) tensile test; (b) tensile test specimens in accordance with ISO 527-2 type-1A standard; (c) 3-point flexural test; (d) flexural test specimens in accordance with ISO 178 standard

3. Results and Discussion

3.1. Chemical Analysis

The aim of analyzing the molecular configuration of PA 66 by means of Fourier transform infrared (FTIR) spectroscopy is to correlate the structures to the performance properties of the final product. With sufficient knowledge about the chemical structure, polymerization reaction can be controlled and hence good performance properties can be achieved. Upon this purpose, FTIR spectra of neat PA66, PA 66/15SGF, PA 66/30SGF and PA 66/30SGF/MWCNT composites were measured and are shown in Figure 3. Due to very small weight fraction of MWCNTs in the composite and the affinity in chemical compositions of PA 66 and MWCNTs, the signature region did not exhibit a notable difference. In neat PA 66, the absorption band at 3267 cm−1 is attributed to the stretching vibrations of N-H group. The absorption bands at 2912 cm−1, 2843 cm−1 and 1192 cm−1 result from the symmetric and asymmetric C–H stretch vibrations and C–H twisting. The data obtained from FTIR analysis confirmed the chemical structure of PA 66 and PA 66/GF. Similar results were obtained by several researchers [64-66].

In this study, FTIR spectra of the composite specimens showed no significant change with regard to chemical composition of the constituent, which means that there are only physical interactions between the constituents. However, owing to the high-temperature (nearly 285oC) and the rotary motion of the screw in the hot resistances of plastic injection machine, chemical interactions between the constituents might occur as well [67].

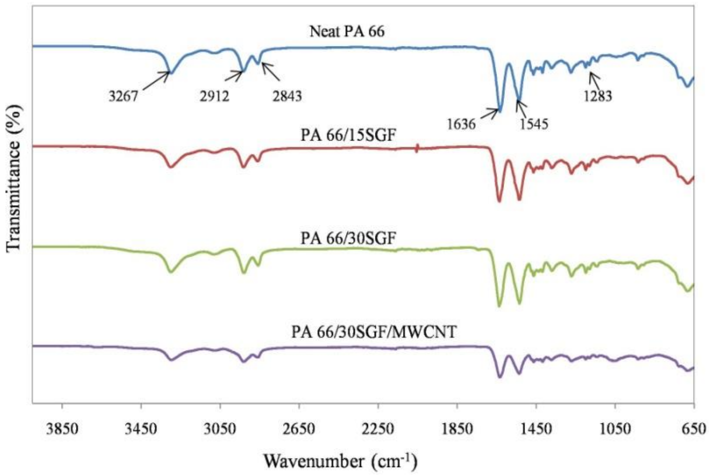


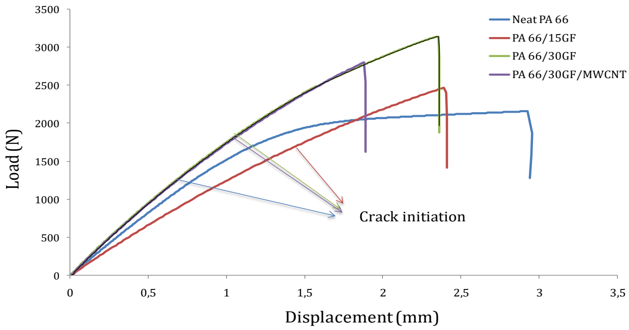
Fig. 3 FTIR spectra of the composite specimens

3.2 Tensile Test Results

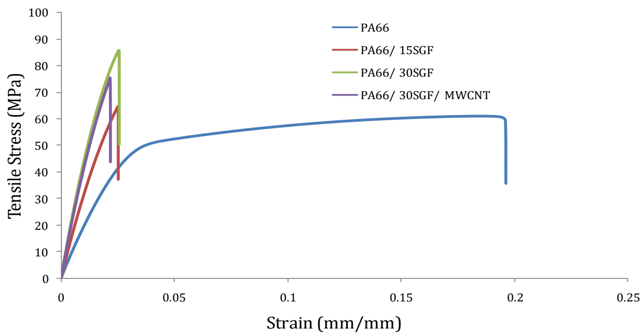
Figure 4 (a) to (c) represent the load-displacement curves, stres-strain curves during tensile tests and the tensile test results of the composites, respectively. PA 66/30SGF exhibits the highest tensile strength (87.05 MPa) whereas PA 66/30SGF/MWCNT exhibits the highest elastic modulus (4.69 GPa). It can be inferred from the graph that the addition of glass fibers improves the tensile strength and elastic modulus of PA 66. This improvement could be explained by the good mechanical performance of glass fibers [10, 13, 68].

In the present study, we note that the addition of 0.4 wt. % MWCNTs leads to a decline by 14% in tensile strength. This negative effect can be attributed to the poor dispersion and random orientation of the MWCNTs as well as their tendency to form agglomerates in the matrix. Moreover, it is obvious that the presence of MWCNTs increases the elastic modulus of PA 66/30SGF by 4.7 %. Therefore, it could be suggested that MWCNTs contributes to the mechanical performance of PA 66/GF by sharing the external stress as well as bridging along the cracks. Moreover, they strengthen the composite system by improving the surface of glass fibers. As a result of even load distribution along the matrix, mechanical properties of the specimens increases. The obtained data also show that MWCNTs are compatible with glass fibers, which is very promising for the development of hybrid-filler composite systems.

