Tekirdağ Namık Kemal University
Çorlu Engineering Faculty
Textile Engineering Department

ICONTEX 2019

2nd INTERNATIONAL CONGRESS OF INNOVATIVE TEXTILES

PROCEEDINGS

17-18 April 2019

www.icon2019.org

International Congress of Innovative Textiles
ICONTEX (17-18.04.2019)

ISBN

TK NO: 978-605-4265-58-9
Vol. 2: 978-605-4265-60-2

Contents

UTILIZATION OF METALLIC FIBERS IN TEXTILES

İ. Borazan*, M. Kaplan and M.B. Üzümcü

Department of Textile Engineering, Bartin University, 74100 Bartın, Turkey
iborazan@bartin.edu.tr

Abstract

Some metal-based fibers should be used in order to provide the technical textiles with desired properties. Therefore, the use of such materials in textile products have been increased with the developing technology. Silver and copper are among the most preferred materials especially in areas such as smart textiles, medical textiles and protective textiles. The advantages of these materials such as conductivity for smart textiles and antibacterial effect for medical textiles are crucial for these types of textiles. In this study, classification of metal and metal-based textile raw materials used in textile products according to their usage areas and a general evaluation of the studies about these areas will be done.

Key Terms

technical textiles, medical textiles, protective clothing, metal fiber

1. Introduction

Electronic device usage is rapidly increasing with the developing technology. In parallel, conductive fibers and yarns have been attracted by the researchers [1]. In contrast, metallic yarns, also known as metallic threads, have a long history goes back more than 3000 years used as decoration [2]. The definition of the metallic fiber means a fiber that is made from metal, manufactured fiber composed of metal, plastic-coated metal, metal-coated plastic, or a core completely covered by metal [3]. Conventional textile fibers can be coated with various methods to produce metallic fibers:

- Sputter coating
- Coating metal powder with binders
- Electro less coating
- Vacuum deposition

Today, metallic yarns or conductive yarns are used to create functional textiles, in other word ‘smart textiles’[1]. Smart textiles is one of those applications which require conductivity integrated in textile structures [4-8]. Metallic yarns [9-13] or electrically conductive polymers coated yarns [14-20] are utilized in such smart textiles applications.

Conductive yarns and fibers are used in various applications such as energy harvesting [21-33], energy storage [34-40], anti-static [41-43], antimicrobial [44, 45], artificial muscles [46-48], sensing [49-58], electromagnetic interference (EMI) shielding [43, 59-84] besides conducting electricity [36, 39, 49, 51-53, 59, 61, 85, 86], filters, electrostatic discharge, plastic welds, data transfer in clothing, military applications [1].

This study gives a brief information about metallic fiber production and utilization in textile applications.

2. Types of Metallic Yarns for the Use in Textiles

2.1 Metal Filaments

Metal filaments are described as their actual diameter opposed to conventional textile fibers according to linear density thereof. Nowadays, various companies produce different size of metal fibers such as Bekaert Fibre Technologies (BFT) [1, 87]. A broad range of metal fibers with the diameter of 1 to 80 μm are available in the market.

Usually, 8 to 14 microns fibers are utilized in most of textile applications. For instance, 1.4 denier polyester fiber has the same diameter with a 12 micron metal fiber [1].

2.2 Braiding Metallic Yarns with Conventional Textile Fibers

This type of metallic fibers can be considered as core spun yarns, wrapped yarns, fibre blending or braiding composed of conventional textile fiber and metal fiber in a single diameter.

Core spun metallic yarns are manufactured in staple fiber spinning systems where the metal yarn in the core and staple fibers are covering it.

Wrapped yarns are where the conventional fiber is in the core and wrapped by a metallic yarn.

Blend metallic fibers can be produced by blending staple metallic and conventional fibers and spinning in a staple yarn spinning system such as polyester-cotton blends.

Braided yarns are carried out by braiding rope-like metallic and conventional fibers in a braiding machine.

2.3 Coating the Conventional Fibers

Conventional textile fibers are coated in a vacuum chamber by either deposition or sputtering the metals in order to get conductivity on the surface of the non-conductive textile fibers.

General textile fibers can be dipped in a conjugated polymer solution or conjugated polymer can be coated on conventional fibers in the production process after getting out the spinnerette.

3. Textile Applications with Metallic Fibers

3.1. Energy Applications

Energy is a part of daily life with rising technology and the population either in industry and social life. Thus, dependence on energy is an attractive area among the researchers. Photovoltaic is one of the most interesting technology to produce energy in an environmental way [33, 88].

Solar cells is a structure that consists of photoactive layer sandwiched by two electrodes placed on a glass substrate. These electrodes are generally metal-based materials. By the portable devices are so popular recently, flexibility has been a part of research. Photovoltaic fibers enables the photovoltaic effect on flexible devices as in textile structures to meet the energy demand for military applications and outdoor activities.

Metallic fibers with the diameters in micron size are used as electrodes to collect electrons or holes produced in the light harvesting layer of the photovoltaic fibers [22, 24, 28, 33, 89].

