The Incorporation of Thermocouples in Knitted Structures

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ABSTRACT

Recent developments in textiles have led to the manufacturing of a variety of fabrics. These developments include spacer fabrics, embroidered fabrics, embedded sensors in fabrics, ECG vests, etc. Electronic components are also being knit within fabrics. The study used a configuration of thermocouples, based on the Seebeck effect, knitted into the main structure using a variety of yarn filaments. The knitted fabric was tested against temperature variation to examine how it affects the impedance of the knitted thermocouples. The testing procedure produced promising results, as it showed that certain combinations of knitting materials may result in positive and negative temperature coefficients of the fabric. The combination of the tested materials provides a guide to developing similar structures for thermoelectric sensor applications.

Keywords-knitted fabric; Seebeck effect; technical textiles; thermocouple; temperature sensing

I. INTRODUCTION

Washable and reusable fabrics have been developed in the form of embedded sensors or a combination of embedded and printed electrodes [1-4]. These fabrics have the advantages of individuality and adaptability to varying climatic conditions and are useful in postoperative, athletics, firefighting, law enforcement, and other conditions [5]. In [6], an approach for a temperature-measuring fabric was presented by encapsulating a commercially available thermistor in knitting yarns. Another scientific approach is to embed temperature sensors in knitting fabrics to measure the temperature of human skin [6-8]. This was part of a series of temperature-sensing electronic fabrics, including armbands, socks, and glove-knit electrodes. In [9], such fabrics were developed and tested under a variety of loading mechanisms, such as stress-compressed. Many developments have been reported in several areas of technical textiles. In [10], a built-in fabric sensor was presented that was able to measure variations in basic parameters such as force, pressure, water content, and thermal activity. Although the material developed remained customizable, there was a trade-off to its robustness compared to the classical family of such sensors. In [11], the materials used for temperature sensing in technical textiles were discussed following the Seebeck effect and the principle of the Peltier effect. In [12], a set of wearable textiles was developed using a range of silver-coated conductive yarns with varied specifications. The behavior of knitted textile impedances developed as a result of knitted fabric using yarns doped with conducting materials was investigated, and the electrothermal performance was calculated to suggest the use of optimum fabric for use in electrothermal garments and other applications.

In [13], several metal-doped filament yarns were used to knit a fabric that would be used as a shield against electromagnetic radiation. In [14], a weft-knitted fabric structure was developed using silver-coated yarn and lycra, based on the variation in resistance values in a variety of knitted fabrics. In [15], a fabric for temperature sensing the human body was developed, using standard available temperature sensors embedded in the fabric during the knitting process. In [16], a knitted glove was presented that incorporated embedded sensors of metal-coated yarn with a base of non-conducting ordinary yarn to respond as strain gauges. The glove was tested for pattern recognition of hand gestures, and the experimental procedure was mainly based on the resistance variation of the developed sensor, which is the basis for a standard strain gauge. In [17], a low-profile knitted antenna was presented for use in wireless body area networks in a bandwidth range of 1.4 GHz. In [18], a wearable antenna was presented and its dielectric properties were tested, focusing on the behavior of the antenna when bent at a certain radius. In [19], flexible strain sensors were presented within a knit structure and tested for human motion detection in a 3D setup. The experimental results showed that it produced very close to realistic human motion sensing. In [20], knitted sensors were used to monitor the body and its surrounding temperature.

In 1834, Peltier discovered that in a junction between two dissimilar metals, a flow of current was established when the junction was subjected to a hot or cold situation. Figure 1 shows a basic standard set-up of a thermocouple. The equation governing such an arrangement is given by:

$$\Delta U = \alpha(\Delta T)$$

where ΔU is the difference in the Seebeck coefficient of two metals and ΔT is the temperature difference between the hot and cold junctions.

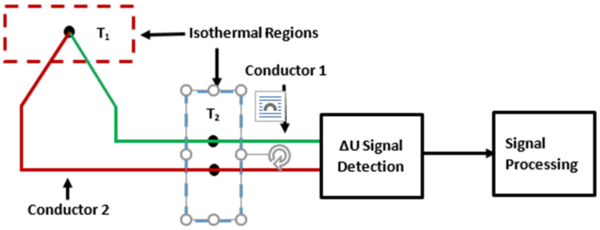

Fig. 1. Thermocouple model and signal conditioning.