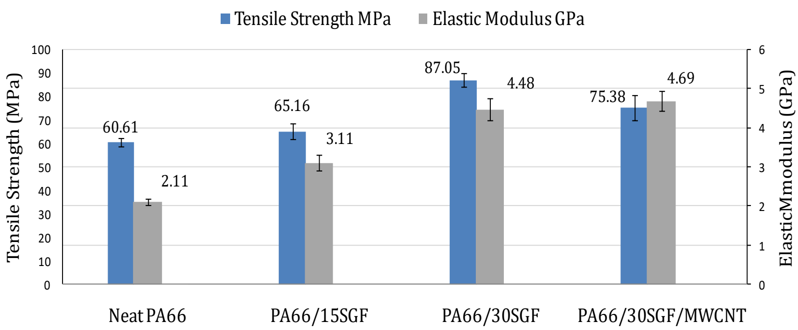
Similar to this study, Jin et al. [69] noted a slight increase in the elastic modulus of PA 66/GF composite with the incorporation of CNTs and MWCNTs, which was attributed to the interconnecting effect between the glass fibers and the PA 66 as a result of MWCNT coating. Qiu et al. [65] reported that the addition of 1.0 wt.% MWCNTs improves the elastic modulus of PA 66 by 3.14%. Furthermore, the authors observed that the SCF reinforced Polyamide 6/MWCNT composites incorporating low MWCNT content behave like polymer composites containing two different types of fillers whereas those incorporating high MWCNT content behave like short fiber reinforced nanocomposites.



(a)



(b)

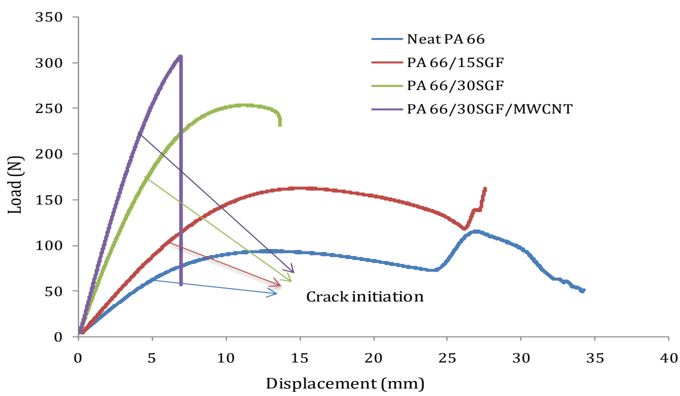


(c)

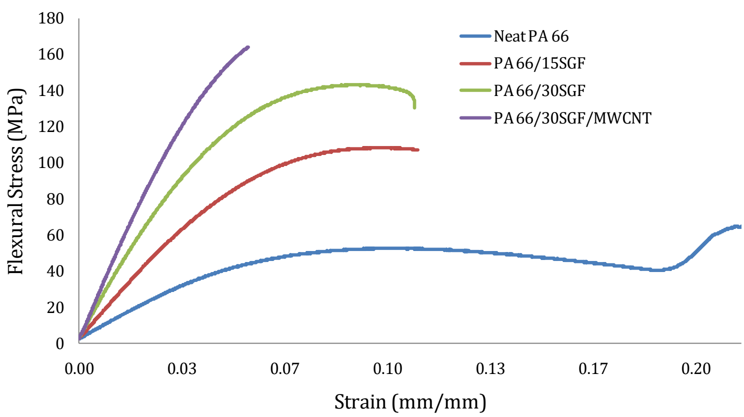
Fig.4 (a) Load-displacement curves of the specimens after the tensile tests; (b) Stress-strain curves of the specimens; (c) Tensile properties of the specimens

3.3 Flexural Test Results

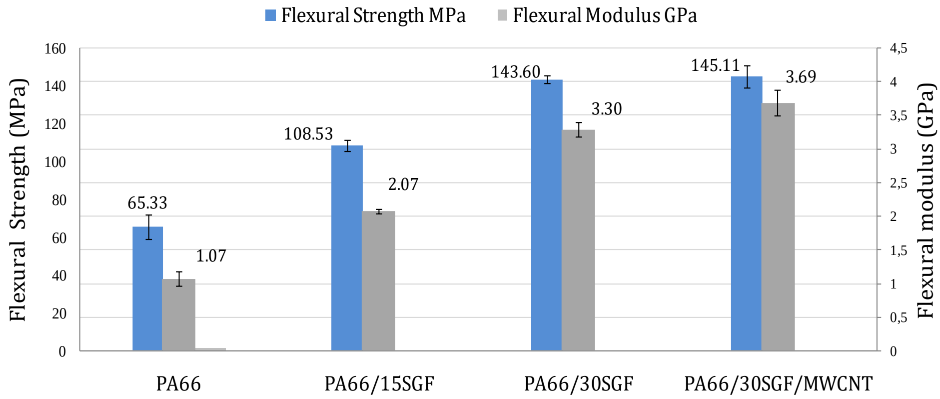
Fig 5 (a) to (c) demonstrate the load-displacement curves and stress-strain curves of the specimens during 3-point flexural tests and the flexural test results of the specimens, respectively PA 66/30SGF/MWCNTs composite exhibits the highest flexural strength (145.11 MPa) and flexural modulus (3.69 GPa) while neat PA 66 exhibits the lowest strength (65.33 MPa) and elastic modulus (1.07 GPa). Flexural strength and flexural modulus of the specimens significantly increase with increasing SGF content, which can be explained by the good mechanical properties of glass fibers as well as their well dispersion and homogeneous distribution in the matrix. Besides, an increase in flexural strength (by 1%) and flexural modulus (by 12%) after MWCNTs integration was observed, which can be attributed to the good surface interaction between the nanotubes and the PA 66 matrix as well as the surface improvement of glass fibers as a result of the MWCNTs coating. These results are compatible with a number of studies in literature. Autay et al. [9] studied the flexural properties of SGF reinforced PA 66 and reported that reinforcement resulted in an enhancement in the maximum flexural stress by nearly 36.3% for PA 66/10GF and 47.2% for PA 66/30GF in comparison to neat PA 66. Koilraj et al. [70] investigated the flexural properties of injection moulded PA 66/MWCNT and reported that the incorporation of 0.5 wt.% CNT content increases the flexural modulus by 5.8%.



