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Laser surface modification of electrically conductive fabrics: Material performance improvement and design effects

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ABSTRACT

Development of lightweight flexible materials for electromagnetic interference shielding has obtained increased attention in recent years particularly for clothing, textiles in-house use and technical applications especially in areas of aircraft, aerospace, automobiles and flexible electronics such as portable electronics and wearable devices. There are many references in the literature concerning development and investigation of electromagnetic shielding lightweight flexible materials especially textile based with different electrically conductive additives. However, only little attention is paid to designing and enhancing the properties of these special fabrics by textile finishing processes. Laser technology applied as a physical treatment method is becoming very popular and can be used in different applications to make improvement and even overcome drawbacks of some of the traditional processes. The main purpose of this study is firstly to analyze the possibilities of transferring design onto the surface of electrically conductive fabrics by laser beam and secondly to study of effect of surface modification degree on performance of conductive fabric including electromagnetic shielding ability and mechanical properties. Woven fabric made of yarns containing 10% of extremely thin stainless steel fiber was used as a conductive substrate.

1. Introduction

Electrically conductive fabrics have obtained increased attention for electromagnetic shielding and anti-electrostatic purposes, mainly because of their desirable flexibility and low weight. There are many references in the literature concerning development and investigation of electromagnetic shielding lightweight flexible materials especially textile based with different electrically conductive additives.

One way to create conductive fabrics is using minute electrically conductive fibers (metal, carbon, conductive polymer fibers). They can be produced in filament or staple lengths and can be incorporated with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity [1–7]. Another way represents conductive coatings on fibers or yarns by metals [8–11] or conductive polymers [12–15]. Fibers containing therein carbon black or other conductive particles can be also used [16,17].

Large amount of literature on preparation and investigation of properties of fabrics in which extremely thin stainless steel staple fiber is incorporated can be found. For example, electromagnetic shielding of woven fabric made of 40 tex PET yarn containing different portion of stainless steel short fibers ($d = 12\ \mu m$) was reported in [18]. The transmissibility of electromagnetic wave power of the fabrics with 10 wt%, 20 wt%, and 30 wt% stainless steel fiber was close to 0% at a frequency ranging from 500 MHz to 1500 MHz. The electromagnetic shielding of the fabrics shows an absorption-dominant mechanism while a shift from absorption to reflection was observed with a decrease in metal fiber percentage as well as with an increased frequency.

In this article [2], similar type of conductive component, i.e. stainless steel short fiber ($d = 8\ \mu m$), was used for production of yarns, and woven and knitted structures were prepared. An effect of metal fiber content, a placement of conductive yarn, geometry of the textile structure, number of layers, material of the nonconductive component, moisture content and correlation with frequencies were studied. It was found that electromagnetic field shielding ability of fabric can be controlled by: (a) content of conductive component in hybrid yarn, (b) hybrid yarn density, (c) thickness of fabric using e.g. multilayered system, (d) moister con-

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tent, (e) type of nonconductive component and (f) compactness of structure.

Influence of washing and drying cycles on the electromagnetic shielding ability was studied in [19]. In this case, hybrid yarns were composed of conventional polypropylene fiber (85 wt%) and staple Bekinox stainless steel metal fiber (15 wt%). Despite the relatively significant increase of electric resistivity after washing, the samples did not totally lose their electromagnetic shielding ability. After applying 20 cycles of wet processing, electromagnetic shielding effectiveness at frequency 1.5 GHz dropped by 9.5% to 29.4 dB for the woven sample compared to reference (unwashed) samples. Electromagnetic shielding ability remained almost the same for the knitted sample at frequency 1.5 GHz after 20 cycles of washing/drying.

Despite many published papers dealing with development and characterization of electrically conductive fabrics containing extremely thin stainless steel fibers as a conductive component, only little attention is paid to designing and enhancing visual characteristics of these special textiles by textile finishing processes.

Changing appearance and visual characteristics of fabrics by applying certain designs to the texture and surface of textiles according to expectations of consumers and therefore increasing their added value is a desired effect in the textile industry [20]. Patterning during weaving and knitting processing using input material of different properties (color, fineness, etc.) represents one way how to get certain design. However, this method is not flexible enough (especially using special conductive yarns). It is time consuming due to problems in work flow and it is unable to apply the original forms, writings and designs on the product. Usage of design-oriented finishing represents another way how to get special design on to the fabric which is already prepared. The color and pattern of textile materials in a particular design can be achieved by dyeing, printing, and other finishing techniques.

