Voltage response of piezoelectric woven fabric, made of tourmaline containing polypropylene filaments

DOI: 10.35530/IT.068.04.1427

VATANSEVER BAYRAMOL DERMAN

REZUMAT – ABSTRACT

Răspunsul la tensiune al țesăturii piezoelectrice din turmalină cu conținut de filamente de polipropilenă

În această lucrare au fost adăugate trei raporturi diferite de greutate (1%, 3% și 5%) a turmalinei (TM) în polimerul de polipropilena (PP), polimer folosind un compounder twin screw. Amestecurile preliminare de PP cu polipropilenă pură și pulbere TM au fost utilizate pentru a produce filament de PP/TM printr-un procedeu de filare din topitură cu o unitate de polarizare aplicată în zona de etirare. Filamente piezoelectrice au fost utilizate pentru a produce țesături piezoelectrice realizate pe o mașină de țesut manuală. Foile de aluminiu au fost atașate pe ambele părți ale probelor de țesătură piezoelectrică în calitate de electrozi. Au fost obținute caracteristicile mecanice, termogramele DSC, spectrele de absorbanță FTIR și micrografiile SEM ale probelor de țesătură piezoelectrică. Pentru a investiga efectul raportului TM asupra răspunsului la tensiune al mostrelor de țesătură piezoelectrică, un sistem de rezistență la impact a fost folosit pentru a permite greutăților să cadă liber pe probe. Tensiunile de ieșire ale probelor au fost înregistrate cu ajutorul unui osciloscop digital. Conform rezultatelor colectate de osciloscopul digital, adiția de TM a contribuit la tensiunea de ieșire a probelor. Tensiunea de vârf înregistrată, generată de proba de țesătură din PP pură (PPP-0TM), a fost de 1,20 V, iar proba de țesătură piezoelectrică cu un conținut de 5% TM (PPP-5TM) a prezentat o tensiune de vârf de 3,92 V.

Cuvinte-cheie: răspuns la tensiune, turmalină, polipropilenă, piezoelectric, țesătură

Voltage response of piezoelectric woven fabric, made of tourmaline containing polypropylene filaments

In this work, three different weight ratios (1%, 3% and 5%) of tourmaline (TM) were added to polypropylene (PP) polymer using a twin screw compounder. Pristine PP and TM powder added PP master batches were used to produce PP/TM filaments via a melt-spinning process with a polarization unit affixed in the drawing zone. Piezoelectric filaments were then used to produce piezoelectric woven fabrics on a handloom. Aluminium sheets were attached on both sides of piezoelectric woven fabric samples as electrodes. Mechanical characteristics, DSC thermograms, FTIR absorbance spectra and SEM micrographs of piezoelectric woven fabric samples were obtained. To investigate the effect of TM ratio on the voltage response of piezoelectric woven fabric samples, an impact rig was used which allowed the weights to drop freely onto the samples. Voltage outputs of the samples were recorded via a digital oscilloscope. According to the results collected from the digital oscilloscope, addition of TM contributed to the voltage output of the samples. Recorded peak voltage generated by the woven fabric sample made of pristine PP (PPP-0TM) was 1.20 V while the piezoelectric woven fabric sample containing 5% TM (PPP-5TM) showed a peak voltage of 3.92 V.

Keywords: voltage response, tourmaline, polypropylene, piezoelectric, fabric

INTRODUCTION

Smart materials have received a significant interest in recent years. The members of smart materials family included but not limited to shape memory polymers and alloys, photovoltaic structures, electro/magneto-rheological fluids, piezoelectric materials etc. Each of these materials shows an extraordinary response as a result of applied stimuli. Piezoelectric materials, for instance, generate an electrical potential when mechanically deformed and conversely undergo a shape change when an electrical potential is applied. From the materials point of view, polymeric materials seem to be more convenient and promising for the applications where the flexibility and lightweight are crucial. In the literature a number of comparative works have been conducted on ceramic and polymer based piezoelectric materials [1–2].