(a)



(b)



(c)

Fig. 5 (a) Load-displacement curves of the specimens after three-point flexural tests; (b) Stress-strain curves of the specimens; (c) Flexural properties of the specimens

Figure 6 (a) and (b) represents the optical micrographs of the tensile fractured specimens after 3-point flexural tests. Failure modes of the composite specimens are dominantly matrix cracks along the direction of loading. Compared to the composite specimens with MWCNTs, longer cracks are observed in fractured PA 66/SGF.

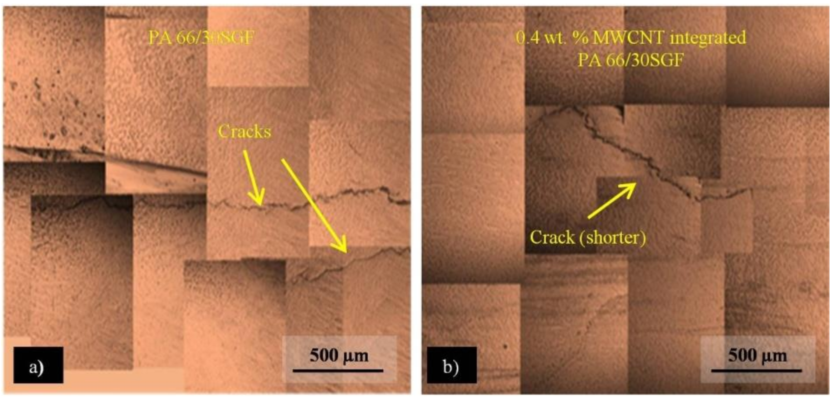


Fig. 6 Optical micrographs of fractured (a) PA 66/30SGF and (b) 0.4 wt.% MWCNT integrated PA 66/30SGF specimens monitored after 3-point flexural tests

3.4. Fracture Aspects of the Composite Specimens

SEM images of fracture surface morphologies of PA 66/30SGF/MWCNT composite are shown in Figure 7 (a) to (c). Figure 7 (a) indicates the SEM image of an individual glass fiber coated with MWCNTs. Higher magnification SEM images of the individual MWCNT coated glass fiber are shown in Figure 7 (b) and (c).

Uniform distribution of the fillers and their facial interaction with the matrix are key parameters for an effective reinforcement mechanism. To obtain good mechanical properties, fillers should evenly share the external stress applied to the matrix material. Regarding the CNT-polymer composites, CNTs are expected to bridge across the cracks formed inside the matrix during the fracture. This behaviour of CNTs prevents the crack opening and propagation and hence improves the mechanical performance of the composite. Furthermore, if incorporated together with fibers, CNTs can function as effective interface modifiers improving the surface area of fibers and facilitate the adhesion between fiber and matrix.

The monitored SEM images in Figure 7 (a) to (c) demonstrate that some individual MWCNTs function as bridges between the surface of glass fiber and the PA 66 matrix. This bridging phenomenon contributes to toughness improvement by allowing the release of stress and absorbing the fracture energy. Similar observations were made in a number of studies. Qian et al. [71] observed nanotubes bridging across the cracks in polystyrene matrix by means of a TEM and noted that the elastic modulus of the composite increases by nearly 25% with the inclusion of 1 wt.% CNT. Punch et al. [72] examined the fractured surface morphology of PA 6/SCF/MWCNT composites by SEM and obtained clear images of nanotubes interconnecting lumps of the PA 6-matrix. Jin et al. [69] too obtained clear SEM images of CNTs and MWCNTs bridging across the cracks formed inside the PA 66/GF composites. The authors also revealed that MWCNTs coating glass fibers can significantly improve the interaction between the glass fiber and the matrix.