In early photovoltaic fiber studies, metals like stainless steel [21, 90-92] and titanium [93, 94] metals are used as primary electrodes and substrates for photovoltaic fibers.

Recently, conductive polymers like poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and Polyaniline (PANi) [22, 28, 33, 88, 95-97] and carbon-based materials [98-101] dip-coated and wrapping, respectively, around the conventional fibers are utilized in photovoltaic textiles. An example of a photovoltaic fiber with conductive polymer coated coonventional fiber as a substrate and bottom electrode is given in Figure 1 [22].

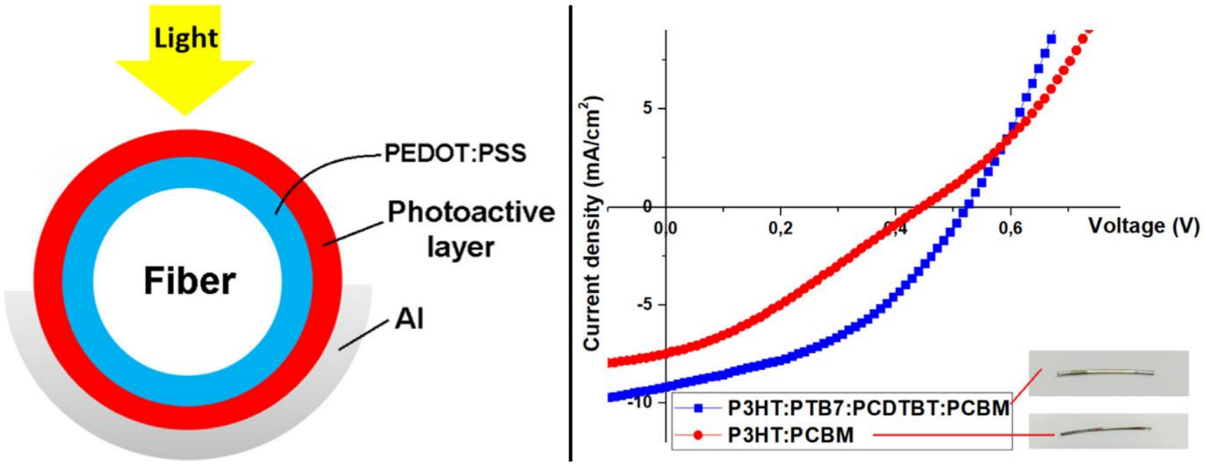

Figure 1. A schematic cross-sectional view of a photovoltaic fiber (left image), and current-voltage graph thereof (right image) reported by Borazan et al. [22].

3.2. EMI Shielding Applications

Rapidly growing of electronic devices such as mobile phones, computers, modems, routers, digital circutis, transfer lines etc. has some drawbacks besides many advantages. Mentioned electronics emit EM waves concluding EMI issues. An EM wave entering an organism can cause a heat by the vibration of the molecules that can cause negative effects for the lives. EM shielding can be possible by the interception of EM waves transmission by a suitable material into required area [21, 98, 12, 102].

3.3. Other Smart Textiles Applications

Smart textiles are textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionality in the textile structure. The stimulus and response can have an electrical, thermal, chemical, magnetic, or other origin [103, 104].

Combination of conventional textiles and electronic fabrication technologies gives possibility to achieve new functionalities [105]. Smart garments collect the data from the body by the interaction of movement or sensors and transfer the collected data to a computer. Conductivity is a must where an electronic circuit is available. Thus, the conductivity in smart textiles is enabled by the metallic fibers. A key motivation for this research is textile production processes has a capability of automatically creating large-area surfaces a very high speeds.

A sensor based smart textile application has a possibility to measure applied pressure which integrated on a textile with metallic fibers. Such sensors can be used in various wearable electronics such as motion and gesture sensors, rehabilitation and medical textiles [106].

In wearable electronics, the use of batteries may be difficult due to heavy-weight, rigidity, and safety reasons. Recharging the battery is another issue considering battery integrated systems. Researchers aimed to study for self-power generating systems that are called nanogenerators [107-109]. A report by Zeng et al. shows that harvesting electrical energy from mechanical energy is possible with the nanogenerators. A polyvinylidene fluoride (PVDF) fiber as a piezoelectric component can fabricate an open-circuit voltage of 3.2 V and current of 4.2 mA power at 0.2 MPa pressure [108, 109].

4. Conclusions

Textiles are expected not only for covering our bodies or for fashion issued but also for advanced functionalities with the developing technology rapidly day by day. Textile producers consider this requirement to produce more value added products. With the advanced technology and nano materials, researches take a challenge to develop innovative solutions for global requirements.

References

1. Alagirusamy, R.; Das, A., *Technical textile yarns industrial and medical applications*. Woodhead Publishing: [Cambridge, U.K.], 2010; p 1 online resource.

2. Koncar, V.; Textile Institute (Manchester England), Smart textiles and their applications. In *Woodhead Publishing series in textiles no. 178* [Online] Woodhead Pub. ;
Textile Institute: Amsterdam
[Manchester, England], 2016; p. 1 online resource.
https://proxying.lib.ncsu.edu/index.php?url=https://www.sciencedirect.com/science/book/9780081005743.

