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# Thermal-Mechanical Sensory Properties of Hot-Air Welded Textile Transmission Lines

## Original Scientific Article

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### Abstract

Hot air welding technology is one of the new promising techniques for integrating conductive yarns on or into fabrics, besides weaving, knitting, printing, coating or inserting conductive yarns by the sewing and/or embroidery processes. A new issue related to the introduction of hot air welding technology for making e-textile transmission lines, i.e., the mechanical-thermal sensory properties of hot air welded e-textile transmission lines, is investigated in this study. Fabric Touch Tester (FTT) was used to evaluate thermal, compressive and bending properties of hot air welded transmission lines. The results show that the bending of welded fabric increased after hot air welding in both warp and weft directions. Furthermore, the maximum thermal flux and thermal conductivity of welded specimens decreased in comparison to the substrate fabric.

Keywords: hot air welding, textile transmission line, Fabric Touch Tester, thermal-mechanical properties

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## 1 Introduction

The touch feeling can be perceived through contacts between the human body skin and the fabrics surfaces. Four types of touch information including thermal, proprioceptive, cutaneous, irritating and painful arise when a fabric touches the skin [1]. A smart protective garment with integrated electrical elements brings many benefits and advantages to the users. During a working day, the use of a protective clothing lasts up to the eight-hour period of time. That is why the garment comfort requirements are very important and should be taken into account when such garment is designed. When designing smart protective garments and wearable electronics, many factors from the concept and purpose of the garment to wearable devices have to be considered. The embedded electronic devices and

their auxiliaries have to satisfy the aesthetic and comfort requirements of end-users.

The properties of conductive yarns integrated into fabrics can drastically affect the properties of these fabrics. There are different textile technologies that have been used to embed conductive yarn on or into textile materials: weaving and knitting technologies, sewing and embroidery techniques, printing or coating electro-conductive polymers.

In the last few years, the hot-air welding technology was introduced as a new technological approach for adhering conductive yarns onto the fabric surfaces to make e-textile transmission lines [2, 3]. From the construction point of view, a hot air welded e-textile transmission line can be presented as a laminated fabric, composed of a thermoplastic tape, a conductive yarn and a fabric substrate (Figure 1).

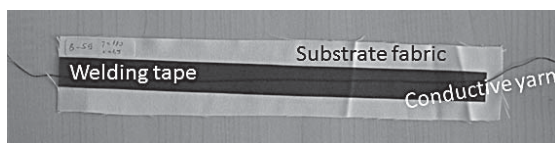


Figure 1: Presentation of a hot air welded e-textile transmission line

The quality of an e-textile welded transmission line depends on the welding parameters settings. The bond strength between a thermoplastic tape and a substrate fabric should be evaluated, followed by the testing of electrical properties such as the conductivity and the signal transmission loss of the welded conductive yarn [2, 3]. The hot air welded transmission line must fulfil the following requirements:

- welded joint bond strength >10 N,
- smooth and wrinkleless surface of the welded area,
- no significant disturbance of the welded surface due to the conductive yarn thickness,
- stable conductivity and signal transmission of conductive yarns.

The aforementioned requirements can be met by proper adjustment of the hot-air welding parameters regarding the selected type of the substrate fabric, thermoplastic welding tape and conductive yarns, as well as the type of the hot-air welding machine used.

Additionally, the integrated welded textile transmission lines influence both the aesthetic and the comfort issues of the garment.

The results of previous experimental works [3, 4] show that the hot-air welding parameters such as air

temperature and pressure, rollers velocity and pressure between rollers have not any significant influence on mechanical stresses of the conductive yarns during the process. On the contrary, these parameters have affected drastically the comfort quality of the welded joint as well as the welded area visual appearance. Furthermore, the bending rigidity of the embedded transmission lines depends significantly on the welding parameters, the thermoplastic welding tape properties and the type of conductive yarns. Moreover, it has been shown that the constructed transmission lines have also adequate electrical properties at certain combinations of welding parameters [2, 3].