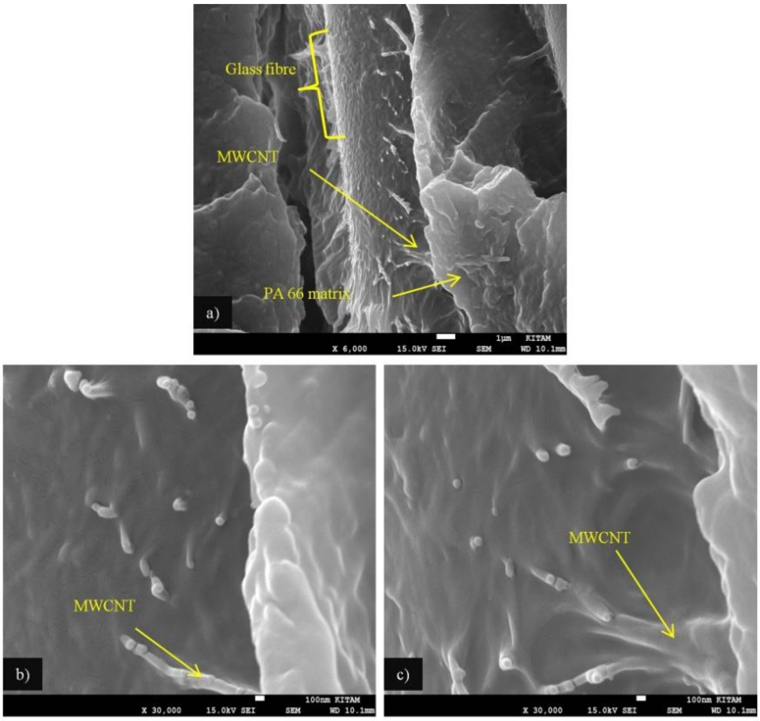


Fig. 7 SEM images of fractured MWCNTs-integrated PA 66/30SGF specimen

Figure 8 (a) and (b) show MWCNT pull-out, which probably occurred due to the fracture and poor interfacial interaction. While a crack is opening, nanotube is stretched absorbing the fracture energy transferred from the matrix. When the fracture ends, the crack somewhat closes and nanotube loosens getting a curved form as shown in Figure 8 (a) and (b).

Figure 9 (a) and (b) show the MWCNTs embedded within polymer matrix, which indicates good interfacial interaction. However, entangled MWCNT agglomerates were also observed as shown in Figure 9 (c), which restricts the dispersion and adversely affects the mechanical properties. MWCNTs are prone to agglomerate. Earlier, agglomeration tendency of CNTs was attributed to the Van der Waals forces alone; however, the long length and high polarizability of the CNTs could also be determining factors that enhance the energy required to disperse a nanotube within the matrix [73].

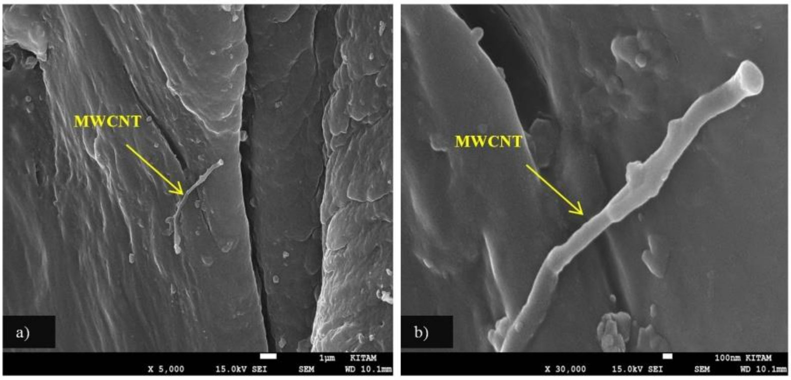


Fig. 8 SEM images of an individual MWCNT pull-out in a fractured PA 66/30SGF matrix

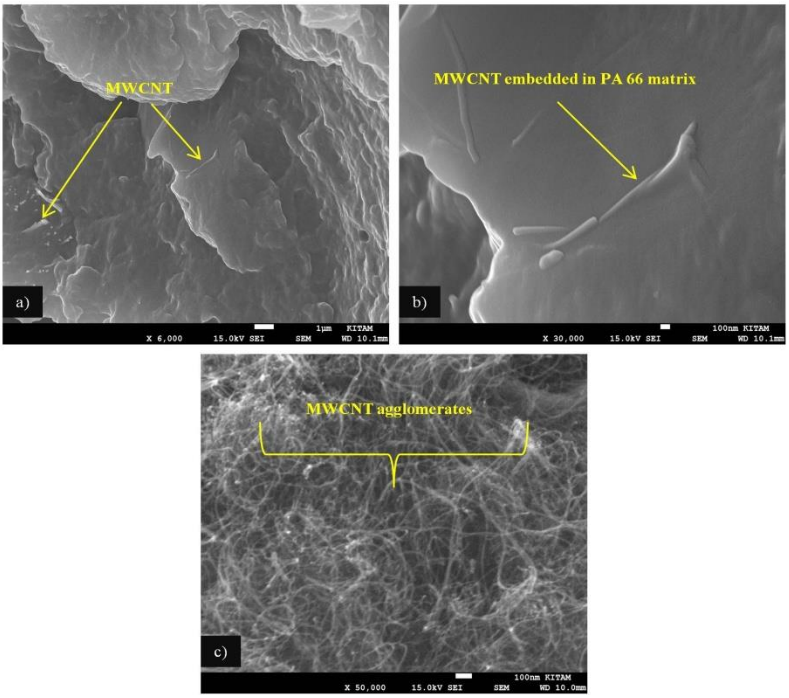


Fig. 9 SEM images of (a) MWCNTs embedded in PA 66/30SGF; (b) (higher-magnification) MWCNT embedded in PA 66/30SGF; (c) agglomerated MWCNTs