3. Rana, S.; Fangueiro, R.; SpringerLink (Online service), *Fibrous and Textile Materials for Composite Applications*. Springer Singapore : Imprint: Springer: Singapore, 2016; p 1 online resource.

4. Alonso-Gonzalez, L.; Ver-Hoeye, S.; Fernandez-Garcia, M.; Vazquez-Antuna, C.; Andres, F. L. H., From Threads to Smart Textile: Parametric Characterization and Electromagnetic Analysis of Woven Structures. *Ieee Access* **2019,** *7*, 1486-1501.

5. Hu, Y. F.; Zheng, Z. J., Progress in textile-based triboelectric nanogenerators for smart fabrics. *Nano Energy* **2019,** *56*, 16-24.

6. Komeily-Nia, Z.; Montazer, M.; Heidarian, P.; Nasri-Nasrabadi, B., Smart photoactive soft materials for environmental cleaning and energy production through incorporation of nanophotocatalyst on polymers and textiles. *Polym Advan Technol* **2019,** *30* (2), 235-253.

7. Lee, D.; Sang, J. S.; Yoo, P. J.; Shin, T. J.; Oh, K. W.; Park, J., Machine-Washable Smart Textiles with Photothermal and Antibacterial Activities from Nanocomposite Fibers of Conjugated Polymer Nanoparticles and Polyacrylonitrile. *Polymers-Basel* **2019,** *11* (1).

8. Lu, Y.; Xiao, X. D.; Fu, J.; Huan, C. M.; Qi, S.; Zhan, Y. J.; Zhu, Y. Q.; Xu, G., Novel smart textile with phase change materials encapsulated core-sheath structure fabricated by coaxial electrospinning. *Chem Eng J* **2019,** *355*, 532-539.

9. Wang, H. T.; Jin, C.; Liu, Y. N.; Kang, X. H.; Bian, S. W.; Zhu, Q., Cotton yarns modified with three-dimensional metallic Ni conductive network and pseudocapacitive Co-Ni layered double hydroxide nanosheet array as electrode materials for flexible yarn supercapacitors. *Electrochim Acta* **2018,** *283*, 1789-1797.

10. Radojkovic, B.; Ristic, S.; Polic, S.; Jancic-Heinemann, R.; Radovanovic, D., Preliminary investigation on the use of the Q-switched Nd:YAG laser to clean corrosion products on museum embroidered textiles with metallic yarns. *J Cult Herit* **2017,** *23*, 128-137.

11. Zhao, Z. Z.; Yan, C.; Liu, Z. X.; Fu, X. L.; Peng, L. M.; Hu, Y. F.; Zheng, Z. J., Machine-Washable Textile Triboelectric Nanogenerators for Effective Human Respiratory Monitoring through Loom Weaving of Metallic Yarns. *Adv Mater* **2016,** *28* (46), 10267-10274.

12. Ghane, M.; Ghorbani, E., Investigation into the Uv-Protection of Woven Fabrics Composed of Metallic Weft Yarns. *Autex Res J* **2016,** *16* (3), 154-159.

13. Liu, L. B.; Yu, Y.; Yan, C.; Li, K.; Zheng, Z. J., Wearable energy-dense and power-dense supercapacitor yarns enabled by scalable graphene-metallic textile composite electrodes. *Nat Commun* **2015,** *6*.

14. Xie, J.; Jia, Y. T.; Miao, M. H., High sensitivity knitted fabric bi-directional pressure sensor based on conductive blended yarn. *Smart Mater Struct* **2019,** *28* (3).

15. Nuramdhani, I.; Jose, M.; Samyn, P.; Adriaensens, P.; Malengier, B.; Deferme, W.; De Mey, G.; Van Langenhove, L., Charge-Discharge Characteristics of Textile Energy Storage Devices Having Different PEDOT:PSS Ratios and Conductive Yarns Configuration. *Polymers-Basel* **2019,** *11* (2).

16. Wang, Y.; Yu, W. D.; Wang, F. M., Structural evolution and predictive modeling for nonlinear tensile behavior of tri-component elastic-conductive composite yarn during stretch. *Text Res J* **2019,** *89* (4), 487-497.

17. Datta, M.; Chaudhuri, A.; Mitra, M.; Nath, D.; Das, D., Development of biodegradable conductive cotton yarns by in-situ polymerisation of pyrrole. *J Text I* **2019,** *110* (1), 10-15.

18. Shahzad, A.; Ali, Z.; Ali, U.; Khaliq, Z.; Zubair, M.; Kim, I. S.; Hussain, T.; Khan, M. Q.; Rasheed, A.; Qadir, M. B., Development and characterization of conductive ring spun hybrid yarns. *J Text I* **2019,** *110* (1), 141-150.