In this study, the mechanical-thermal sensory properties of hot air welded e-textile transmission lines are investigated.

## 2 Experimental

In this research work the combinations of two conductive yarns (Table 1) and two welding tapes produced by Bemis company (Table 2) were used and embedded on a substrate laminated fabric. The latter, consisting of a 100% polyester woven fabric laminated by water- and windproof Sympatex® membrane, had a mass of 186 gm<sup>-2</sup>. The purpose of the membrane and the waterproof welding tape was: (i) to protect the conductive yarn from both body moisture and environmental humidity, (ii) to provide maximum insulation and (iii) ensure uninterrupted electrical transmission line functionality during garment wearing.

Table 1: Conductive yarns characteristics

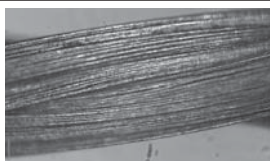
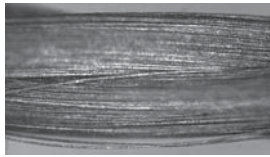
Yarn	Raw material	Weight [gm <sup>-1</sup> ]	Diameter [μm]	Count [dtex]	Yarn twist [tm <sup>-1</sup> ]	Linear resistance [Ωm <sup>-1</sup> ]	Image
1	100% stainless steel	0.19	464	90 fx2	207	<35	
2		0.82	632	275 fx3	224	<12	

Table 2: Welding tape characteristics and recommended welding parameters

Sample code	WT1	WT2
Features	Soft type designed for light weight fabrics where soft hand and minimal tape lines are desired. It can be applied to heat sensitive fabrics using low temperature	Designed special for 3-layer waterproof fabrics
Number of layers	2	3
Softening point [°C]	105	95
Ambient temperature for welding [°C]	40–60	40–80
Washability [°C]	Excellent up to 40	Excellent up to 40

For the welding process, H&H AI-001 hot-air welding machine was used. The selected values of the machine parameters were in accordance with the recommended welding tape specifications, i.e., hot air temperature 550 °C (recommended 550–700 °C), air pressure of 0.58 bar and roller pressure of 3.92 bar. The roller velocity was 5 m.min<sup>-1</sup> (recommended 4.0–7.0 m.min<sup>-1</sup>).

In Figures 2 and 3 the design structure of the experimental work is presented.

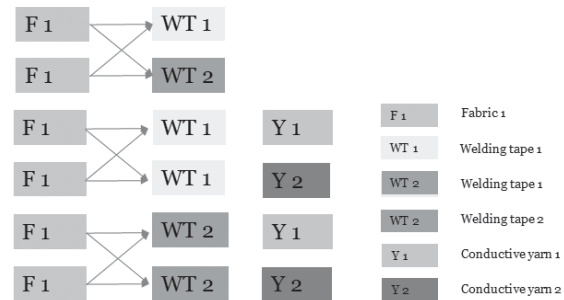


Figure 2: Experimental plan

Table 3: Measuring parameters using FTT tester [6]