4. Conclusions

In this study mechanical properties of neat PA 66, PA 66/15SGF, PA 66/30SGF and 0.4 wt.% MWCNT integrated PA 66/30SGF were investigated. Furthermore, the effects of MWCNTs contents on the micro-structure and morphology of the composites were investigated by using a scanning electron microscope (SEM), fourier transform infrared spectroscopy analysis (FTIR) and optical microscopy (OM). The conclusions based on the findings are summarized as follow:

- FTIR spectra revealed no chemical interaction between PA 66, SGF and MWCNTs, which means that there are only physical interactions between the constituents.
- The mechanical tests shows that PA 66/15GF and PA 66/30GF composites exhibit improved tensile and flexural properties compared with neat PA 66, which is due to the good mechanical properties of the glass fibers and the sufficient distribution of the external stress throughout the matrix.
- Regarding PA 66/30SGF/MWCNT composites, the presence of MWCNTs results in improvement in elastic modulus by 4.7%, flexural strength by 1% and flexural modulus by 12%.
- The improvement in the mechanical properties with the addition of MWCNTs is explained by i) high mechanical properties of MWCNTs, ii) the bridging phenomenon of MWCNTs, which prevents crack opening and propagation during the fracture of the composite
- Despite the improvement in elastic modulus and flexural properties, a decrease in the tensile strength was observed. This failure is due to the presence of MWCNT agglomerates acting as defects or stress concentration sites in PA 66/30SGF composite system.
- From the SEM images of MWCNT coated glass fibers, we can deduce that MWCNTs modify the surface area of fibers and some individual MWCNTs function as bridges between the surface of glass fiber and the PA 66 matrix.
- Considering the improvement in elastic modulus, flexural modulus and flexural strength, it can be concluded that even a small mass fraction of MWCNT is capable of enhancing the mechanical performance of glass fiber filled PA 66. This achievement proves that MWCNTs are quite promising for designing new thermoplastic composites.

Our future study will be investigating the tensile, bending and Charpy impact properties of hemp fiber reinforced thermoplastic composite materials.

Acknowledgement

The authors acknowledge that the fund of this study has been provided by Research fund of Ondokuz Mayıs University Project No: PYO.MUH.1901.18.008.

References

[1] Hv D. Processing Techniques of polymer matrix composites-A review. International Journal Of Engineering Research and General Science. 2016;Volume 4.

[2] Yern Chee C, Chuah CH, Ching KY, Luqman Chuah A, Rahman A. Applications of thermoplastic-based blends. 2017. p. 111-29. https://doi.org/10.1016/B978-0-08-100408-1.00005-4

[3] Gilbert M. Chapter 1 - Plastics Materials: Introduction and Historical Development. In: Gilbert M, editor. Brydson's Plastics Materials (Eighth Edition): Butterworth-Heinemann; 2017. p. 1-18.

[4] Awaja F, Zhang S, Tripathi M, Nikiforov A, Pugno N. Cracks, microcracks and fracture in polymer structures: Formation, detection, autonomic repair. Progress in Materials Science. 2016;83:536-73. https://doi.org/10.1016/j.pmatsci.2016.07.007

[5] Rajak DK, Pagar DD, Kumar R, Pruncu CI. Recent progress of reinforcement materials: a comprehensive overview of composite materials. Journal of Materials Research and Technology. 2019;8:6354-74. https://doi.org/10.1016/j.jmrt.2019.09.068