The current study used conducting yarns to act as a basic Thermocouple (TC) knitted arrangement. These TCs act as an array of temperature-sensing elements at each junction of knitted stitches. Therefore, they are capable of sensing temperature variations in their vicinity or on the surface to which they are subjected. The TC can easily be adjusted to become a part of any knitted structure. The two basic yarns act as scaffolds for the knit structure and have different enrichment metals doped into them. Therefore, when these yarns are incorporated into a knit structure, they act as a loose form of a thermocouple junction. This suffices for the appearance of impedance variation at the output terminals of the fabric. This variation in impedance is a function of change in temperature. The change can be linear or exponential, depending on the choice of the conducting yarns. In addition to basic developments in technical textiles, a high number of applied fields have been explored in this area.

II. DESCRIPTION

Basic knit structures can be used in various combinations and beneficial ways. This can be achieved using a variety of conducting and semiconducting material-enriched filament yarns. In basic categories of knitting, there are the weft and warp knitting methods. Figure 2 shows the simplest weft-knitted structure, while Figure 3 shows a tuck loop within the weft-knit. This is the very loop used for the realization of the fabric under consideration.

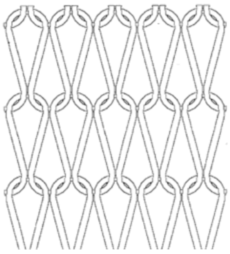

Fig. 2. Basic weft knit.

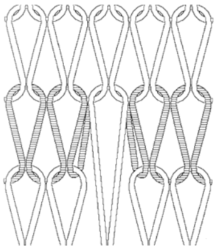

Fig. 3. A tuck loop within weft knit.

A range of platforms can be used to insert conducting wires and filaments in a knit structure, ranging from single-layer to multiple-layer fabrics, depending on the cause and target application. However, this study used a single-layer setup. The samples were knit on a flatbed machine with a modified feed arrangement, as shown in Figure 4.

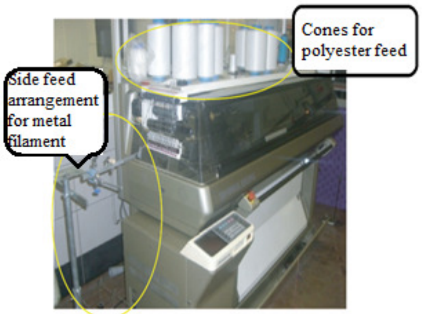

Fig. 4. Flatbed machine with side feed arrangement.

A range of metal yarns and filaments were used to knit fabric samples. These materials were procured from various manufacturing resources and supplied in the form of small spools or reels. It was not feasible to use them as such on the knitting machine due to various reasons, such as repeated wire breaks due to friction with the flanges of the spools and the tension in the wire. Each sample was developed in such a way that the combination of wire/filament was sufficient to withstand the Seebeck effect. The Seebeck effect is supposed to work very effectively when there is a strong connection/conductive bonding between two different metals. However, in the experiment, a loose connection between the two metals was inevitable because of the knitting process. This led to some promising results, whereas, the connection between the two yarns was in the loose form. This idea was incorporated into the knit structures using a few combinations of metal and metal-enriched yarns. These yarns were used as part of knitted structures, as shown in Figures 5-9.

Fig. 5. A sample using stainless steel and tungsten yarns.

Fig. 6. A sample using two tungsten yarns of varying diameter.

Fig. 7. Silver enriched yarn with stainless steel wire of 0.15 mm diameter.

Fig. 8. Stainless steel yarn and wire of 0.15 mm diameter.

Fig. 9. Silver and nickel-coated yarns.

Due to the knit pattern, both metal yarns had a loose connection to each other, so each crossing of the yarns acted as a loose thermocouple. These loose connections behave as a large number of thermocouples connected in a series arrangement. Therefore, a small change in impedance occurs at each junction, which then adds up to show a considerable change in the readings at the output terminals of the fabric. As a result, the knitted fabric by this technique has several advantages over the conventional thermocouple. The resulting fabric was washable, wearable, durable, and flexible, opening more avenues for thermocouple applications. The range of applications could range from very basic to sophisticated applications, such as those in the medical and sports fields.