	Description	Abbreviation	Unit	Usual interpretations
1	Bending Average Rigidity	BAR	gf.mm.rad <sup>-1</sup>	Forces needed to bend per radian
2	Bending Work	BW	gf.mm.rad	Works needed to bend the specimen
3	Thickness	T	mm	Normal load on gf/cm <sup>2</sup>
4	Compression Work	CW	gf.mm	Works needed to compress the specimen
5	Compression Recovery Rate	CRR	nul (gf.mm.gf <sup>-1</sup> .mm <sup>-1</sup> )	Thickness changes after compressed
6	Compression Average Rigidity	CAR	gf.mm <sup>-3</sup>	Forces needed to compress per mm
7	Recovery Average Rigidity	RAR	gf.mm <sup>-3</sup>	Forces reflected when recovery per mm
8	Surface Friction Coefficient	SFC	nul (gf.gf <sup>-1</sup> )	Friction coefficient on surface
9	Surface Roughness Amplitude	SRA	μm	Roughness irregular wave amplitude
10	Surface Roughness Wavelength	SRW	mm	Roughness irregular wave wavelength
11	Thermal Conductivity when Compression	TCC	W.m <sup>-1</sup> .C <sup>-1</sup>	Energy transmitted per degree per mm when compresses the specimen
12	Thermal Conductivity when Recovery	TCR	W.m <sup>-1</sup> .C <sup>-1</sup>	Energy transmitted per degree per mm when the specimen recovers
13	Thermal Maximum Flux	Qmax	W.mm <sup>-2</sup>	Maximum energy transmitted during compression

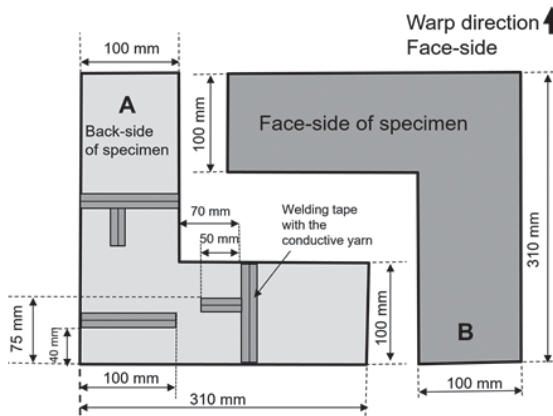


Figure 3: Specimens arrangement

The thermal properties of the fabric specimens were evaluated by Fabric Touch Tester (FTT) [5] through the conducted measurements of the mechanical-thermal sensory properties such as fabric thickness, compression, bending, surface friction and roughness made on the same device. All tests were carried out under standard laboratory environmental conditions (20°C and 65% RH). The fabric sample was cut in the shape of letter “L” on two sides [6] as shown in Figure 2. The fabric face-side was tested first, the testing of its back-side followed. FTT enabled the measurement of all fabric properties with one simple test within the duration of 2–3 minutes, and provided within one measurement 13 parameters that are presented in Table 3.

The parameters BAR, BW, SFC, SRA and SRW are defined into warp and weft directions [5].

### 3 Results and discussion

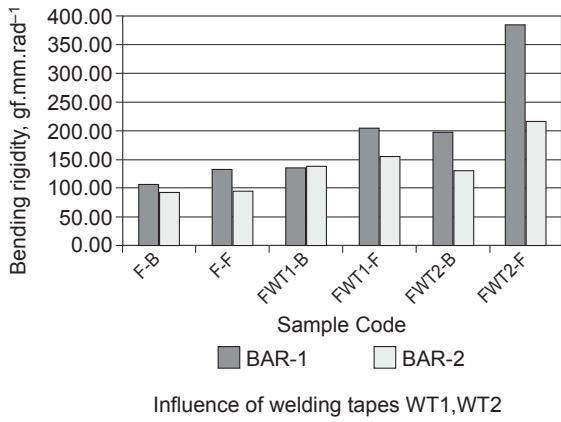
The specimens were tested on both face and back sides in warp and weft directions. The results in a graphic mode present the influence of welding tapes and conductive yarns on bending properties (Figure 4), thickness (Figure 5), compression work (Figure 6), thermal conductivity during compression and recovery (Figure 7) and maximum thermal flux (Figure 8). Due to the peculiar construction of the welded areas of the specimens, their roughness and friction properties could not be properly measured

by roughness sensor and evaluated by using FTT, therefore, other testing methods should be used for this purpose.

The bending rigidity of the welded textile transmission lines was evaluated on the face and back sides in warp and weft directions. The influence of welding tapes and conductive yarns on the bending rigidity of the welded specimens was confirmed by previous research achievements [2–4]. Both the welding tapes and the conductive yarns increased the bending rigidity of welded transmission lines.