[6] Xanthos M. Polymers and Polymer Composites. Functional Fillers for Plastics2005. p. 1-16. https://doi.org/10.1002/3527605096.ch1
[7] Chow WS, Mohd Ishak ZA. Polyamide blend-based nanocomposites: A review. Express Polymer Letters. 2015;9:211-32. https://doi.org/10.3144/expresspolymlett.2015.22
[8] Vagholkar P. Nylon (Chemistry, Properties and Uses). International Journal of Scientific Research. 2016;5:349-51.
[9] Autay R, Missaoui S, Mars J, Dammak F. Mechanical and tribological study of short glass fiber-reinforced PA 66. Polymers and Polymer Composites. 2019;27:587-96. https://doi.org/10.1177/0967391119853956
[10] Çuvalci H, Erbay K, İpek H. Investigation of the Effect of Glass Fiber Content on the Mechanical Properties of Cast Polyamide. Arabian Journal for Science and Engineering. 2014;39:9049-56. https://doi.org/10.1007/s13369-014-1409-8
[11] Ho Ming H, Hwang Jiun R, Wang Pin N, Kuo Shun C. Study on Tensile Properties of Nylon 66 Reinforced Composites. Proceedings of the 2016 International Conference on Education, Management, Computer and Society: Atlantis Press; 2016. p. 1660-3.
[12] Javangula S, Ghorashi B, Draucker CC. Mixing of glass fibers with nylon 6,6. Journal of Materials Science. 1999;34:5143-51. https://doi.org/10.1023/A:1004777520458
[13] Kim J-W, Kim H-S, Lee D-G. Tensile Strength of Glass Fiber-Reinforced Plastic by Fiber Orientation and Fiber Content Variations. International Journal of Modern Physics: Conference Series. 2012;06:640-5. https://doi.org/10.1142/S201019451200390X
[14] Lingesh BV, Rudresh BM, Ravikumar BN. Effect of Short Glass Fibers on Mechanical Properties of Polyamide66 and Polypropylene (PA66/PP) Thermoplastic Blend Composites. Procedia Materials Science. 2014;5:1231-40. https://doi.org/10.1016/j.mspro.2014.07.434
[15] Nuruzzaman DM, Iqbal AKMA, Oumer AN, Ismail NM, Basri S. Experimental investigation on the mechanical properties of glass fiber reinforced nylon. IOP Conference Series: Materials Science and Engineering. 2016;114. https://doi.org/10.1088/1757-899X/114/1/012118
[16] Srivastava VK, Lal S. Mechanical properties of E-glass fibre reinforced nylon 6/6 resin composites. Journal of Materials Science. 1991;26:6693-8. https://doi.org/10.1007/BF02402662
[17] Ünal H, Ermis K. Determination of mechanical performance of glass fiber reinforced and elastomer filled polyamide 6 composites. International Advanced Researches and Engineering Journal. 2021;5:405-11. https://doi.org/10.35860/iarej.934740
[18] Bernasconi A, Cosmi F. Analysis of the dependence of the tensile behaviour of a short fibre reinforced polyamide upon fibre volume fraction, length and orientation. Procedia Engineering. 2011;10:2129-34. https://doi.org/10.1016/j.proeng.2011.04.352
[19] Sato N, Kurauchi T, Sato S, Kamigaito O. Reinforcing Mechanism by Small Diameter Fiber in Short Fiber Composite. Journal of Composite Materials. 1988;22:850-73. https://doi.org/10.1177/002199838802200905
[20] Thomason JL. Structure-property relationships in glass reinforced polyamide, part 2: The effects of average fiber diameter and diameter distribution. Polymer Composites. 2007;28:331-43. https://doi.org/10.1002/pc.20260
[21] Thomason JL. Structure-property relationships in glass-reinforced polyamide, part 1: The effects of fiber content. Polymer Composites. 2006;27:552-62. https://doi.org/10.1002/pc.20226
[22] Güllü A, Özdemir A, Özdemir E. Experimental investigation of the effect of glass fibres on the mechanical properties of polypropylene (PP) and polyamide 6 (PA6) plastics. Materials & Design. 2006;27:316-23. https://doi.org/10.1016/j.matdes.2004.10.013
[23] Zainudin ES, Sapuan S, Imihezri SSS. A Review of the Effect of Moulding Parameters on the Performance of Polymeric Composite Injection Moulding. Turkish Journal of Engineering and Environmental Sciences. 2006;30:23-34.

[24] Baughman R, Zakhidov A, Heer W. Carbon Nanotubes-The Route Toward Applications. Science (New York, NY). 2002;297:787-92. https://doi.org/10.1126/science.1060928
[25] Coleman JN, Khan U, Gun'ko YK. Mechanical Reinforcement of Polymers Using Carbon Nanotubes. Advanced Materials. 2006;18:689-706. https://doi.org/10.1002/adma.200501851
[26] Zhang C, Wu L, de Perrot M, Zhao X. Carbon Nanotubes: A Summary of Beneficial and Dangerous Aspects of an Increasingly Popular Group of Nanomaterials. Frontiers in Oncology. 2021;11. https://doi.org/10.3389/fonc.2021.693814
[27] Iijima S, Ichihashi T. Single-shell carbon nanotubes of 1-nm diameter. Nature. 1993;363:603-5. https://doi.org/10.1038/363603a0
[28] Iijima S. Helical microtubules of graphitic carbon. Nature. 1991;354:56-8. https://doi.org/10.1038/354056a0
[29] Yu M-F, Lourie O, Dyer M, Moloni K, Kelly T, Ruoff R. Strength and Breaking Mechanism of Multiwall Carbon Nanotubes Under Tensile Load. Science. 2000;287:637-40. https://doi.org/10.1126/science.287.5453.637
[30] Salvetat J-P, Briggs GAD, Bonard J-M, Bacsa RR, Kulik AJ, Stöckli T, et al. Elastic and Shear Moduli of Single-Walled Carbon Nanotube Ropes. Physical Review Letters. 1999;82:944-7. https://doi.org/10.1103/PhysRevLett.82.944
[31] Du JH. The present status and key problems of carbon nanotube based polymer composites. Express Polymer Letters - EXPRESS POLYM LETT. 2007;1:253-73. https://doi.org/10.3144/expresspolymlett.2007.39
[32] Sahoo N, Rana S, Cho J, Li L, Chan SH. Polymer Nanocomposites Based on Functionalized Carbon Nanotubes. Progress in Polymer Science. 2010;35:837-67. https://doi.org/10.1016/j.progpolymsci.2010.03.002
[33] Shankar S, Rhim J-W. Polymer Nanocomposites for Food Packaging Applications. 2016. p. 29-55. https://doi.org/10.1002/9781118542316.ch3
[34] Song K, Zhang Y, Meng J, Green EC, Tajaddod N, Li H, et al. Structural Polymer-Based Carbon Nanotube Composite Fibers: Understanding the Processing-Structure-Performance Relationship. Materials. 2013;6:2543-77. https://doi.org/10.3390/ma6062543
[35] Du JH, Bai J, Cheng HM. The present status and key problems of carbon nanotube based polymer composites. Express Polymer Letters. 2007;1:253-73. https://doi.org/10.3144/expresspolymlett.2007.39
[36] Arash B, Wang Q, Varadan VK. Mechanical properties of carbon nanotube/polymer composites. Sci Rep. 2014;4:6479. https://doi.org/10.1038/srep06479
[37] Chen T, Liu H, Wang X, Zhang H, Zhang X. Properties and Fabrication of PA66/Surface-Modified Multi-Walled Nanotubes Composite Fibers by Ball Milling and Melt-Spinning. Polymers (Basel). 2018;10. https://doi.org/10.3390/polym10050547
[38] Coleman JN, Khan U, Blau WJ, Gun'ko YK. Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites. Carbon. 2006;44:1624-52. https://doi.org/10.1016/j.carbon.2006.02.038
[39] Hassani J A, Ishak Z, Mohamed A. Preparation and characterization of polyamide 6 nanocomposites using MWCNTs based on bimetallic Co-Mo/MgO catalyst. Express Polymer Letters. 2013;8:177-86. https://doi.org/10.3144/expresspolymlett.2014.21
[40] Jin F-L, Park S-J. A review of the preparation and properties of carbon nanotubes-reinforced polymer compositess. Carbon letters. 2011;12:57-69. https://doi.org/10.5714/CL.2011.12.2.057
[41] Khan W, Sharma R, Saini P. Carbon Nanotube-Based Polymer Composites: Synthesis, Properties and Applications. Carbon Nanotubes - Current Progress of their Polymer Composites2016. https://doi.org/10.5772/62497
[42] Moniruzzaman M, Chattopadhyay J, Billups WE, Winey KI. Tuning the mechanical properties of SWNT/nylon 6,10 composites with flexible spacers at the interface. Nano Lett. 2007;7:1178-85. https://doi.org/10.1021/nl062868e

