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Electromagnetic shielding mechanisms using soft magnetic stainless steel fiber enabled polyester textiles

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ABSTRACT

This work studied the effects of conductivity, magnetic loss, and complex permittivity when using blended textiles (SSF/PET) of polyester fibers (PET) with stainless steel fibers (SSF) on electromagnetic wave shielding mechanisms at electromagnetic wave frequencies ranging from 30 MHz to 1500 MHz. The 316L stainless steel fiber used in this study had 38 vol% γ austenite and 62 vol% α' martensite crystalline phases, which was characterized by an x-ray diffractometer. Due to the magnetic and dielectric loss of soft metallic magnetic stainless steel fiber enabled polyester textiles, the relationship between the reflection/absorption/transmission behaviors of the electromagnetic wave and the electrical/magnetic/dielectric properties of the SSF and SSF/PET fabrics was analyzed. Our results showed that the electromagnetic interference shielding of the SSF/PET textiles show an absorption-dominant mechanism, which attributed to the dielectric loss and the magnetic loss at a lower frequency and attributed to the magnetic loss at a higher frequency, respectively.

1. Introduction

Because electronic devices and communication instruments are used extensively, shielding against electromagnetic interference (EMI) by radio frequency radiation is a serious concern. EMI attenuation can arise from three different sources: reflection, absorption, and multiple reflection [1]. At present, shielding against EMI by absorption rather than by reflection is important for many applications. Metals or materials coated with a metallic compound have a very high EMI shielding efficiency (SE) ranging from 40 dB to 100 dB. However, they cannot be used as an electromagnetic wave absorbent since the shallow depth of their skin forces them to mainly shield against EMI through surface reflection [2].

Electromagnetic wave absorption is related to dielectric and magnetic losses [3]. Compared to traditional ferrite absorbents, metallic soft magnetic materials are a potential candidate for microwave absorption at high frequency over GHz [4]. Soft metallic magnetic nanomaterials are able to absorb EM waves at high GHz frequency, since they have both a dielectric and a magnetic loss, a high saturation magnetization with the result that the magnetic loss remains high in a high-frequency range [3]. The 316L stainless steel is a molybdenum-bearing low-carbon austenitic stainless steel. The 316L stainless steel fibers were produced using a cold drawing process [5,6]. During the cold working of 316L stainless steel, a strain-induced martensite transformation occurs, depending on the chemical composition, the cold working temperature, as well as the strain rate [5,7]. Most austenitic stainless steels are known to undergo martensitic transformation from a paramagnetic γ-fcc austenite to a ferromagnetic α'-bcc martensite by plastic deformation [5,8]. In ferromagnetic metal-based composites, the space charge polarization mechanism can be used to explain the frequency dependence of complex permittivity. Space-charge polarization occurs between adjacent metallic components and contributes to a high dielectric constant [9,10].

When polyester fiber is blended with stainless steel fibers to form a stainless steel/polyester (SSF/PET) blended yarn, the dielectric property of the SSF/PET blended yarn is anticipated. The EMI shielding mechanism of SSF/PET fabric is of particular interest for controlling the SE of the EMI. This study aimed to understand the electromagnetic wave shielding mechanisms of the SSF/PET fabric in terms of the overall effectiveness of EMI shielding. In this study we measured the electrical/magnetic/dielectric characteristics of the SSF/PET fabric, and analyzed the reflectivity, absorptivity, and transmissibility of the electromagnetic wave power for the SSF/PET fabric. In addition we investigated the contribution of magnetic loss and dielectric loss on the absorption of stainless steel fiber-enabled polyester textiles for EMI shielding.

2. Experimental

2.1. Materials

316L stainless steel fiber (SSF) with a 12 μm diameter was used in this work [5]. The stainless steel filament yarn (SSF yarn) had a linear density of 500 tex and consisted of 100% continuous

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stainless steel fibers. The SSF/PET yarns with a linear density of 40 tex were PET short fibers blended with stainless steel short fibers of 10 wt%, 20 wt%, 30 wt%, and 40 wt%, respectively. Here, 1 tex is the weight in grams of 1000 m of a linear material. Two kinds of fabrics were woven by SSF yarns and SSF/PET yarns, respectively. The SSF fabric woven from 316L stainless steel filament yarns and the SSF/PET fabrics woven from SSF/PET yarns with varied SSF wt% were about 0.5 mm thick.

2.2. *Characterization*

The 316L stainless steel fiber used here was characterized by a multipurpose thin-film x-ray diffractometer (Bruker, D8 SSS) with Cu-*K*α radiation, operating at 40 kV and 300 mA. The angular range was from 35° to 85° with a step size of 0.02°/s. The XRD profile was refined using the Rietveld Method which employs a materials analysis using diffraction (MAUD) software. The volume fraction of the crystalline phases of the fiber was estimated through a quantity process [5].

The electrical conductivity of the fabrics was measured by a low resistance meter (Loresta GP, MCP-T600) using a 4-pin probe method. The electrical conductivity value of each fabric was the average of nine measurements in a matrix. The magnetic hysteresis measurements of the SSF yarn and the SSF/PET yarns were performed using a superconducting quantum interference device magnetometer (Quantum Design, MPMS5) under the maximum magnetic applied field of 5000 Oe at room temperature. The complex permittivity of the SSF and SSF/PET fabrics was measured using a RF impedance/material analyzer (Agilent, HP 4291B) at room temperature with an applied frequency of 30–1500 MHz.