The highest value of the bending rigidity was obtained by the combination of a three-layered welding tape (WT2, Table 2) and the thicker conductive yarn (Y2, Table 1), leading to the conclusion that the bending rigidity depends on the number of layers of welding tapes and the thickness of conductive yarn. The bending rigidity of the fabric in warp direction was higher than in weft direction irrespectively of the fabric side. Furthermore, the thickness of the welded specimens depends on four factors, i.e., the welding tape and conductive yarn thicknesses, the applied pressure and the temperature during the welding process.

The heat transfer between fabrics and human skin gives the feeling of thermal comfort. Considering the effect of the specimen thickness, the thermal conductivity during compression (TCC) and recovery (TCR) presents a warm-cool feeling of fabrics. The results presented in Figure 7 show that hot-air welded specimens having thicker welding tape have higher warm-cool feeling in comparison to the substrate fabric. It is clearly evident that the fabrics after welding exhibit almost constant thermal conductivity during compression and recovery irrespectively of the conductive yarn thickness. Another index, named “thermal maximum flux”, is defined as the maximum thermal flux during the measurement process. In general, the hot air welded transmission lines exhibited lower maximum thermal flux than the substrate fabric (Figure 8), even though the differences are small. This confirms the fact that the hot air welding process and the used components for making textile transmission lines do not affect significantly the heat absorption by the substrate fabric.



Influence of welding tapes WT1, WT2

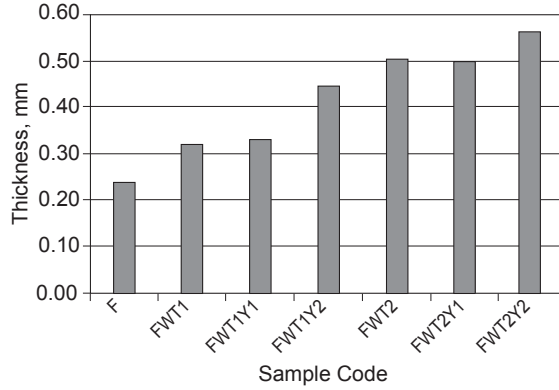
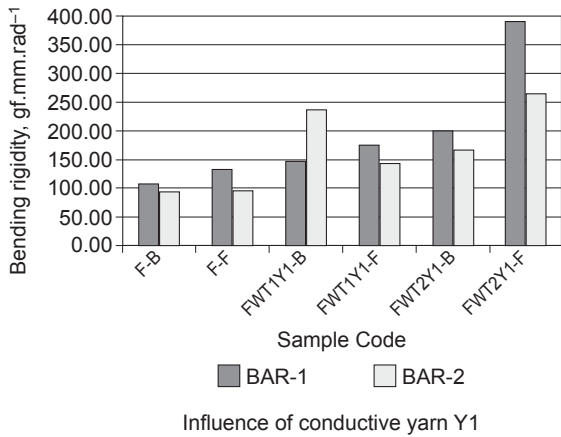