19. Sun, X. Q.; He, J. X.; Qiang, R.; Nan, N.; You, X. L.; Zhou, Y. M.; Shao, W. L.; Liu, F.; Liu, R. T., Electrospun Conductive Nanofiber Yarn for a Wearable Yarn Supercapacitor with High Volumetric Energy Density. *Materials* **2019,** *12* (2).

20. Souri, H.; Bhattacharyya, D., Highly stretchable and wearable strain sensors using conductive wool yarns with controllable sensitivity. *Sensor Actuat a-Phys* **2019,** *285*, 142-148.

21. Peng, M.; Zou, D. C., Flexible fiber/wire-shaped solar cells in progress: properties, materials, and designs. *J Mater Chem A* **2015,** *3* (41), 20435-20458.

22. Borazan, I., A study about lifetime of photovoltaic fibers. *Sol Energ Mat Sol C* **2019,** *192*, 52-56.

23. Peng, M.; Dong, B.; Zou, D. C., Three dimensional photovoltaic fibers for wearable energy harvesting and conversion. *J Energy Chem* **2018,** *27* (3), 611-621.

24. Peng, M.; Dong, B.; Cai, X.; Wang, W.; Jiang, X. M.; Wang, Y. H.; Yang, Y.; Zou, D. C., Organic dye-sensitized photovoltaic fibers. *Sol Energy* **2017,** *150*, 161-165.

25. Sun, H.; Jiang, Y. S.; Xie, S. L.; Zhang, Y.; Ren, J.; Ali, A.; Doo, S. G.; Son, I. H.; Huang, X. L.; Peng, H. S., Integrating photovoltaic conversion and lithium ion storage into a flexible fiber. *J Mater Chem A* **2016,** *4* (20), 7601-7605.

26. Song, W. X.; Wang, H.; Liu, G. C.; Peng, M.; Zou, D. C., Improving the photovoltaic performance and flexibility of fiber-shaped dye-sensitized solar cells with atomic layer deposition. *Nano Energy* **2016,** *19*, 1-7.

27. Pan, S. W.; Yang, J. H., Polyaniline/Carbon Nanotube Composite Fiber-Based Dye-Sensitized Photovoltaic Wire. *J Nanosci Nanotechno* **2015,** *15* (9), 7412-7415.

28. Borazan, I.; Bedeloglu, A.; Demir, A., The effect of MWCNT-PEDOT:PSS layer in organic photovoltaic fiber device. *Optoelectron Adv Mat* **2015,** *9* (3-4), 347-352.

29. Takeda, Y.; Iizuka, H.; Mizuno, S.; Hasegawa, K.; Ichikawa, T.; Ito, H.; Kajino, T.; Ichiki, A.; Motohiro, T., Silicon photovoltaic cells coupled with solar-pumped fiber lasers emitting at 1064 nm. *J Appl Phys* **2014,** *116* (1).

30. Jin, E. M.; Park, J. Y.; Zhao, X. G.; Lee, I. H.; Jeong, S. M.; Gu, H. B., Photovoltaic properties of TiO2-ZrO2 fiber composite electrodes for dye-sensitized solar cells. *Mater Lett* **2014,** *126*, 281-284.

31. Jiang, Y. S.; Sun, H.; Peng, H. S., Synthesis and photovoltaic application of platinum-modified conducting aligned nanotube fiber. *Sci China Mater* **2015,** *58* (4), 289-293.

32. Kim, T.; Yang, S. J.; Sung, S. J.; Kim, Y. S.; Chang, M. S.; Jung, H.; Park, C. R., Highly Reproducible Thermocontrolled Electrospun Fiber Based Organic Photovoltaic Devices. *Acs Appl Mater Inter* **2015,** *7* (8), 4481-4487.

33. Bedeloglu, A.; Demir, A.; Bozkurt, Y.; Sariciftci, N. S., A Photovoltaic Fiber Design for Smart Textiles. *Text Res J* **2010,** *80* (11), 1065-1074.

34. Zhang, C. J.; Chen, Z. Q.; Rao, W. D.; Fan, L. L.; Xia, Z. G.; Xu, W. L.; Xu, J., A high-performance all-solid-state yarn supercapacitor based on polypyrrole-coated stainless steel/cotton blended yarns. *Cellulose* **2019,** *26* (2), 1169-1181.

35. Wei, H. M.; Hu, H. B.; Feng, J.; Zhang, M.; Hua, T., Yarn-form electrodes with high capacitance and cycling stability based on hierarchical nanostructured nickel-cobalt mixed oxides for weavable fiber-shaped supercapacitors. *J Power Sources* **2018,** *400*, 157-166.

36. Ma, Y.; Wang, Q. F.; Liang, X.; Zhang, D. H.; Miao, M. H., Wearable supercapacitors based on conductive cotton yarns. *J Mater Sci* **2018,** *53* (20), 14586-14597.

37. Kim, J. H.; Choi, C.; Lee, J. M.; de Andrade, M. J.; Baughman, R. H.; Kim, S. J., Ag/MnO2 Composite Sheath-Core Structured Yarn Supercapacitors. *Sci Rep-Uk* **2018,** *8*.