The first piezoelectric polymer reported was poly(vinylidene) fluoride (PVDF) [3]. Cellular polypropylene is one of the other polymers which were reported to exhibit piezoelectric behaviour [4–8]. Polypropylene (PP) provides a number of advantages upon other polymers which makes it preferable for technical applications. However, piezoelectric strain coefficient of polymer-based materials is much lower than that of ceramic-based piezoelectric materials. Therefore, there is a number of works to test the power generation characteristics, the durability and stability and the enhancement on piezoelectric behaviour of polymeric materials [9–15]. There is limited number of works on the effect of tourmaline when used as an additive to a polymer matrix. Tourmaline (TM) is a complex borosilicate and it is naturally piezoelectric with spontaneous and permanent poles [16–17]. These poles create dipoles which induce an electric field on the surface of the tourmaline when subjected to a mechanical strain [18]. Furthermore, TM is very sensitive to uniformly applied pressure in all directions that makes it suitable for pressure sensor applications [19].

In this work, TM powder has been blended with PP polymer and the effect of the addition of TM powder in PP polymer was investigated. First of all, PP monofilaments were successfully produced and polarized simultaneously. Filaments underwent thermal, mechanical and electrical conditions in the draw area on a laboratory scale melt extruder. To investigate the effects of tourmaline on the voltage output of PP, the produced filaments were woven in a handloom. The woven piezoelectric samples with an active area of 50 mm × 75 mm were produced and then subjected to an impact. The voltage response of the samples was recorded via a digital oscilloscope and the result was comparatively evaluated.

MATERIALS AND METHODs

Materials

Isotactic polypropylene pellets with a melting temperature of ~165°C and a melt flow index of 25 g/10 min at 230°C under an applied load of 2.16 kg were obtained from Lyondellbasell Polymers. Tourmaline powder was obtained from Shanghai HuZhengNano Technology Company (China).

Masterbatch and filament production method

Pristine isotactic PP polymer and TM powder were compounded by using a ThermoFisher Scientific Prism EuroLab16 twin-screw compounder to produce masterbatches having 1%, 3% and 5% TM in PP. The temperature parameters were 170°C, 190°C, 200°C, 200°C, 210°C and 210°C from the feeding barrel to the die. Molten PP polymer and TM powder were mixed in the heating zone via the twin-screw with a rotation speed of 250 rpm. A thick PP/TM monofilament was produced, cooled in a water bath, dried and cut into small pallets to produce masterbatches. Then the produced PP/TM masterbatches were dried at 80°C in the oven for at least 2 hours.

A laboratory scale melt extruder having a single screw (∅ 22 mm) was used for PP/TM filament production. The extruder screw was operated at a speed of 2 rpm. The temperature of the five heating zones was maintained at 100°C, 170°C, 180°C, 190°C and 200°C, respectively. In an ordinary PP filament production process, the temperature of Barrel 1 is kept just above the melting point of the polymer. The detailed information on melt extrusion can be found in the literature [14, 21, 22]. A portable polarization unit was inserted between temperature controlled slow rollers and the fast roller where the filament is mechanically stretched. The speed of the slow rollers was 15 rpm while the fast rollers rotated with a speed of 37.5 rpm. A Spellman SL300 series high voltage power supply was used to apply 15 kV high voltage to the filaments. The produced filaments were named as PPP-0TM, PPP-1TM, PPP-3TM and PPP-5TM. The first letter "P" stands for polarized monofilaments. "PP" presents the main polymeric material which is isotactic polypropylene and the numbers 0-1-3-5 together with "TM" show the weight ratio of tourmaline in the produced monofilaments.

Weaving of the piezoelectric PP/TM filaments

A handloom was used for the purpose of producing woven piezoelectric textile structures. Piezoelectric monofilaments were used as weft and warp threads to produce plain woven textile structures. The produced woven textile structures were sandwiched between two aluminium sheets which were used as electrodes as seen in figure 1. The whole sample was wrapped by a non-conductive transparent tape to keep the electrodes in place. The size of the woven textile structures was 70 mm × 100 mm while the size of the electrodes was 50 mm × 75 mm.

