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Effects of Dip-coating Processing Parameters on the Functional Performances of $Ti_3C_2T_x$ MXene-silk Yarns

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Abstract

Mxenes, as a new group of two-dimensional materials in form of transition metal carbides, carbonitrides and/or nitrides, have been playing an important role in the wearable smart electronic field. Due to their abundance surface functional groups, Mxenes have showed their superior dispersions in various solvents which is beneficial to simply the fabrication process of textile-based electronics while their electrical performance guaranteed. In this work, we report a novel fine silk yarn dip-coated in an aqueous solution of $Ti_3C_2T_x$ MXene to obtain low electrical resistance (~25.6 Ohms/cm). Yarns structures and morphologies were observed by transmission and scanning electron microscopy (TEM & SEM) together with energy dispersive spectroscopy (EDS). Besides, Fourier transform infrared (FTIR) and Raman spectroscopy, and X-ray diffraction (XRD) analysis were carried out to reveal the chemical compositions. By controlling two coating parameters as design of experiments (DoE) factors, we found both solution concentration and soaking time had significant effects on yarn performances. The mechanical performance of yarn fabricated under the optimised coating condition was evaluated by means of tensile testing, resulting in a significant 23% increase in breaking strength (~107 MPa). In responding to tensile deformation, the dip-coated yarn also performed a linear variation in resistance, which indicated its capability in sensing applications.

Keywords: MXenes; Electrically Conductive Yarns; Dip-coating; DoE; Yarn Tensile Strength

1 Introduction

It has already been over a decade since the two-dimensional (2D) material $Ti_3C_2T_x$ was found as the first MXene [1] and followed by a rapid develop of the whole transition metal carbides, carbonitrides and/or nitrides family. From the chemical formula, Ti refers to the early transition metal titanium, C represents carbides, and T stands for surface termination functional groups involving hydroxyl (-OH), oxygen (-O) and fluorine (-F) which are beneficial to the hydrophilic nature of $Ti_3C_2T_x$ [2, 3]. $Ti_3C_2T_x$ MXene started to be very appealing to the wearable smart textile field because of its promising high electrical conductivity inherited from transition metal

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[4], the reported applications include but not limited to energy storage [5, 6], different types of sensors [7-9] and electromagnetic interference (EMI) shield [10, 11].

However, new findings pointed out one major issue would affect the long-term usage of MXene is degradation caused by oxidation in aqueous solution [12, 13]. Thus, the method to fabricate MXene with textile substrate can be critically complicated. As one of the most common used coating techniques for textiles, dip coating can be simply carried out regardless of production scales and keep the cost low while provide an uniform coating on cylindrical substrates efficiently [14]. Considering silk, as one of nature fibres, is also well known for its rich surface functional groups [15] which may lead to an efficient integrating with MXene, and therefore avoiding the degradation.

Herein, a cost-effective dip coating process was used in this work to fabricate a conductive silk yarn in order to shorten the producing time and additionally stabilised the MXene. Also, the impacts of the coating process parameters on yarns performance were studied in Minitab via a two-factor two-level method. The dip-coating process was then optimised with the best combination of settings. The as-made silk will then be tested for its mechanical and electrical behaviours. A relevant pilot study was reported in Textile Bioengineering and Informatics Society, 2022 [16].

2 Methodology

2.1 Materials

The two-ply 2/60 Nm Italian spun silk yarn was used as the substrate yarn for the dip-coating process in this work and was supplied by Uppingham Yarns, UK. The delaminated $Ti_3C_2T_x$ MXene powders was purchased from Nanoplexus Ltd.

2.2 Design of Experiments (DoE)

Considering the existed two parameters in the dip-coating process, one was the concentration of prepared coating solution, and another was the time duration of yarns soaked in the solution, a two-factor two-level DoE was used to figure out if these coating variables would affect the mechanical and electrical performance of coated yarn. The solutions were prepared in 10 mg/mL as low concentration and 15 mg/mL as high concentration, respectively, while the soaking duration was controlled in three minutes and five minutes, as shown in Table 1. The sample groups under different coating conditions were marked as 10-3 (10 mg/mL; 3 min), 10-5 (10 mg/mL; 5 min), 15-3 (15 mg/mL; 3 min) and 15-5 (15 mg/mL; 5 min). In each group, three specimens were prepared with 8 times repeated coating and tested for their electrical resistance. The results were analysed by using Minitab DoE software to identify the key processing parameters that have effects on the electrical resistance, and the best processing setup to achieve highest electrical conductivity. The details of DoE design settings in Minitab are as shown in Table 2.

Based on the results of the first experiment, the best experiment set-up was selected to conform the results with a number of repeating dip-coating processes from one to eight times for understanding the effects of morphology and chemical composition distribution during coating on mechanical and electrical properties of the yarns.