The reflectivity, absorptivity, and transmissibility of the electromagnetic wave power of the fabrics were evaluated using a network analyzer (Adventest, R3765CG) with two coaxial connectors and two attenuators (10 dB). The fabric was clamped between two coaxial connectors, measuring 133 mm in outside diameter. The transmission attenuation (S_{21}) and return loss (S_{11}) were measured at a frequency range from 30 MHz to 1500 MHz. The applied power was 1 mW. The transmissibility (T) and the reflectivity (R) of the EM wave power were calculated by the transmission and reflection spectra, respectively. All values were the average of three measurements. The standard deviation of the values was less than ±1.0 dB.

3. Results and discussion

3.1. *Crystalline phases of 316L SSF*

The 316L stainless steel is a molybdenum-bearing low-carbon austenitic stainless steel. The properties of 316L SSF are governed primarily by its chemical composition, microstructure, and drawing process. During the cold drawing of 316L SSF, a strain-induced martensite transformation occurs [5]. The XRD profile of 316L SSF is shown in Fig. 1. It was found that the crystal structure of the fiber consists of paramagnetic fcc-γ austenite crystalline and ferromagnetic bcc-α′ martensite crystalline phases. The volume fraction of the crystalline phases of the fiber was estimated using MAUD software. After refining the background, microstructure, and texture parameters, the volume fraction of each crystalline phase was obtained. The γ austenite crystalline and α′ martensite crystalline phases of the fiber were 38 vol% and 62 vol%, respectively.

3.2. *The electrical, magnetic, and dielectric properties of the fabrics*

First we should examine the crystalline phases of the SSF resulting in the specific electrical, magnetic, and dielectric properties of the fabrics. Fig. 2 shows the electrical conductivity of SSF and SSF/PET fabrics as a function of SSF wt% in the fabrics. The electrical conductivity of the fabrics was exponential, with a coefficient of determination (R^2) of 0.94, with SSF wt%. The contact resistance of the fabrics was taken as the performance of the effect of SSF wt% on the electrical conductivity of the fabrics. The electrical contact resistance was the sum of the constriction resistance and the interfacial film resistance [11,12]. The contact interfaces between the fibers and between the yarns resulted in a non-negligible contact resistance in the SSF and SSF/PET fabrics. The discontinuity of the stainless steel short fibers in the SSF/PET fabric increased with the decrease of the weight ratio of the SSF in the SSF/PET fabrics, resulting in an increased contact resistance of the SSF/PET fabrics. It was evident that the contact resistance between the SSFs exponentially decreased the electrical conductivity of the SSF/PET fabrics with the decrease of SSF wt%.

The ferromagnetic α′ martensite phase had the characteristic of a magnetic hysteresis loop. The magnetization hysteresis loop measurement indicates that the product has a ferromagnetic character [13]. The magnetic hysteresis loss is induced by the irreversible domain movement and magnetic moment rotation of magnetic material [14]. The magnetic hysteresis loops of the ferromagnetic SSF yarn and SSF/PET yarns with varied SSF ratios were measured (see Fig. 3). The area of the magnetic hysteresis loop represents an energy loss per unit weight of the yarn within a magnetization-demagnetization cycle. In the SSF/PET fabric, the PET fiber was diamagnetic. In this study the measured magnetization of the PET fiber was −0.04 emu/g at a magnetic field of 5000 Oe at room temperature. The value of diamagnetic PET fiber in SSF/PET yarns was small. It can be ignored in this work. The saturation magnetization of the SSF yarn was 37 emu/g at a magnetic field of 1500 Oe. The magnetic hysteresis loss of SSF yarns and SSF/PET yarns with varied SSF weight ratios are shown in Fig. 4. It was found that the magnetic hysteresis losses of the yarns were proportional to the SSF weight ratio in the yarn.

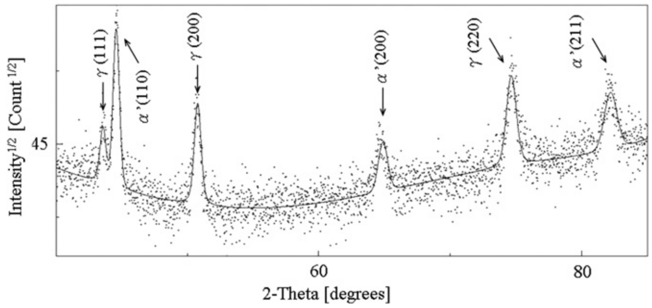

Fig. 1. XRD profile of 316L SSF.

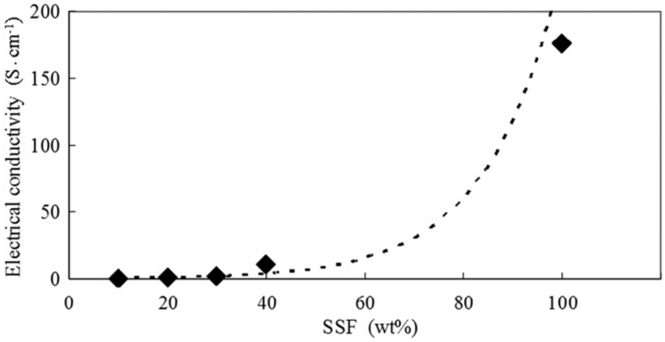

Fig. 2. Electrical conductivity of the fabrics as a function of SSF wt%.