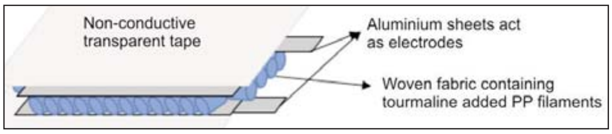

Fig. 1. Example of the composite structures having piezoelectric woven textile layer sandwiched between two aluminium sheets which are also sandwiched between non-conductive transparent tape

Characterisation

It should be noted that filament count, mechanical properties, thermal and infrared investigations and also microstructural evaluations of the PP/TM blend structures were carried out in filament form. The voltage response of PP/TM blends was studied after the filaments were woven to form a textile structure. For the measurement of the count of the filaments precision scales were used. 10 measurements were carried out for each set of filament sample and average value was recorded. The mechanical properties of the filaments were measured by using a Textechno Statimat M Test Equipment. Testing parameters were set to 100 mm for gauge length, 10 N for the load cell and 300 mm/min. for test speed. 10 measurements were carried out for each type of filament sample. Individual results and total evaluation was obtained from the equipment. Morphology of the samples were studied by using a Hitachi S-3400N Scanning Electron Microscope (SEM). Microstructural images of PP/TM filaments were captured at an accelerating voltage of 5 kV and various magnifications. Thermal characteristics of the PP/TM monofilaments were studied by using a TA Instruments DSC Q2000 equipment. The samples were scanned from −50°C to 200°C under nitrogen atmosphere with a heating rate of 10°C/min. Absorbance spectra of the filaments as a function of wave numbers were investigated by using a Thermo Scientific's IS10 Nicolet FT-IR Spectrometer with smart iTR accessory.

Voltage response of the produced PP/TM filaments were studied under an InstronDynatup® Mini Tower®, using ASTM D 3763 standard impact test method. The prepared samples were located in the test equipment one by one. An impact caused by a weight of 2.25 lbs was free-fallen from a height of 5 cm onto the samples. A digital oscilloscope was used for investigation of the voltage response of the woven piezoelectric structures and the results were directly recorded to an external data storage device.

RESULTS AND DISCUSSIONS

Mechanical properties of the produced filaments were investigated. 10 measurements were carried out for each type of filament for the determination of their count, tenacity, elongation and work to rupture values. The count of each filament was the main input for the TextechnoStatimat M Test Equipment. The values provided from the tensile test equipment are given in table 1.

Table 1

COUNTS AND TEXTECHNOSTATIMAT M TEST RESULTS FOR PRODUCED PP/TM FILAMENTS

	PPP-0TM	PPP-1TM	PPP-3TM	PPP-5TM
Count (tex)	16.91	17.28	17.61	17.41
Tenacity (cN/tex)	14.55	15.63	13.67	13.43
Elongation (%)	150.04	105.28	75.49	111.86
Work to rupture (cN*cm)	2571.14	2124.96	1484.07	2039.55

Since the production parameters were the same for each sample, the count of the filaments were found to be in a range of 16.91–17.61 tex. This variation may have caused by the melt extruder which was a laboratory scale unit. On the other hand, if the number of count measurements is increased, the count values would be expected to converge. The tenacity of the filaments containing 1 wt% TM got higher values as compared to the pristine PP filaments and the filaments containing 3 wt% and 5 wt% TM. Due to good dispersion of TM nanoparticles in the polymer matrix, tenacity of the filament improved from 14.55 cN/tex to 15.63 cN/tex when 1 wt% TM was added in polymer matrix. However, the tensile properties of filaments containing higher than 1 wt% TM in the structure were slightly reduced, which could be due the agglomeration of TM particles in filament structure. The energy or work required to break the filaments decreased when TM particles were added to the polymer matrix. However, there was no clear trend in the change of the work to rupture values.