[43] Spitalsky Z, Tasis D, Papagelis K, Galiotis C. Carbon nanotube-polymer composites: Chemistry, processing, mechanical and electrical properties. Progress in Polymer Science. 2010;35:357-401. https://doi.org/10.1016/j.progpolymsci.2009.09.003
[44] Tarfaoui M, Lafdi K, El Moumen A. Mechanical properties of carbon nanotubes based polymer composites. Composites Part B: Engineering. 2016;103:113-21. https://doi.org/10.1016/j.compositesb.2016.08.016
[45] Zabegaeva ON, Sapozhnikov DA, Buzin MI, Krestinin AV, Kotelnikov VA, Baiminov BA, et al. Nylon-6 and single-walled carbon nanotubes polyamide composites. High Performance Polymers. 2016;29:411-21. https://doi.org/10.1177/0954008316645848
[46] Zhang J, Gao X, Zhang X, Liu H, Zhang H, Zhang X. Polyamide 66 and amino-functionalized multi-walled carbon nanotube composites and their melt-spun fibers. Journal of Materials Science. 2019;54:11056-68. https://doi.org/10.1007/s10853-019-03619-0
[47] Su X, Wang R, Li X, Araby S, Kuan H-C, Naeem M, et al. A comparative study of polymer nanocomposites containing multi-walled carbon nanotubes and graphene nanoplatelets. Nano Materials Science. 2021. https://doi.org/10.1016/j.nanoms.2021.08.003
[48] Khan FSA, Mubarak NM, Khalid M, Khan MM, Tan YH, Walvekar R, et al. Comprehensive review on carbon nanotubes embedded in different metal and polymer matrix: fabrications and applications. Critical Reviews in Solid State and Materials Sciences. 2021:1-28. https://doi.org/10.1080/10408436.2021.1935713
[49] Miyagawa H, Misra M, Mohanty AK. Mechanical properties of carbon nanotubes and their polymer nanocomposites. J Nanosci Nanotechnol. 2005;5:1593-615. https://doi.org/10.1166/jnn.2005.181
[50] Hiremath A, Murthy AA, Thipperudrappa S, K N B. Nanoparticles Filled Polymer Nanocomposites: A Technological Review. Cogent Engineering. 2021;8:1991229. https://doi.org/10.1080/23311916.2021.1991229
[51] Gorga RE, Lau KKS, Gleason KK, Cohen RE. The importance of interfacial design at the carbon nanotube/polymer composite interface. Journal of Applied Polymer Science. 2006;102:1413-8. https://doi.org/10.1002/app.24272
[52] Gupta AK, Harsha SP. Effect of crack and determination of fracture energy of carbon nanotube-reinforced polymer composites. Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems. 2014;229:110-6. https://doi.org/10.1177/1740349914531758
[53] Kuronuma Y, Shindo Y, Takeda T, Narita F. Fracture behaviour of cracked carbon nanotube-based polymer composites: Experiments and finite element simulations. Fatigue & Fracture of Engineering Materials & Structures. 2010;33:87-93. https://doi.org/10.1111/j.1460-2695.2009.01419.x
[54] Kuronuma Y, Shindo Y, Takeda T, Narita F. Crack growth characteristics of carbon nanotube-based polymer composites subjected to cyclic loading. Engineering Fracture Mechanics. 2011;78:3102-10. https://doi.org/10.1016/j.engfracmech.2011.09.006
[55] Shindo Y, Kuronuma Y, Takeda T, Narita F, Fu S-Y. Electrical resistance change and crack behavior in carbon nanotube/polymer composites under tensile loading. Composites Part B: Engineering. 2012;43:39-43. https://doi.org/10.1016/j.compositesb.2011.04.028
[56] Takeda T, Shindo Y, Naraoka F, Kuronuma Y, Narita F. Crack and Electrical Resistance Behaviors of Carbon Nanotube-Based Polymer Composites under Mixed-Mode I/II Loading. Materials Transactions. 2013;54:1105-9. https://doi.org/10.2320/matertrans.M2013080
[57] Ajayan PM, Schadler LS, Giannaris C, Rubio A. Single-Walled Carbon Nanotube-Polymer Composites: Strength and Weakness. Advanced Materials. 2000;12:750-3.

