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EFFECT OF TENSILE FATIGUE CYCLIC LOADING ON PERFORMANCE OF TEXTILE-BASED STRAIN SENSORS

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ABSTRACT

Textile-based strain sensors are a potential platform used in wearable devices for sensing and. 8 sensors containing monitoring the human body. These sensors not only have all the conventional sensors benefits but also, they are low-cost, flexible, light-weight, and easily adopted with three-dimensional shape of the body. Moreover, recent research has shown they are the best candidates for monitoring human's body motion. In this study, the effect of tensile fatigue cyclic loads on performance and sensitivity of textile-based strain sensors was investigated polyester/stainless steel staple fiber blend yarn as a conductive part with different structures were produced. The sensors varied in weft and warp density, percentage of stainless steel in conductive yarn, the number of conductive yarns, and weave pattern. The sensors were subjected to 500 cyclic loads operations and their tensile properties and sensitivity were investigated and compared before and after applying tensile fatigue cyclic loads. The results showed the textile-based strain sensors containing less percentage of stainless-steel fiber, lower number of conductive yarns, twill weave pattern and lower density in warp and weft direction have shown better performance after tensile fatigue cyclic loads.

KEYWORDS

Tensile fatigue cyclic loading; Strain sensor; Smart textile; Conductive yarn; Woven fabric; Sensitivity.

INTRODUCTION

In the last decade, the products of the textile industry have found especial applications in the field of intelligent textiles, so the use of electrical fibers, yarns, and textiles is growing rapidly [16]. Electronic textiles (e-textiles) known as smart textiles are structures with conductive properties that can be used in a variety of applications such as sensors, communication, health care, computation, thermal purposes, protective clothing, wearable electronics, and fashion [7]. Electronic textiles can be produced by different methods such as weaving, knitting, embroidery and printing [10]. Sensors convert non-electrical physical or chemical quantities into electrical signals or other recognized electronic outputs [18]. Textile-based sensors especially strain sensors are desired because of their flexibility, ease of deformation, elastic recovery and fatigue resistance [18]. Strain deformation in e-textiles can be sensed in different mechanisms such as piezoelectricity, optical diffraction or interferometry, capacitance and piezoresistance. The must usual strain sensors in smart textiles are piezoresistive because of their manufacturing process and ease of use [11,19]. The "piezoresistive" term refers to materials that change their electrical resistance by applying mechanical force due to microstructure change in conductive materials [3]. As mechanical force is applied to piezoresistive material, a mechanical deformation occurs. These deformations may change the electronic properties; therefore, the resistance will change [4]. As the force is removed, the electrical resistance regains regard to re-establishing structures [2]. The resistance can be evaluated by equation (1) which R is electrical resistance, ρ is the resistivity of material and A and L are the area and pathway length which the current flows respectively [12]. To evaluate the performance of a strain sensor, required information about the key parameters such as sensitivity, limit of detection (LOD), linearity, response time, and stability is needed [19].

$$R = \rho \frac{L}{A} \tag{1}$$

Fatigue is defined as the failure of a structure or component due to repetition and a load cycle which is less than a load to cause failure of the structure in a single application [14]. The failure occurs due to the cyclic nature of the load which causes microscopic material imperfections to grow into a

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macroscopic crack [6]. Fabrics are subjected to tensile cyclic loads in different applications. Therefore, the study of the fatigue behavior of textiles in some applications such as sportswear is very important [17]. The fatigue failure in textiles usually is due to a reduction of elasticity during textile consumption. Fabric properties such as fabric density, weave design, yarn type and structure and material may affect the fatigue behavior of fabric [6].