In the last decade, laser technology has been used to enhance visual and tactile characteristics of fabrics to create new structures and surfaces, often by combining conventional textile techniques with laser processing [21] as laser technology is a low-energy, dry and efficient approach that does not involve chemicals and is therefore considered environmentally friendly.

The use of laser beam enables to cause controlled deformation on textile surfaces and thus create new designs by making use of the polymeric and heat-sensitive materials in the structure of the fabric [20]. Certain adjustment of laser beam (power, wavelength) is possible according to the nature of substrate and various adaptations of patterns can be created by means of certain adjustment. Another effect represents visual features of textile surfaces which becomes wrinkled and three-dimensional by means of deformation as well as designing on leather. The same mechanism can also be used for the purpose of cutting and creating designs through cutting [20].

In this study, electrically conductive and electromagnetically shielding woven fabric was modified with CO_2 laser technology to engineer pattern on to the fabric with high-resolution graphics. Laser patterns were generated by CO_2 laser technology involving preparation of design in graphical software. The work considers the aesthetic possibilities, production opportunities and also effect of degree of surface modification connected with various laser treatment parameters on performance of patterned conductive fabric including mainly electromagnetic shielding ability and mechanical properties. Furthermore morphology and color change of modified samples was studied by the help of SEM and image processing. An understanding of levels of color of modified samples was used to define the optimum laser energy for application. Material changes of laser irradiated samples were explored using infrared spectroscopy. Woven fabric with twill 2/2 weave made of conductive yarn containing 10 wt% stainless steel staple fibers was used as a substrate.

2. Experimental

2.1. Materials

2.1.1. Hybrid yarns

Hybrid yarns were composed of conventional polyester (PET) fiber (59 wt%) and cotton (CO) fiber (31 wt%). Both nonconductive fibers had white color. As a conductive component staple BEKINOX stainless steel (SS) metal fibers (10 wt%) were used. This particular percentage of conductive fiber was chosen with respect to previous studies [2,3]. Usage of 10% metal fiber guarantees electrical conductivity close to the percolation threshold of conductive component and achieves satisfactory electromagnetic shielding performance of fabrics made of these metal fiber containing yarns. On the other hand, this particular content of conductive fiber does not change significantly process ability of the yarns and fabrics made of. Also physiological properties, roughness and appearance of fabrics made of these yarns are comparable with traditional fabrics used in the textile area. The aspect ratio (length/diameter ratio, l/d) of the SS used in this study is 5625, since the diameter of the SS is 8 μm and the average fiber length of the SS is 45 mm. These three components were mixed at the drawing frame and a ring spinning system was used to produce blended single yarns with linear density 30 tex.

2.1.2. Hybrid fabric

Metal fiber containing fabric for patterning was created using hybrid yarns described above. Hybrid fabric has twill 2/1 weave made of 100% of conductive yarn (warp sett 39 1/cm, weft sett 22 1/cm). The characteristics of the hybrid fabric are shown in Table 1.

2.2. Methods

2.2.1. Laser irradiation

Irradiation of conductive sample was carried out by commercial pulsed CO_2 laser (Marcatex 150 Flexi, Easy-Laser) under atmospheric condition in the air [22]. The laser is used for cutting and marking textiles and produces laser beam of wavelength of 10.6 μm. The samples were irradiated by the laser beam directly on one side of the fabric. The duty cycle and pixel time was set constant to 50% and 100 μs. Laser power was 100 W at duty cycle 50% and frequency 5 kHz. Threshold color as well as threshold pointer were set to 220.

2.2.2. Laser patterning method

Digital laser patterns were formed with multiple tones generating a tonal spectrum. High-resolution capability of the laser beam spot when modifying textile fabric enabled patterning likened to "dots-per-inch", as in digital printing processes. Raster beam scanning method was used for patterning, Adobe Photoshop was used to create files and laser software was used for laser processing.

A grayscale design approach was used for laser image depiction and variable modification levels of the textile surface in the form of percentages of black (gray scale GS) [%] – e.g. 30%, 60%, etc. which represent intensity of an input image pixels within given range between minimum and maximum. This range is from 0 (total absence of intensity, white) to 1 (total presence, black), with any fractional values between. Different percentages of black influence energy density of laser and therefore variable power output is controlled. When combined with special laser parameters, this system