The surface and the cross-sectional characteristics of the produced filaments were investigated by using SEM images illustrated in figure 2. Images coded with “L” shows surface morphology of the filaments while images coded with “C” shows cross-sectional view of the filaments. The numbers from 0 to 5 present the weight ratio of TM in the polymer matrix. As seen in figure 2, L0 and C0, pristine PP filaments have a smoother surface and cross-section as compared to TM added PP filaments due to having no TM in the structure. An increasing unevenness is seen with an increase in TM ratio in the filaments. Holes and pits can be seen in the cross-sectional images of C1, C3 and C5 and it is seen that these holes and pits tend to grow larger with the increase in the TM ratio, which may be due to the increase in the agglomeration of the TM nano particles.

Figure 3 shows DSC thermograms of the produced filaments while table 2 gives the melting temperature [Tm (°C)], melting enthalpy [ΔHm (J/g)] and degree of crystallinity [Xc (%)] of the filaments. Tm and ΔHm were directly taken from the DSC thermograms while Xc was calculated via the standard heat of crystallinity for 100% crystalline PP taken as 209 J/g [14, 22–25]. The results given in table 2 show that addition of TM powder resulted an increase in the crystallinity of the PP/TM filaments. The calculated crystallinity of PPP-1TM filament is 41.8% while the crystallinity values of the filaments containing higher ratios of TM, namely PPP-3TM and PPP-5TM, were found higher than that of pristine but lower than that of PPP-1TM. This can be interpreted as that the addition of TM powder up to 1wt% contributed crystallisation of PP however beyond this point TM nano powder may act as impurity and result in the observed decrease in crystallinity of the filaments. An XRD analysis can be carried out for further investigation on the crystalline structure of the pristine and PP/TM filaments.

Chemical compositions of the produced pristine PP and PP/TM filaments were evaluated by using

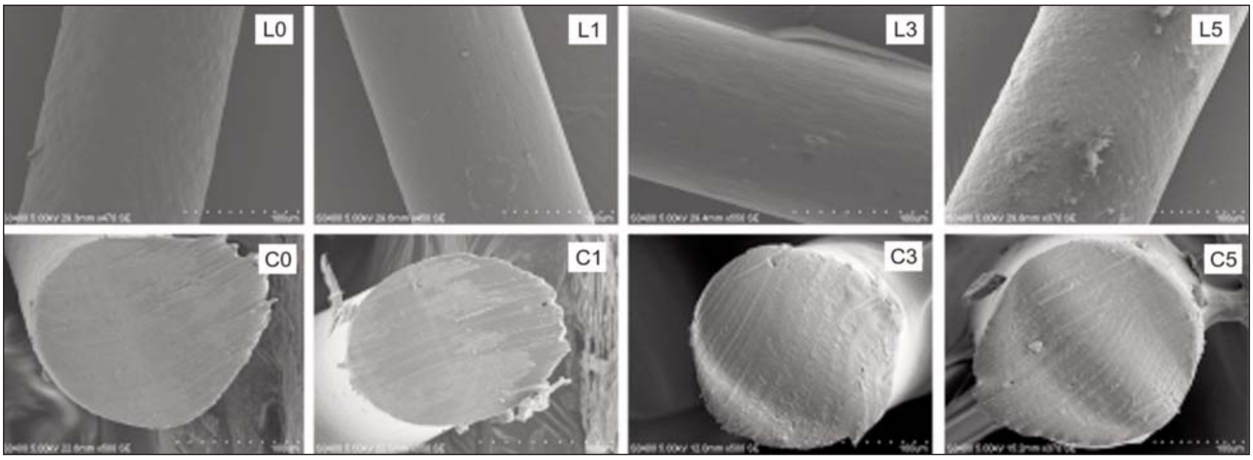

Fig. 2. Longitudinal (L) and cross-sectional (C) SEM images of pristine PP and PP/TM filaments; numbers following the letters present the amount of TM in filament structure