There are many research work related textile-based strain sensors and their application. Shanbeh et al. produced woven strain sensors with different electrical conductivity and weft densities. They analyzed the effect of two different percentages of stainless-steel fibers in staple blend yarns that used in purpose-built strain sensors. They compared the sensitivity of strain sensors during 5 times cyclic loading. Their study showed that sensors containing less stainless-steel fiber have better performance. Moreover, the textile base strain sensor behavior during tensile cyclic loading wasn’t stable. They claimed the electromechanical behavior of sensors under tensile loading is due to crimp, fiber migration, conductive fibers contact points and yarn diameter variation. [13]. Guo et al. presented four different textile-based strain sensors; two of them were conducted by coating and others by using conductive yarns in weaving process. Linear range of the sensor’s work was reported [8]. Fen et al. developed a polyaniline (PANI)-coated polyurethane (PU) fiber with conductivity of $10^{-2}\Omega/\mathrm{cm}$. They used fibers as a piezoresistive strain sensor which were subjected to 1500% strain deformation. The results showed that the resistivity was increased by applying strain but there were 3 different intensities. Furthermore, the fibers were under tensile cyclic loads on maximum 50% of strain level which results revealed the reversible response on the sensor. However, the reversibility wasn’t absolute due to the hysteresis [5]. Liang et al. analyzed 16 knitted strain sensors’ performance parameters such as sensitivity, linearity, hysteresis, responsiveness and fatigue during dynamic and static process. The sensors were made of three different materials consisting of a fabric coated with a conductive polymer, spun stainless steel yarn and silver-plated with different material composites. The sensors were tested at 10% strain and 100 times load-unload cycles. The results showed that sensors made of silver-plated yarn performed the best among other sensors. Moreover, sensors made of stainless-steel yarn performed the worst, because of knitted fabric properties [9]. Teyeme et al. developed a piezoresistive strain sensor from conductive fabric. The sensor had a stable dynamic response after 30 seconds, therefor they reported this sensor was suitable for slow-moving applications. They also found that the sensor wasn’t sweat independent. Thus, they conclude the sensor was not acceptable for sports applications [15].

In this work, we study effect of tensile fatigue cyclic loading on performance of textile-based strain sensors. Moreover, effect of different structural parameters of textile-based strain sensors on their performance during tensile fatigue cyclic loading was evaluated.

EXPERIMENTAL

Materials

Eight different textile-based strain sensors were woven by using two different conductive yarns produced by Xiamen JL-fiber Science and Technology Co. Ltd., Xiamen, China. The conductive yarn was polyester/stainless steel staple fiber blend. The fineness of stainless-steel fiber was 12μm. Tensile properties of yarns were measured by Zwick tensile tester, which works based on constant rate of elongation. In Table 1, the properties of yarns are shown.

The sensors were produced by polyester filament yarn (75 den) as warp with two different densities (23 and 40 per cm). The conductive yarns were used as weft in combination with polyester filament/spandex yarns in two different densities (15 and 25 per cm). In designated textile-based strain sensors two different numbers of conductive yarns i.e. 9 and 20 was inserted. In Figure 1, the picture of one produced sample is illustrated. Moreover, the samples were produced with Plain and Twill (2/1) patterns. Optimax rapier weaving machine with 180 width and 450 PPM speed was used to produce all samples.

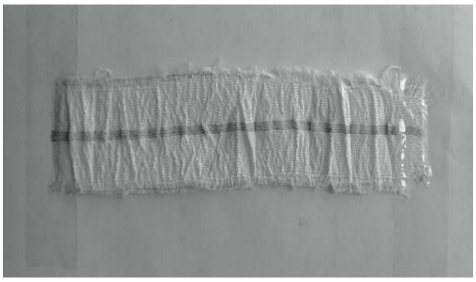

Figure 1. Textile-based strain sensor

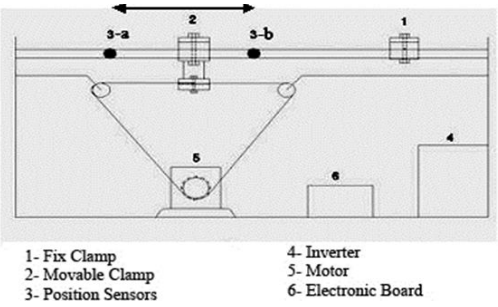

Figure 2. The schematic of equipment used for cyclic load [1]

Table 1. Mechanical and electrical properties of conductive yarns.

Yarn code	Percentage of stainless steel (%)	Nominal Count of yarn (Ne)	Breaking elongation (mm)	Breaking strength (cN)	Resistance (Ω/m)	Yarn diameter (μm)
A	28	20	3.080	31.604	2982	248.25 μm
B	40	20	3.246	28.228	2307	249.46 μm

Table 2. Specifications of samples.

Sample code	Conductive yarn code	Number of conductive yarns	Weave pattern	Warp density (1/cm)	Weft density (1/cm)	Shrinkage (%)	Test speed (mm/min)	Breaking Strength (N)	Breaking Elongation (%)
1	A	9	Plain	40	15	32.4	230	56.20	174.76
2	A	20	Plain	40	15	24.2	230	78.04	129.26
3	B	9	Plain	40	15	29.5	230	55.63	154.87
4	B	20	Plain	40	15	21.3	230	61.00	128.30
5	A	9	Plain	40	25	29.6	140	175.02	89.70
6	B	9	Plain	40	25	15.7	130	187.49	82.56
7	B	9	Twill	40	25	15.7	210	143.10	251.07
8	B	9	Plain	23	25	16.5	140	146.22	152.08

Methods

For measuring sensors' sensitivity and resistance variation of textile-based strain sensors during tensile test an electronic circuit was used which the strain sensor was one of the resistors series with other reference resistors as proposed by Guo et al. [8]. A purposed-built instrument was used for applying cyclic loads on sensors which is shown in Figure 2 [1]. The details operating method of instrument was explained in reference 1.