38. Li, X. L.; Liu, R.; Xu, C. Y.; Bai, Y.; Zhou, X. M.; Wang, Y. J.; Yuan, G. H., High-Performance Polypyrrole/Graphene/SnCl2 Modified Polyester Textile Electrodes and Yarn Electrodes for Wearable Energy Storage. *Adv Funct Mater* **2018,** *28* (22).

39. Wang, Z. P.; Cheng, J. L.; Guan, Q.; Huang, H.; Li, Y. C.; Zhou, J. W.; Ni, W.; Wang, B.; He, S. S.; Peng, H. S., All-in-one fiber for stretchable fiber-shaped tandem supercapacitors. *Nano Energy* **2018,** *45*, 210-219.

40. Sankar, K. N. A.; Mohanta, K., Preparation of Highly Conductive Yarns by an Optimized Impregnation Process. *J Electron Mater* **2018,** *47* (3), 1970-1978.

41. Bashir, T.; Skrifvars, M.; Persson, N. K., High-strength electrically conductive fibers: Functionalization of polyamide, aramid, and polyester fibers with PEDOT polymer. *Polym Advan Technol* **2018,** *29* (1), 310-318.

42. Lin, Z. I.; Lou, C. W.; Pan, Y. J.; Hsieh, C. T.; Huang, C. H.; Huang, C. L.; Chen, Y. S.; Lin, J. H., Conductive fabrics made of polypropylene/multi-walled carbon nanotube coated polyester yarns: Mechanical properties and electromagnetic interference shielding effectiveness. *Compos Sci Technol* **2017,** *141*, 74-82.

43. Bedeloglu, A.; Sunter, N.; Bozkurt, Y., Manufacturing and Properties of Yarns Containing Metal Wires. *Mater Manuf Process* **2011,** *26* (11), 1378-1382.

44. Shahid-ul-Islam; Wani, S. A.; Mohammad, F., Imparting functionality viz color, antioxidant and antibacterial properties to develop multifunctional wool with Tectona grandis leaves extract using reflectance spectroscopy. *Int J Biol Macromol* **2018,** *109*, 907-913.