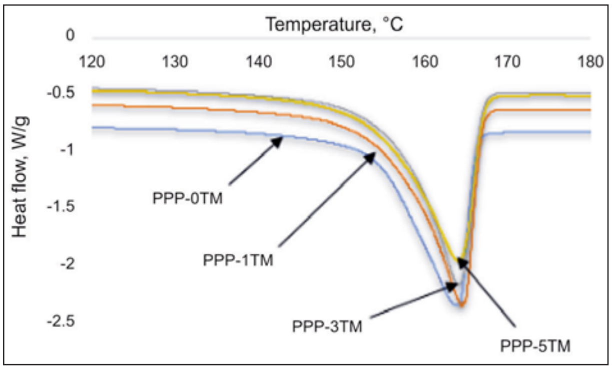

Fig. 3. Melting characteristics of produced PP/TM filaments taken from DSC thermograms

Table 2

THERMAL CHARACTERISTICS OF THE FILAMENTS; MELTING TEMPERATURE AND MELTING ENTHALPY VALUES WERE OBTAINED FROM DSC, DEGREE OF CRYSTALLINITY			
Sample ID	**Melting temperature Tm** (°C)	**Melting enthalpy ΔHm** (J/g)	**Degree of crystallinity Xc** (%)
PPP-0TM	163.69	77.39	37.0
PPP-1TM	164.53	87.30	41.8
PPP-3TM	164.07	84.11	40.2
PPP-5TM	164.16	83.05	39.7

Thermo Scientific's IS10 Nicolet FT-IR Spectrometer. There were no new peaks or peak shifts observed in the spectra obtained for the various filaments. However, the intensities of some peaks increased when TM was added to the polymer structure. This can be explained in two ways; a change in the polarity of the molecule or increased number of functional groups for that specific wave number.

Typical voltage generation characteristics of the prepared woven fabric samples are given in figure 4. Five measurements were carried out for each sample. Sample without TM addition showed a voltage response of 1.20 V while samples produced from TM added PP filaments showed higher voltage outputs. Sample named as PPP-1TM produced 1.46 V while voltage outputs of PPP-3TM and PPP-5TM were 2.84 V and 3.92 V, respectively. In figures 4, it is clearly seen that an increase in voltage generation was observed with an increase in the weight ratio of TM in the filament structure. This can be attributed to the addition of TM, which is a naturally occurring piezoelectric material [19, 25–26], and contributed to enhanced voltage generation of the filament structure. Since the samples were located on a non-conductive paper type covered metal plate, free falling impact weight bounced and impacted on to the sample few more times before it came to a stop.

Therefore, piezoelectric samples showed a voltage output smaller than the one caused by the first impact. The reason was that the gravity and the mass

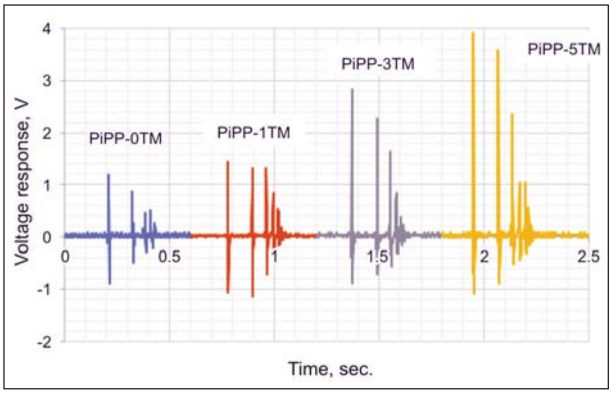

Fig. 4. Comparable graph for voltage responses of the produced piezoelectric woven fabric samples under applied impact

of the rig were constant while the falling height of the rig was lower than 5 cm which caused a decrease in the voltage generated by the second fall.

CONCLUSIONS

Pristine PP and TM added PP filaments were successfully melt-spun and poled via a polarization unit fixed in the drawing area of the extruder. The produced filaments were first examined for their mechanical, thermal, infrared characteristics and morphology. An increase in tenacity of the filament was observed when 1 %wt TM was added to the polymer. However, the tenacity was decreased further addition of TM. This is because of the tendency of TM particles to agglomerate at higher concentration and act as impurity in the polymer, which results in the observed decrease in the tensile property. Similar results were also observed for degree of crystallinity. The produced filaments were then used to produce piezoelectric woven fabrics by using a handloom. Aluminium sheets were used as electrodes and attached on both sides of piezoelectric woven fabric samples.