III. THE EXPERIMENT

Several knit fabric samples were developed, with different metal yarns and knit patterns. The output terminals of each sample were connected directly to a digital Ohm meter. A Fisher Scientific hot plate was used for the gradual heating of each sample. Each sample was covered with a plane piece of ceramic when placed on the hot plate to provide rigidity and a uniform environment to the sample. Figure 10 shows the experimental setup. Each sample showed variations in the overall impedance of the incorporated thermocouples across the conducting leads, depending on the type of metal used. The overall impedance of conducting junctions in the samples was the result of temperature variation.

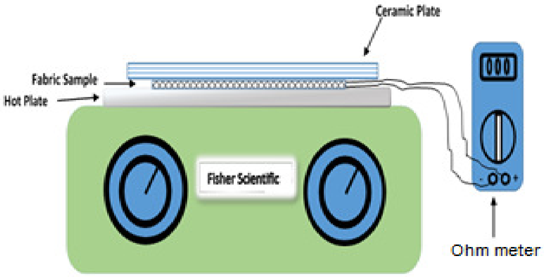

Fig. 10. Experimental arrangement for fabric heating up.

IV. RESULTS AND DISCUSSION

A selection of metal-enriched yarns and thin wires was used to knit a total of 10 samples. Each sample was tested for its response to temperature variation. The samples were chosen for their good response to thermal variation.

Figure 11 shows the results for a knit combination of fine stainless steel and tungsten wires. Due to the nature of the combination, a limitation in the temperature range was found. A nearly linear relationship between the temperature and the observed impedance was observed. The temperature range covered in this case was 31-73^{o}C. The impedance response was stable in certain temperature ranges. However, the largest span of impedance stability was in the temperature range of 35-38°C.

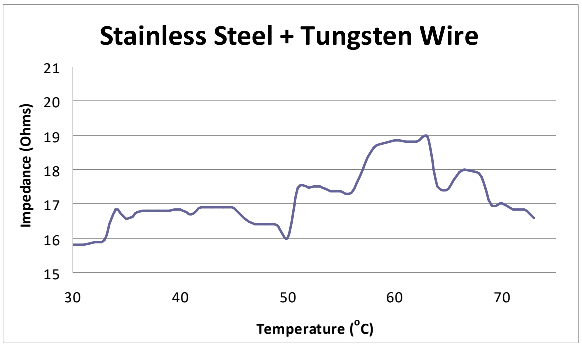

Fig. 11. Combination of stainless steel and tungsten wires for knit sample.

Figure 12, shows the results obtained using tungsten wires for both conductors. However, the diameter chosen for the two conductors was different, as mentioned in the title of the figure. In this case, the results were very encouraging compared to those obtained in Figure 11, as it shows more linearity in the impedance variation for temperature changes. The temperature range covered in this case was 35-90^{o}C.

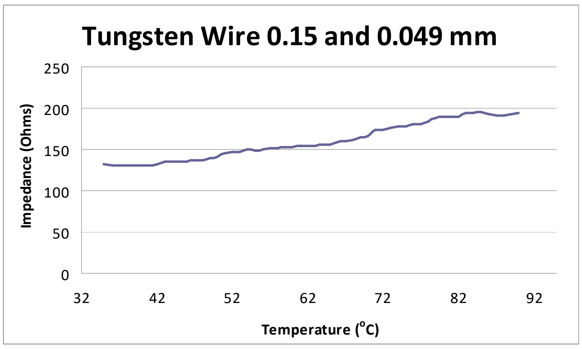

Fig. 12. Tungsten wires used for both conductors.

Figure 13 presents the results for a knit sample using a combination of stainless steel and silver-enriched yarns. In the experiment, 50% of the junctions were bonded using conductive adhesive. The variation in impedance was observed to be linear. However, dips in the plot appear due to the flexibility of the filament yarns at the junction of the two metals.

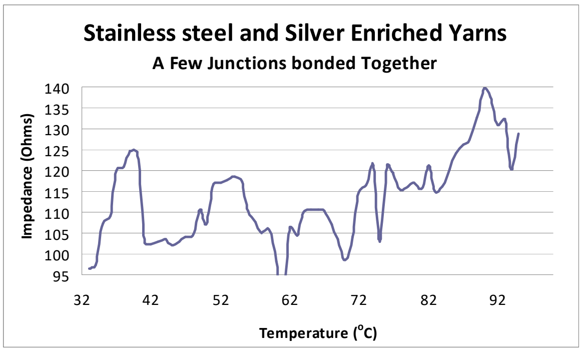

Fig. 13. Combination of stainless steel and silver-enriched yarns.