The dimension of textile-based strain sensors was 25 × 200 mm. The samples were then subjected to wet relaxing process. Samples were immersed in 90° water for 10 minutes. Then, they were dried in ambient temperature and the shrinkage percentage was calculated by equation 2 which l_1 is the initial length of sample and l_2 is the length of sample after wet relaxation.

$$shrinkage(\%) = \frac{l_1 - l_2}{l_1} \times 100 \qquad (2)$$

Tensile properties of samples were tested in weft direction based on ASTM-D5034 (2007) using Zwick tensile tester. In Table 2, the specifications of samples are shown.

The samples were tested in 10 cyclic loading at 50% of breaking strain level in weft direction. The resistance variation was recorded during cyclic test. The sampling rate was set at 10 per second similar to 10 Hz in frequency.

The sensitivity of each sensor was calculated using equation 3, which G is sensitivity of the sensor, V_{max} and V_{min} are the maximum and minimum voltage that has been recorded in each tensile cyclic load from beginning to end and ε is strain. The average sensitivity of 10 cycles was considered as sensor's sensitivity.

$$G = \frac{(V_{max} - V_{min})/V_{min}}{\varepsilon} \qquad (3)$$

Each sample was subjected to 500 tensile fatigue cyclic loads. They were loaded up to 50% of its breaking elongation and 3.4 Hz cyclic loading frequency was set, based on average running speed of a normal person.

The microtomy technique was used to evaluate the width cross-section of conductive yarns before and after tensile fatigue cyclic loads. The sensitivity of each sensor was also measured 24 hours after tensile fatigue cyclic loads test using mentioned methods

RESULTS AND DISCUSSION

In Figures 3a and 3b, the voltage variation of textile-based strain sensors before and after tensile fatigue cyclic loading of two samples is shown. By applying tension to the fabric, the yarns are subjected to compressive forces at interchange points. This pressure may cause the variation of yarns' cross-section and the more possibility of contact between the stainless-steel fibers into the yarn. Although, the electro-mechanical properties of all samples during tensile cyclic loads revealed the same trend but the effect of structural parameters of samples on voltage variation was observed. The electro-mechanical variation of samples during tensile cyclic loads may be influenced by woven fabric shrinkage after wet relaxation.

Figure 4 displays the sensitivity of textile-based strain sensors before and after tensile fatigue cyclic loading. The increase of contact pressure between yarns into fabric structure during tensile force could be the reason for compactness of yarns and therefore more possibility of conductive fiber contacts into yarn structure. This phenomenon may cause the decrease of sensitivity of samples during tensile cyclic loading.

As shown in Figure 4 the sensitivity of sample 2 after tensile fatigue cyclic loads decreased from 0.695 to 0.370 during 1st to 10th cyclic loading. Moreover, the sensitivity of sample 5 during tensile cyclic loading increased. The sensitivity (G) of eight textile-based strain sensors is shown in Table 3.

As can be seen in Table 3, the sensitivity of samples after tensile fatigue cyclic loading confirmed the structural variation of samples. It seems that the tensile fatigue cyclic loads in predetermined elongation may cause shrinkage removal of samples which cause the electro-mechanical variation of textile-based strain sensors.

It was observed that the sensitivity has a direct relation with conductivity of yarns before tensile fatigue cyclic loading, but this trend was not observed after tensile fatigue loading. The cross-section of conductive yarns (as shown in Figure 6) confirmed the fiber displacement in yarn cross-section which could be the reason for this phenomenon.

The textile-based strain sensor woven with plain pattern showed higher sensitivity compare with Twill 2/1 woven fabric before and after tensile fatigue cyclic loading. However, the sensitivity sample 7 woven with Twill pattern is more stable than plain ones (sample 6) that is maybe because of yarn float in fabric structure.