The peak voltage generation of the woven samples were investigated. It was observed that PPP-0TM sample showed a peak voltage of 1.20 V while TM containing PP filaments showed higher voltage generation. The recorded peak voltage values were 1.46 V, 2.84 V and 3.92 V for PPP-1TM, PPP-3TM and PPP-5TM, respectively. Therefore, it can be concluded that the addition of natural piezoelectric TM particles in PP polymer contributed the enhanced voltage output of the material. The results of the study show that the TM containing polymer filaments are very promising for green technical textile applications.

ACKNOWLEDGEMENTS

This work was indirectly supported by The Newton-KatipCelebi Fund. The author would like to thank the staff of University of Bolton for their hospitality and assistance.

BIBLIOGRAPHY

[1] Patel, I., Siores, E., Shah, T. *Utilisation of smart polymers and ceramic based piezoelectric materials for scavenging wasted energy*, In: Sensors and Actuators A: Physical, 2010, vol. 159, pp. 213–218.
[2] Vatansever, D., Hadimani, R.L., Shah, T., Siores, E. *An investigation of energy harvesting from renewable sources with PVDF and PZT*, In: Smart Materials and Structures, 2011, vol. 20, 055019.
[3] Kawai, H. *The piezoelectricity of poly(vinylidene fluoride)*, In: Japanese Journal of Applied Physics, 1969, vol. 8, pp. 975–976.
[4] Zhang, X., Sessler, G.M., Hillenbrand, J. *Improvement of piezoelectric coefficient of cellular polypropylene films by repeated expansions*, In: Journal of Electrostatics, 2007, vol. 65, pp. 94–100.
[5] Qaiss, A., Saidi, H., Fassi-Fehri, O., Bousmina, M. *Cellular polypropylene-based piezoelectric films*, In: Polymer Engineering & Science, 2012, vol. 52, pp. 2637–2644.
[6] Gilbert-Tremblay, H., Mighri, F., Rodrigue, D. *Morphology development of polypropylene cellular films for piezoelectric applications*, In: Journal of Cellular Plastics, 2012, vol. 48, pp. 341–354.
[7] Mellinger, A., Wegener, M., Wirges, W., Mallepally, R.R., Gerhard-Multhaupt, R. *Thermal and temporal stability of ferroelectret films made from cellular polypropylene/air composites*, In: Ferroelectrics, 2006, vol. 331, pp. 189–199.
[8] Klimiec, E., Krolikowski, B., Machnik, M., Zaraska, W., Dzwonkowski, J. *Increase of piezoelectric constant and thermal durability of polypropylene electret by introducing SiO_2 and kaolin filler and creating a cellular structure*, In: Journal of Electronic Materials, 2015, vol.44, pp. 2283–2291.
[9] Matsouka, D., Vassiliadis, S., Prekas, K., Vatansever Bayramol, D., Soin, N., Siores, E. *On the measurement of the electrical power produced by melt spun piezoelectric textile fibres*, In: Journal of Electronic Materials, 2016, vol. 45, no. 10, pp. 5112–5126.
[10] Matsouka, D., Vassiliadis, S., Vatansever Bayramol, D., Soin, N., Siores, E. *Investigation of the durability and stability of piezoelectric textile fibres*, In: Journal of Intelligent Material Systems and Structures, 2017, vol. 28, no. 5, pp. 663–670.
[11] Baur, C., DiMaio, J.R., McAllister, E., Hossini, R., Wagener, E., Ballato, J., Priya, S., Ballato, A., Smith Jr., D.W. *Enhanced piezoelectric performance from carbon fluoropolymer nanocomposites*, In: Journal of Applied Physics, 2012, vol. 112, 124104.