45. Rather, L. J.; Akhter, S.; Padder, R. A.; Hassan, Q. P.; Hussain, M.; Khan, M. A.; Mohammad, F., Colorful and semi durable antioxidant finish of woolen yarn with tannin rich extract of Acacia nilotica natural dye. *Dyes Pigments* **2017,** *139*, 812-819.
46. Mirvakili, S. M.; Hunter, I. W., Artificial Muscles: Mechanisms, Applications, and Challenges. *Adv Mater* **2018,** *30* (6).
47. Maziz, A.; Concas, A.; Khaldi, A.; Stalhand, J.; Persson, N. K.; Jager, E. W. H., Knitting and weaving artificial muscles. *Sci Adv* **2017,** *3* (1).
48. Haines, C. S.; Li, N.; Spinks, G. M.; Aliev, A. E.; Di, J. T.; Baughman, R. H., New twist on artificial muscles. *P Natl Acad Sci USA* **2016,** *113* (42), 11709-11716.
49. Seyedin, S.; Zhang, P.; Naebe, M.; Qin, S.; Chen, J.; Wang, X. A.; Razal, J. M., Textile strain sensors: a review of the fabrication technologies, performance evaluation and applications. *Mater Horiz* **2019,** *6* (2), 219-249.
50. Afzal, A.; Harzallah, O.; Drean, J. Y.; Akhtar, N. A.; Ahmad, S., Performance characterization of multifunctional different cross-sectional-shaped coaxial composite filaments for SMART textile applications. *J Ind Text* **2019,** *48* (6), 1059-1080.
51. Li, C. J.; Cao, R.; Zhang, X. L., Breathable Materials for Triboelectric Effect-Based Wearable Electronics. *Appl Sci-Basel* **2018,** *8* (12).
52. Grancaric, A. M.; Jerkovic, I.; Koncar, V.; Cochrane, C.; Kelly, F. M.; Soulat, D.; Legrand, X., Conductive polymers for smart textile applications. *J Ind Text* **2018,** *48* (3), 612-642.
53. Adhikari, S.; Richter, B.; Mace, Z. S.; Sclabassi, R. J.; Cheng, B.; Whiting, D. M.; Averick, S.; Nelson, T. L., Organic Conductive Fibers as Nonmetallic Electrodes and Neural Interconnects. *Ind Eng Chem Res* **2018,** *57* (23), 7866-7871.
54. Xue, Q.; Sun, J. F.; Huang, Y.; Zhu, M. S.; Pei, Z. X.; Li, H. F.; Wang, Y. K.; Li, N.; Zhang, H. Y.; Zhi, C. Y., Recent Progress on Flexible and Wearable Supercapacitors. *Small* **2017,** *13* (45).
55. Liang, Y.; Sias, D.; Chen, P. J.; Tawfick, S., Tough Nano-Architectured Conductive Textile Made by Capillary Splicing of Carbon Nanotubes. *Adv Eng Mater* **2017,** *19* (7).
56. Roh, J. S.; Kim, S., All-fabric intelligent temperature regulation system for smart clothing applications. *J Intel Mat Syst Str* **2016,** *27* (9), 1165-1175.
57. Tu, H. G.; Chen, X. Y.; Feng, X. C.; Xu, Y., A post-CMOS compatible smart yarn technology based on SOI wafers. *Sensor Actuat a-Phys* **2015,** *233*, 397-404.
58. Lee, J.; Kwon, H.; Seo, J.; Shin, S.; Koo, J. H.; Pang, C.; Son, S.; Kim, J. H.; Jang, Y. H.; Kim, D. E.; Lee, T., Conductive Fiber-Based Ultrasensitive Textile Pressure Sensor for Wearable Electronics. *Adv Mater* **2015,** *27* (15), 2433-2439.
59. Tugirumubano, A.; Vijay, S. J.; Go, S. H.; Shin, H. J.; Ku, K. L.; Kim, H. G., The evaluation of electromagnetic shielding properties of CFRP/metal mesh hybrid woven laminated composites. *J Compos Mater* **2018,** *52* (27), 3819-3829.
60. Tugirumubano, A.; Vijay, S. J.; Go, S. H.; Kwac, L. K.; Kim, H. G., Investigation of Mechanical and Electromagnetic Interference Shielding Properties of Nickel-CFRP Textile Composites. *J Mater Eng Perform* **2018,** *27* (5), 2255-2262.
61. Liang, R. R.; Cheng, W. J.; Xiao, H.; Shi, M. W.; Tang, Z. H.; Wang, N., A calculating method for the electromagnetic shielding effectiveness of metal fiber blended fabric. *Text Res J* **2018,** *88* (9), 973-986.
62. Safarova, V.; Militky, J., Multifunctional Metal Composite Textile Shields Against Electromagnetic Radiation-Effect of Various Parameters on Electromagnetic Shielding Effectiveness. *Polym Composite* **2017,** *38* (2), 309-323.
63. Lou, C. W.; Li, T. T.; Hwang, P. W.; Chen, A. P.; Lin, J. H., Preparation Technique and EMI Shielding Evaluation of Flexible Conductive Composite Fabrics Made by Single and Double Wrapped Yarns. *J Eng Fiber Fabr* **2017,** *12* (4), 78-88.
64. Liu, Z.; Li, Y. P.; Pan, Z.; Su, Y.; Wang, X. C., FDTD computation of shielding effectiveness of electromagnetic shielding fabric based on weave region. *J Electromagnet Wave* **2017,** *31* (3), 309-322.
65. Wang, S.; Zhang, T. H.; Cheng, L.; Li, J. L.; Tang, H.; Guo, M., Comprehensive performance of compound fabrics in terms of electromagnetic shielding and wearability based on the Euclid approach degree of fuzzy matter elements. *J Text I* **2017,** *108* (3), 341-346.
66. Tunakova, V.; Technikova, L.; Militky, J., Influence of washing/drying cycles on fundamental properties of metal fiber-containing fabrics designed for electromagnetic shielding purposes. *Text Res J* **2017,** *87* (2), 175-192.
67. Lou, C. W.; Lin, T. A.; Chen, A. P.; Lin, J. H., Stainless steel/polyester woven fabrics and copper/polyester woven fabrics: Manufacturing techniques and electromagnetic shielding effectiveness. *J Ind Text* **2016,** *46* (1), 214-236.
68. Ceven, E. K.; Aytas, H., Investigation of Tensile and Stiffness Properties of Composite Yarns with Different Parameters. *Fibres Text East Eur* **2016,** *24* (4), 51-58.