The combination of stainless steel enriched yarn and 27% nickel-coated copper filament was tried. Two knit structures were developed for this combination. The first was a complete knitting pattern and the other had a pattern with a miss out of 3 stitches. Figures 14 and 15 show the excellent linear relationship between temperature and impedance in both cases.

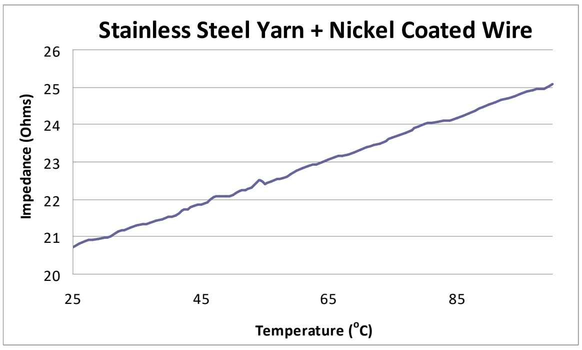

Fig. 14. Combination of stainless steel-enriched yarn and nickel-coated copper wire in a complete knit sample.

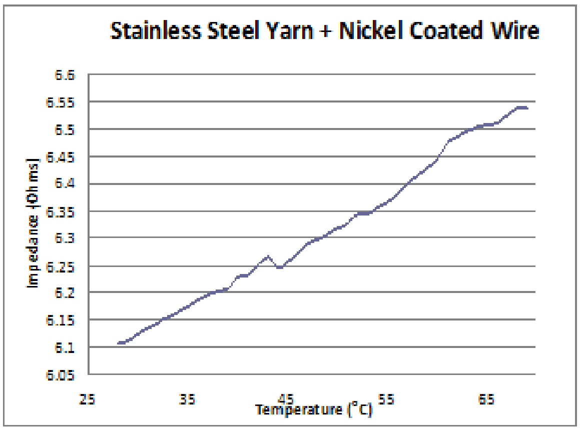

Fig. 15. Combination of stainless steel enriched yarn and nickel-coated copper wire in the 3 missed-out stitches in the knit sample.

A further combination was tried to achieve a good linear relationship between temperature and impedance variation, using silver-enriched yarn and nickel-coated copper wire. In this case, a round trip of temperature variation was carried out. Figure 16 shows the results.

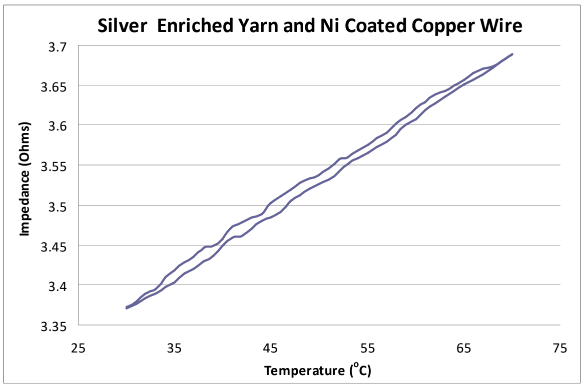

Fig. 16. Combination of silver-enriched yarn and nickel-coated copper wire in the knit sample.

The data obtained from the custom knit samples show that their performance was very satisfactory in terms of the aim of this study. The performance of the incorporated thermocouples is great compared to that of the investigations discussed in the introduction of this article. The novelty of this work is the flexibility, durability, and washability of the thermocouples compared to the classical ones, which are rigid in physical nature, thus making their application difficult in specialized situations in general engineering and medical applications. In the medical field, such samples can be easily used to avoid bedsore situations.

V. CONCLUSION

The materials used to develop the samples showed diverse responses to the subjected temperature changes. This experimental study was conducted to collect consistent data. However, the samples worked based on positive and negative temperature coefficients. The establishment of the coefficient in the positive or negative direction was due to the choice of combination of metals used in the samples. The results of the knit structures were found to be satisfactory. This study can be used as a guide for developing thermosensitive knit structures. Such structures are long-lasting and can be used for temperature sensing in various applications that have access difficulties, such as medical, sports, and other high-tech fields.

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