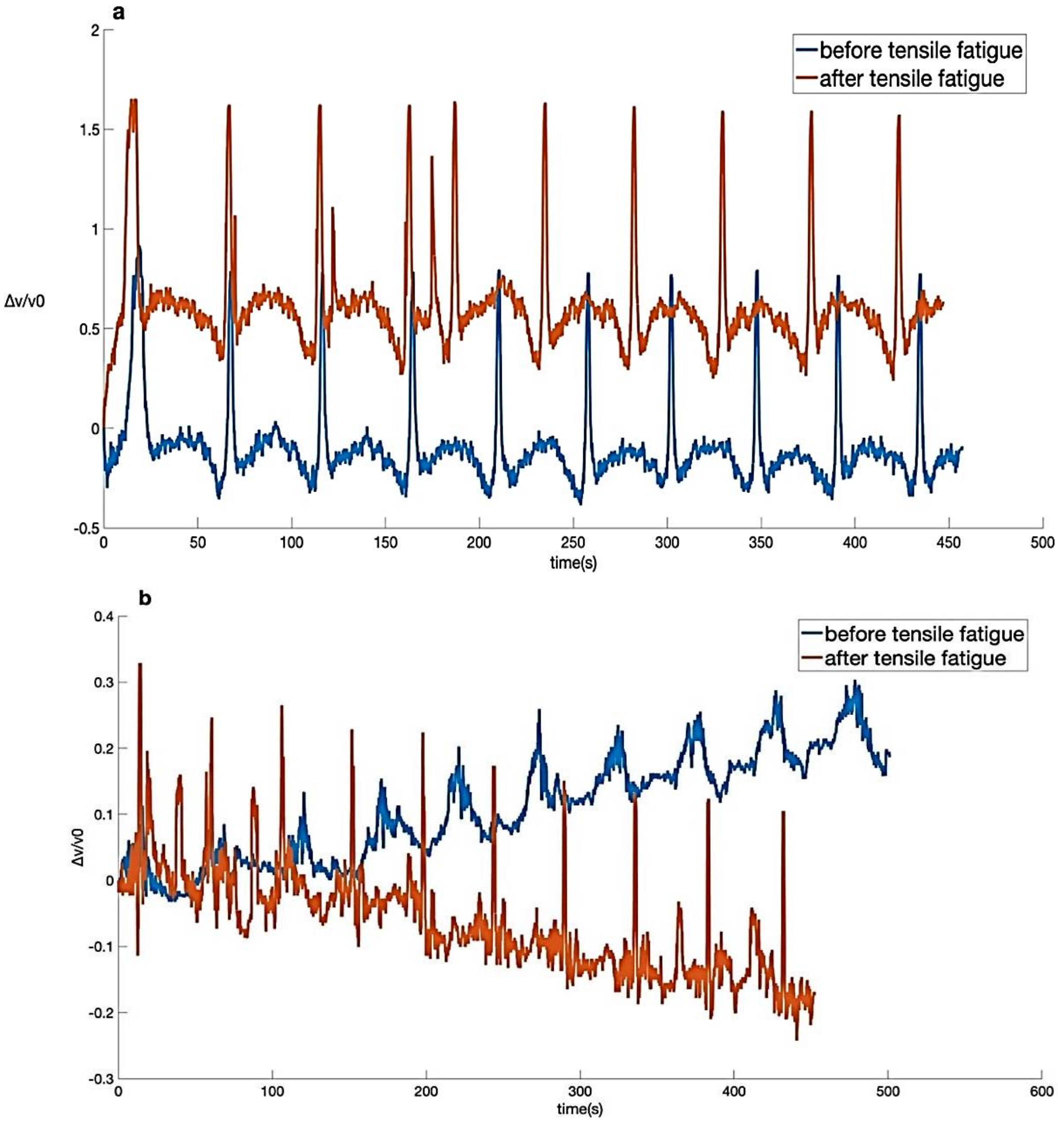

Figure 3. Voltage variation of two textile-based strain sensor during tensile cyclic loading before and after tensile fatigue cyclic loading. a) sample 5, b) sample 2. (The blue curve is before tensile fatigue cyclic loads and red curve after tensile fatigue cyclic loads.).