69. Zhang, T. H.; Guo, M.; Cheng, L.; Yu, Y. Y.; Tang, H.; Li, S. P., Investigation on production, analytical models, and characteristics of monofilaments/staple fibers composite yarn. *J Text I* **2016,** *107* (5), 589-595.
70. Yu, Z. C.; Lu, Y. H.; He, H. L.; Zhang, J. F.; Lou, C. W.; Chen, A. P.; Lin, J. H., Antibacterial properties and electrical characteristics of multifunctional metal composite fabrics. *J Ind Text* **2016,** *45* (5), 834-852.
71. Zhang, T. H.; Cheng, L.; Guo, M.; Xue, W., Evaluation of electromagnetic shielding and wearability of metal wire composite fabric based on grey clustering analysis. *J Text I* **2016,** *107* (1), 42-49.
72. Liu, Z.; Su, Y.; Li, Y. P.; Pan, Z.; Wang, X. C., Numerical calculation of shielding effectiveness of electromagnetic shielding fabric based on finite difference time domain. *Int J Appl Electrom* **2016,** *50* (4), 593-603.
73. Gupta, K. K.; Abbas, S. M.; Abhyankar, A. C., Ultra-lightweight hybrid woven fabric containing stainless steel/polyester composite yarn for total EMI shielding in frequency range 8-18 GHz. *J Electromagnet Wave* **2015,** *29* (11), 1454-1472.
74. Liu, Z.; Zhang, Y. H.; Rong, X.; Wang, X. C., Influence of Metal Fibre Content of Blended Electromagnetic Shielding Fabric on Shielding Effectiveness Considering Fabric Weave. *Fibres Text East Eur* **2015,** *23* (4), 83-87.
75. Cheng, L.; Zhang, T. H.; Guo, M.; Li, J. L.; Wang, S.; Tang, H., Electromagnetic shielding effectiveness and mathematical model of stainless steel composite fabric. *J Text I* **2015,** *106* (6), 577-586.
76. Rubeziene, V.; Baltusnikaite, J.; Varnaite-Zuravliova, S.; Sankauskaite, A.; Abraitiene, A.; Matuzas, J., Development and investigation of electromagnetic shielding fabrics with different electrically conductive additives. *J Electrostat* **2015,** *75*, 90-98.
77. Lin, Y.; Kim, J. W.; Connell, J. W.; Lebron-Colon, M.; Siochi, E. J., Purification of Carbon Nanotube Sheets. *Adv Eng Mater* **2015,** *17* (5), 674-688.
78. Safarova, V.; Tunak, M.; Militky, J., Prediction of hybrid woven fabric electromagnetic shielding effectiveness. *Text Res J* **2015,** *85* (7), 673-686.
79. Eren, S.; Ulcay, Y., Production of Bi-Component Polyester Fibres for Emr (Electromagnetic Radiation) Protection and Examining Emr Shielding Characteristics. *Tekst Konfeksiyon* **2015,** *25* (2), 140-147.
80. Erdumlu, N., Evaluation of Drape, Bending and Formability of Woven Fabrics Made from Metal Covered Hybrid Yarns. *Tekst Konfeksiyon* **2015,** *25* (1), 47-53.
81. Liu, Z.; Rong, X.; Yang, Y. L.; Wang, X. C., Influence of Metal Fiber Content and Arrangement on Shielding Effectiveness for Blended Electromagnetic Shielding Fabric. *Mater Sci-Medzg* **2015,** *21* (2), 265-270.
82. Yu, Z. C.; Zhang, J. F.; Lou, C. W.; Lin, J. H., Investigation and fabrication of multifunctional metal composite knitted fabrics. *Text Res J* **2015,** *85* (2), 188-199.
83. Varnaite-Zuravliova, S.; Kavaliauskiene, L.; Baltusnikaite, J.; Valaseviciute, L.; Verbiene, R., Investigation of Shielding Properties of Yarns, Twisted with Metal Wire. *Mater Sci-Medzg* **2014,** *20* (1), 73-78.
84. Bedeloglu, A. C.; Sunter, N., Investigation of Polyacrylic/Metal Wire Composite Yarn Characteristics Manufactured on Fancy Yarn Machine. *Mater Manuf Process* **2013,** *28* (6), 650-656.
85. Yin, Z.; Jian, M. Q.; Wang, C. Y.; Xia, K. L.; Liu, Z. H.; Wang, Q.; Zhang, M. C.; Wang, H. M.; Liang, X. P.; Liang, X.; Long, Y. W.; Yu, X. H.; Zhang, Y. Y., Splash-Resistant and Light-Weight Silk-Sheathed Wires for Textile Electronics. *Nano Lett* **2018,** *18* (11), 7085-7091.
86. Yu, C. Y.; Gong, Y. J.; Chen, R. Y.; Zhang, M. Y.; Zhou, J. Y.; An, J. N.; Lv, F.; Guo, S. J.; Sun, G. Z., A Solid-State Fibriform Supercapacitor Boosted by Host-Guest Hybridization between the Carbon Nanotube Scaffold and MXene Nanosheets. *Small* **2018,** *14* (29).
87. Payvandy, P.; Latifi, M.; Agha-Mirsalim, M.; Shokrolahi-Moghani, J., Rotational electromagnetic-field-aided false twisting of metallic filaments. *J Text I* **2010,** *101* (6), 514-519.
88. Bedeloglu, A.; Koeppe, R.; Demir, A.; Bozkurt, Y.; Sariciftci, N. S., Development of Energy Generating Photovoltaic Textile Structures for Smart Applications. *Fiber Polym* **2010,** *11* (3), 378-383.
89. O'Connor, B.; Pipe, K. P.; Shtein, M., Fiber based organic photovoltaic devices. *Appl Phys Lett* **2008,** *92* (19).
90. Ji, X. Y.; Cheng, H. Y.; Grede, A. J.; Molina, A.; Talreja, D.; Mohney, S. E.; Giebink, N. C.; Badding, J. V.; Gopalan, V., Conformal coating of amorphous silicon and germanium by high pressure chemical vapor deposition for photovoltaic fabrics. *Apl Mater* **2018,** *6* (4).
91. Wang, W.; Zhao, Q.; Li, H.; Wu, H. W.; Zou, D. C.; Yu, D. P., Transparent, Double-Sided, ITO-Free, Flexible Dye-Sensitized Solar Cells Based on Metal Wire/ZnO Nanowire Arrays. *Adv Funct Mater* **2012,** *22* (13), 2775-2782.
92. Zou, D. C.; Wang, D.; Chu, Z. Z.; Lv, Z. B.; Fan, X., Fiber-shaped flexible solar cells. *Coordin Chem Rev* **2010,** *254* (9-10), 1169-1178.