Figure 5: Thickness of welded specimens



Influence of conductive yarn Y1

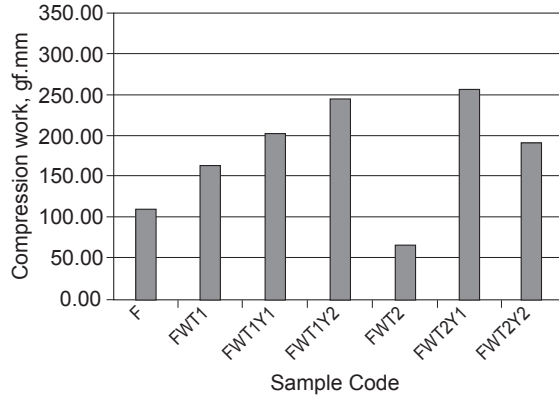
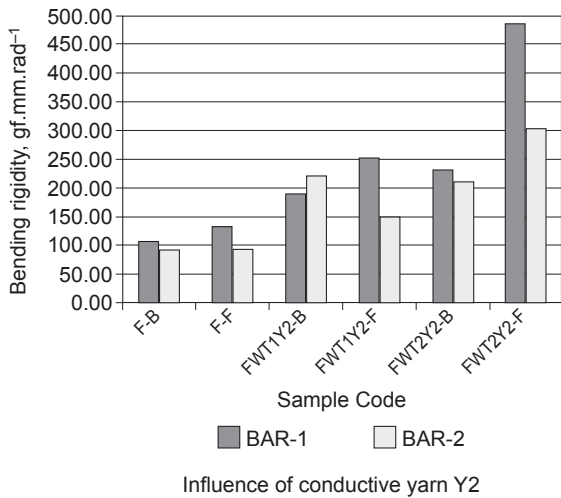


Figure 6: Compression work



Influence of conductive yarn Y2

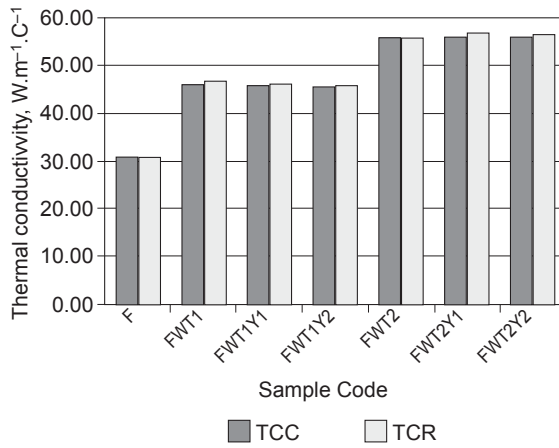


Figure 7: Thermal conductivity during compression (TCC) and recovery (TCR)

Figure 4: Bending rigidity of welded specimens with and without conductive yarns

Explanation of symbols:  
 F – face-side of specimen  
 B – back-side of specimen  
 1 – Warp direction  
 2 – Weft direction

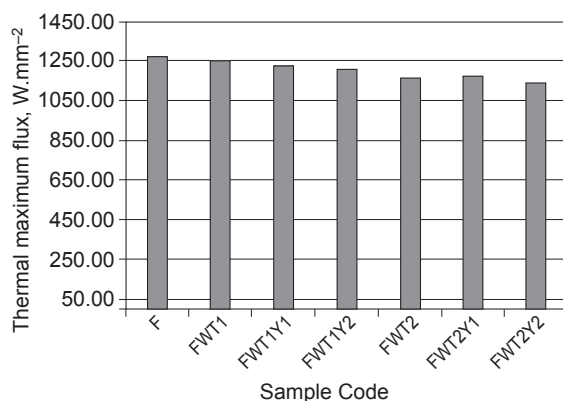


Figure 8: Thermal maximum flux

## 4 Conclusion

Fabric Touch Tester was used to evaluate the mechanical and thermal properties of the fabrics by examining the face and back sides in warp and weft directions at the same time. Two stainless steel conductive yarns were embedded on a waterproof polyester substrate fabric encapsulated by two waterproof welding tapes to protect the conductive yarn from air humidity, human moisture and friction during wearing.

On the basis of the obtained results it can be concluded that the construction properties of the used welding tape and conductive yarns have very important influence on bending rigidity, thickness and thermal conductivity of the welded transmission lines. The properties of these components should be taken into account when they are embedded on a smart garment. Although the hot-air welding is a very flexible technique, providing many alternatives for making e-textile transmission lines, the properties of the used components and the welding parameters should be selected very carefully in order to achieve the desired three-dimensional shape and thermal comfort properties of the produced garment.

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