[12] Zhao, X.L., Wang, J.L., Tia, B.B., Liu, B.L., Wang, X.D., Sun, S., Zou, Y.H., Lin, T., Sun, J.L., Meng, X.J., Chu, J.H., *Enhanced piezoelectric response in the artificial ferroelectric polymer multilayers*, In: Applied Physics Letters, 2014, vol. 105, 222907
[13] Ouyang, Z-W., Chen, E-C., Wu, T-M. *Enhanced piezoelectric responses and crystalline arrangement of electroactive polyvinylidene fluoride/magnetite nanocomposites*, In: Journal of Applied Polymer Science, 2014, vol. 131, 40941.
[14] Vatansever Bayramol, D., Soin, N., Hadimani, R.L., Shah, T., Siores, E. *Effect of addition of multiwalled carbon anotubes on the piezoelectric properties of polypropylene filaments*, In: Journal of Nanoscience and Nanotechnology, 2015, vol. 15, pp. 7130–7135.
[15] Bhavanasi, V., Kumar, V., Parida, K., Wang, J., Lee, P.S. *Enhanced piezoelectric energy harvesting performance of flexible PVDF-TrFE bilayer films with graphene oxide*, In: ACS Applied Materials & Interfaces, 2016, vol. 8, pp. 521–529.
[16] Nakamura, T., Kubo, T. *The tourmaline group crystals reaction with water*, In: Ferroelectrics, 1992, vol. 137, pp. 13–31.
[17] Ji, Z.J., Jin, Z.Z., Liang, J.S., Wang, J., Yan, X.W. *Observation of electric dipole on polar crystalline tourmaline granules*, In: Journal of Synthetic Crystals, 2002, vol. 31, p. 503.
[18] Yamaguchi, S. *Surface electric fields of tourmaline*, In: Applied Physics A, 1983, vol. 31, pp. 183–185.
[19] Pandey, C.S., Schreuer, J. *Elastic and piezoelectric constants of tourmaline single crystals at non-ambient temperatures determined by resonant ultrasound spectroscopy*, In: Journal of Applied Physics, 2012, vol. 111, 013516.
[20] Hadimani, R.L., Vatansever Bayramol, D., Sion, N., Shah, T., Qian, L., Shi, S., Siores, E. *Continuous production of piezoelectric PVDF fibre for e-textile applications*, In: Smart Materials and Structures, 2013, vol. 22, 075017.
[21] Vatansever Bayramol, D. *Effects of tourmaline on the voltage response of PVDF filaments*, In: IndustriaTextila, 2017, vol. 68, no. 1, pp. 47–53.
[22] Yeo, S.Y., Jeong, S.H. *Preparation and characterization of polypropylene/silver nanocomposite fibers*, In: Polymer International, 2003, vol. 52, pp. 1053–1057.
[23] Selvakumar, V., Manoharan, N. *Thermal properties of polypropylene/montmorillonite nanocomposites*, In: Indian Journal of Science and Technology, 2014, vol. 7, pp. 136–139.
[24] Pan, W., Ding, X., Gu, H., Hu, G. *Effect of talc on crystallization and properties of polypropylene*, In: American Journal of Materials Research, 2015, vol. 24, pp. 35–43.
[25] Buchanan, J.P. *Physical characteristics of piezoelectric crystals*, In: Handbook of Piezoelectric Crystals for Radio Equipment Designers WADC TR-56-156 Philco Corporation, Ohio, USA (1956).
[26] Yazıcı, E.Y., Alp, I., Yılmaz, A.O., Celep, O., *Piezoelektrik teknolojive piezo-malzemeolarakturmalin* 5. Endüstriyel Hammaddeler Sempozyumu, 13–14 May 2004, Izmir-Turkey 279–285.

Authors:

VATANSEVER BAYRAMOL DERMAN

Namık Kemal University, CorluFaculty of Engineering
Department of Textile Engineering, 59860, Tekirdag, Turkey
dvbayramol@nku.edu.tr

Corresponding author:

VATANSEVER BAYRAMOL DERMAN
dvbayramol@nku.edu.tr