93. Gu, X. Y.; Chen, E. Z.; Ma, M. Y.; Yang, Z. Y.; Bai, J. L.; Chen, L. L.; Sun, G. Z.; Zhang, Z. X.; Pan, X. J.; Zhou, J. Y.; Xie, E. Q., Effect of TiO2-rGO heterojunction on electron collection efficiency and mechanical properties of fiber-shaped dye-sensitized solar cells. *J Phys D Appl Phys* **2019,** *52* (9).

94. Aziz, S. B.; Abdullah, O. G.; Rasheed, M. A., A novel polymer composite with a small optical band gap: New approaches for photonics and optoelectronics. *J Appl Polym Sci* **2017,** *134* (21).

95. Bedeloglu, A.; Demir, A.; Bozkurt, Y.; Sariciftci, N. S., Photovoltaic properties of polymer based organic solar cells adapted for non-transparent substrates. *Renew Energ* **2010,** *35* (10), 2301-2306.

96. Bedeloglu, A.; Jimenez, P.; Demir, A.; Bozkurt, Y.; Maser, W. K.; Sariciftci, N. S., Photovoltaic textile structure using polyaniline/carbon nanotube composite materials. *J Text I* **2011,** *102* (10), 857-862.

97. Du, Q. G.; Kam, C. H.; Demir, H. V.; Yu, H. Y.; Sun, X. W., Enhanced optical absorption in nanopatterned silicon thin films with a nano-cone-hole structure for photovoltaic applications. *Opt Lett* **2011,** *36* (9), 1713-1715.

98. Monreal-Bernal, A.; Vilatela, J. J.; Costa, R. D., CNT fibres as dual counter-electrode/current-collector in highly efficient and stable dye-sensitized solar cells. *Carbon* **2019,** *141*, 488-496.

99. Jaksik, J.; Moore, H. J.; Trad, T.; Okoli, O. I.; Uddin, M. J., Nanostructured functional materials for advanced three-dimensional (3D) solar cells. *Sol Energ Mat Sol C* **2017,** *167*, 121-132.

100. Lv, T.; Yao, Y.; Li, N.; Chen, T., Wearable fiber-shaped energy conversion and storage devices based on aligned carbon nanotubes. *Nano Today* **2016,** *11* (5), 644-660.

101. Uddin, M. J.; Daramola, D. E.; Velasquez, E.; Dickens, T. J.; Yan, J.; Hammel, E.; Cesano, F.; Okoli, O. I., A high efficiency 3D photovoltaic microwire with carbon nanotubes (CNT)-quantum dot (QD) hybrid interface. *Phys Status Solidi-R* **2014,** *8* (11), 898-903.

102. Palanisamy, S.; Tunakova, V.; Militky, J., Fiber-based structures for electromagnetic shielding - comparison of different materials and textile structures. *Text Res J* **2018,** *88* (17), 1992-2012.

103. Schneegass, S.; Amft, O.; SpringerLink (Online service), *Smart Textiles Fundamentals, Design, and Interaction*. Springer International Publishing : Imprint: Springer: Cham, 2017; p 1 online resource.

104. Harms, H.; Amft, O.; Roggen, D.; Troster, G., Rapid prototyping of smart garments for activity-aware applications. *J Amb Intel Smart En* **2009,** *1* (2), 87-101.

105. Cherenack, K.; van Pieterson, L., Smart textiles: Challenges and opportunities. *J Appl Phys* **2012,** *112* (9).

106. Eom, J.; Lee, W.; Kim, Y.; Kim, Y. In *Textile-based wearable sensors using metal-nanowire embedded conductive fibers*, 2016 IEEE SENSORS, 30 Oct.-3 Nov. 2016; 2016; pp 1-3.

107. Li, L. X.; Liu, S.; Tao, X. M.; Song, J., Triboelectric performances of self-powered, ultra-flexible and large-area poly(dimethylsiloxane)/Ag-coated chinlon composites with a sandpaper-assisted surface microstructure. *J Mater Sci* **2019,** *54* (10), 7823-7833.

108. Heo, J. S.; Eom, J.; Kim, Y. H.; Park, S. K., Recent Progress of Textile-Based Wearable Electronics: A Comprehensive Review of Materials, Devices, and Applications. *Small* **2018,** *14* (3).

109. Paosangthong, W.; Torah, R.; Beeby, S., Recent progress on textile-based triboelectric nanogenerators. *Nano Energy* **2019,** *55*, 401-423.

Author Information (including all contact information)*

Ismail Borazan
Bartin University
Bartin Universitesi Muhendislik Fakultesi, Kutlubeyyazicilar kampusu, Bartin, Turkey
+90 543 355 75 66
iborazan@itu.edu.tr