https://doi.org/10.1002/(SICI)1521-4095(200005)12:10<750::AID-ADMA750>3.0.CO;2-6
[58] Liu, Phang IY, Shen L, Chow SY, Zhang W-D. Morphology and Mechanical Properties of Multiwalled Carbon Nanotubes Reinforced Nylon-6 Composites. Macromolecules. 2004;37:7214-22. https://doi.org/10.1021/ma049132t
[59] Ferreira T, Paiva MC, Pontes AJ. Dispersion of carbon nanotubes in polyamide 6 for microinjection moulding. Journal of Polymer Research. 2013;20. https://doi.org/10.1007/s10965-013-0301-7
[60] Chopra S, Deshmukh KA, Deshmukh AD, Peshwe DR. Functionalization and Melt-compounding of MWCNTs in PA-6 for Tribological Applications. IOP Conference Series: Materials Science and Engineering. 2018;346. https://doi.org/10.1088/1757-899X/346/1/012005
[61] Kartel M, Sementsov Y, Mahno S, Trachevskiy V, Bo W. Polymer Composites Filled with Multiwall Carbon Nanotubes. Universal Journal of Materials Science. 2016;4:23-31. https://doi.org/10.13189/ujms.2016.040202
[62] Mahato KK, Rathore DK, Prusty RK, Dutta K, Ray BC. Tensile behavior of MWCNT enhanced glass fiber reinforced polymeric composites at various crosshead speeds. IOP Conference Series: Materials Science and Engineering. 2017;178. https://doi.org/10.1088/1757-899X/178/1/012006
[63] Nguyen-Tran HD, Hoang VT, Do VT, Chun DM, Yum YJ. Effect of Multiwalled Carbon Nanotubes on the Mechanical Properties of Carbon Fiber-Reinforced Polyamide-6/Polypropylene Composites for Lightweight Automotive Parts. Materials (Basel). 2018;11. https://doi.org/10.3390/ma11030429
[64] Lakkur Munirajappa M, Harijan Basavaraju R. Microstructural characterization of short glass fiber and PAN based carbon fiber reinforced nylon 6 polymer composites. Polymer Engineering & Science. 2018;58:1428-37. https://doi.org/10.1002/pen.24737
[65] Qiu L, Chen Y, Yang Y, Xu L, Liu X. A Study of Surface Modifications of Carbon Nanotubes on the Properties of Polyamide 66/Multiwalled Carbon Nanotube Composites. Journal of Nanomaterials. 2013;2013. https://doi.org/10.1155/2013/252417
[66] Navarro-Pardo F, Martínez-Hernández AL, Castaño VM, Rivera-Armenta JL, Medellín-Rodríguez FJ, Martínez-Barrera G, et al. Influence of 1D and 2D Carbon Fillers and Their Functionalisation on Crystallisation and Thermomechanical Properties of Injection Moulded Nylon 6,6 Nanocomposites. Journal of Nanomaterials. 2014;2014:1-13. https://doi.org/10.1155/2014/670261
[67] Demircan O, Al-darkazali A, İnanç İ, Eskizeybek V. Investigation of the effect of CNTs on the mechanical properties of LPET/glass fiber thermoplastic composites. Journal of Thermoplastic Composite Materials. 2020;33:1652-73. https://doi.org/10.1177/0892705719833105
[68] Hsiung HM, Ren HJ, Ning WP, Chi KS. Study on Tensile Properties of Nylon 66 Reinforced Composites. Atlantis Press; 2016. p. 1660-3. https://doi.org/10.2991/emcs-16.2016.415
[69] Jin J, Zhang L, Chen W, Li C-Z. Synthesis of glass fiber-multiwall carbon nanotube hybrid structures for high-performance conductive composites. Polymer Composites. 2013;34:1313-20. https://doi.org/10.1002/pc.22544
[70] Koilraj TT, Kalaichelvan K. Experimental Study on Mechanical Properties of PA66 Blended with MWNTs. Applied Mechanics and Materials. 2015;766-767:383-8. https://doi.org/10.4028/www.scientific.net/AMM.766-767.383
[71] Qian D, Dickey EC, Andrews R, Rantell T. Load transfer and deformation mechanisms in carbon nanotube-polystyrene composites. Applied Physics Letters. 2000;76:2868. https://doi.org/10.1063/1.126500

[72] Puch F, Hopmann C. Morphology and tensile properties of unreinforced and short carbon fibre reinforced Nylon 6/multiwalled carbon nanotube-composites. Polymer. 2014;55:3015-25. https://doi.org/10.1016/j.polymer.2014.04.052

[73] Banerjee J, Dutta K. Melt-mixed carbon nanotubes/polymer nanocomposites. Polymer Composites. 2019;40:4473-88. https://doi.org/10.1002/pc.25334