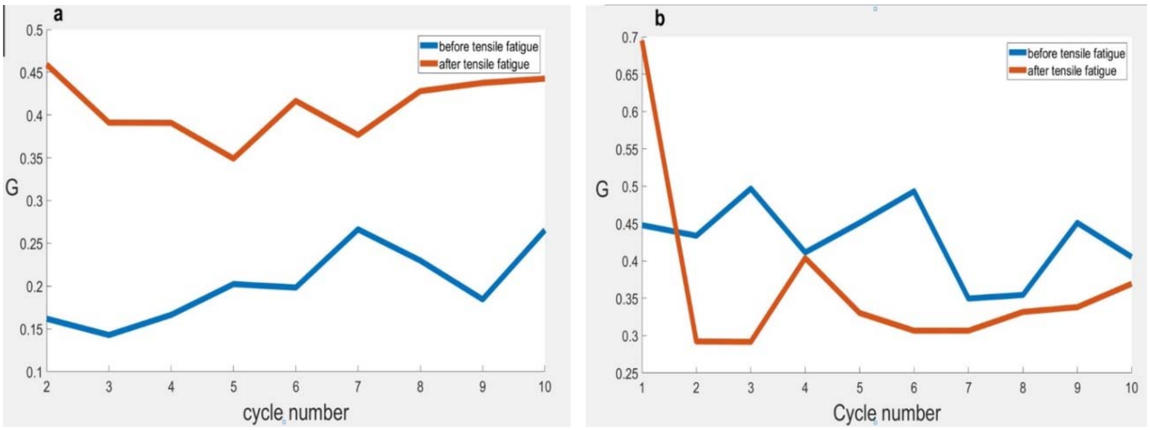

Figure 4. sensitivity (G) variation of two textile-based strain sensors during tensile cyclic loads before and after 500 tensile fatigue cyclic loading a) sample 5, b) sample 2. (The blue curve is before tensile fatigue cyclic loads and red curve after tensile fatigue cyclic loads.).

Table 3. The sensitivity (G) of textile-based strain sensors before and after tensile fatigue cyclic loads.

Sample code	Sensitivity of samples before tensile fatigue	Sensitivity of samples after tensile fatigue
1	0.156	2.29
2	0.131	0.409
3	0.138	0.171
4	0.273	5.22
5	0.205	0.420
6	0.131	0.409
7	0.409	0.402
8	0.838	0.358

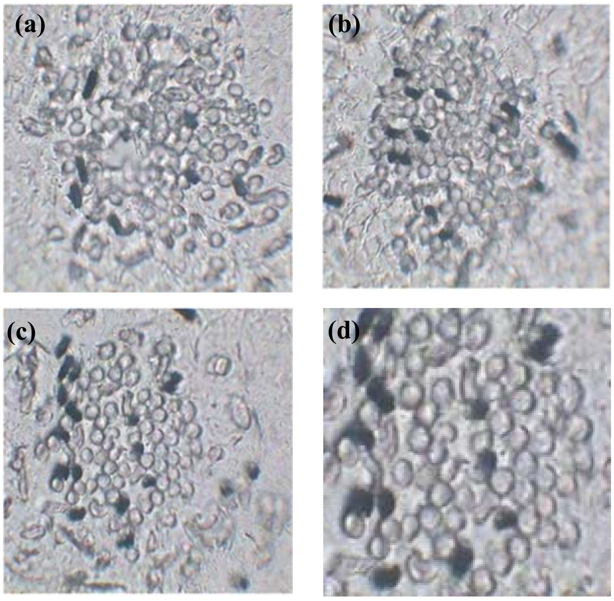

Figure 6. Conductive yarn cross-sections (a) before tensile fatigue cyclic loads of yarn A pulled out from sample 2, (b) after tensile fatigue cyclic loads of yarn A pulled out from sample 2, (c) before tensile fatigue cyclic loads of yarn B pulled out from sample 2, (d) after tensile fatigue cyclic loads of yarn B pulled out from sample 8.

It was found that by increasing the weft density, the sensitivity of textile-based strain sensors increased (As shown in Table 3). This trend can be because of lower shrinkage of woven fabrics with higher value of weft density. Moreover, by increasing the number of conductive yarns, the sensitivity or the voltage variation during tensile cyclic loading was increased. This observation could be explained by lower shrinkage values of samples produced by higher number of conductive yarns. It seems that the structural variation of these samples was prominent because of tensile fatigue cyclic loading.

CONCLUSIONS

In this study, 8 different textile-based strain sensors were produced by using weaving method. The sensitivity and electro-mechanical properties of samples during tensile cyclic loading showed the effectiveness of tensile fatigue cyclic loading. Moreover, the evaluation of cross-section of conductive yarns before and after tensile fatigue cyclic loading showed displacement of conductive fibers in yarn structure. Our finding confirmed the effect of percentage of conductive fibers in the yarn, weft and warp density, number of weft yarn, weave pattern on sensitivity and electro-mechanical properties of textile-based strain sensors after tensile fatigue cyclic loading. The minimum and maximum values of sensitivity before tensile fatigue loading was 0.131 and 0.409, respectively, but after tensile fatigue loading was 0.171 and 5.22. In future, we aim to work on effect of tensile fatigue cyclic loading parameters on sensitivity of textile-based strain sensors in different testing conditions.

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