Fundamental Analysis of Embroidered Contacts for Electronics in Textiles

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Abstract

Integration of electronics into textiles has been a growing topic in recent years. However, a reliable contact between conductive textile structures and electronics modules is still an insufficiently solved problem. One approach is to embroider the conductive textile right to the electronics. This research describes the constitution of the electrical contact and explains resistance changes during temperature variation. This is done by studying the thermo-mechanical and electrical behavior of the conductive yarn. Experiments are conducted with actual embroidered contacts. The interpretation of results has been confirmed by a simplified contact model. A theory describing the contact mechanism in embroidered contacts has been developed.

Introduction

In recent years, a number of research projects have proposed using embroidery of conductive yarn to build textile based circuit boards. However, the lack of a reliable and volume producible connection technology for embroidered yarns and electronics modules kept the embroidered circuit technology from evolving to actual products.[1],[2]

One approach to connecting such circuits with electronics modules is by embroidery itself. Thereby, the embroidery needle is piercing through a conductive pad on a thin electronics substrate and is laying the conductive yarn over the pad. This way an electrical contact is made between the conductive pad and the conductive thread as shown in figure 1. Previous publications of one of the authors (e.g. [3]) describe this contacting process which can be carried out with a fully automated embroidery machine. A precondition is that the thread is surface conductive and machine embroiderable. It has been shown that silver-coated Nylon yarns can be used for this purpose. In this paper as well as in the previous publications *Shieldex 117/17 twine* will be used.

The objective of this paper is to establish a theory of the contact mechanism of embroidered contacts and to identify resulting failure mechanisms during thermal cycling.

Contact Theory

The embroidery process forms a loop consisting of needle thread and bobbin thread (both being conductive). These are held by an interlacing knot at the bottom side of the fabric substrate. The conductive pad and the fabric substrate below the pad are enclosed by this loop. The 3D X-ray image in figure 2 shows the cross section of the contact. The embroidery needle bends the pad downwards

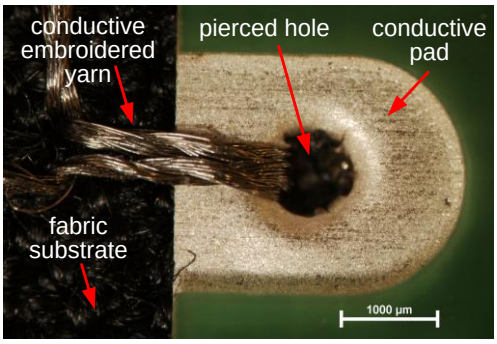

Figure 1. Embroidered contact: a conductive pad made from flexible polymer substrate with metallization is being pierced by an embroidery needle which lays a conductive yarn over the pad creating an electrical contact between the conductive yarn and the pad.

and lays the thread onto and around the bent pad. This results in a contact area that stretches from the left end of the pad (in fig. 2) along the flat area of the pad to the bent part of the pad. The strongest contact force may be expected in the bent part.

The resistance of the embroidered contact $R_{contact}$ can be defined as a sum of: the actual contact resistance $R_{pad2fibers}$ between the pad and the few fibers that are in contact with the pad; the constriction resistance $R_{fiber2fiber}$ within the yarn that results from distributing the current to all fibers; and the resistance of the yarn (parallel on top and bottom side) R_{yarn} to the first knot next to the pad.

However, these components cannot be measured individually as placing the prober needles anywhere on the loop would change contact force and thus contact resistance. Only the sum, which is $R_{contact}$, is accessible by measuring from the pad to the first knot next to the pad. This knot is on the left side in both figures above. (The constriction resistance in the pad itself can be neglected.)

Although the resistances of these components cannot be separated that easily, the temperature influence on these components is very individual. The yarn's resistance mainly depends on the temperature behavior of the silver-coating. The combination of $R_{pad2fiber}$ and $R_{fiber2fiber}$ is significantly influenced by the contact force,

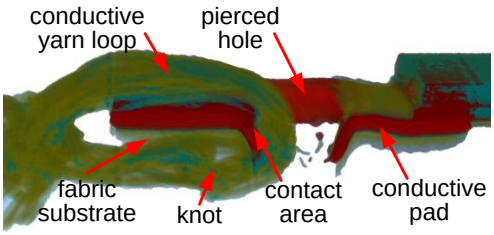

Figure 2. Computed tomography image of an embroidered contact.

Published at the 3rd Electronics System Integration Technology Conference (ESTC), Berlin, September 2010.

which depends on the thermo-mechanical behavior of the assembly.

The resistance changes of the yarn can be expected to be limited within a limited temperature range and can be measured easily in a separate experiment. The range of possible values for the force dependent part is from a difficult to estimate lowest value to infinity when the contact force becomes zero.

This means the dominance of one or the other component may depend on the temperature and if aging must be considered on time, as well.

Furthermore, it can be estimated that the thermo-mechanical behavior of the assembly is such that the electronics substrate (i.e. the conductive pad) dictates the dimensional changes and the thread follows these as long as it is tensioned. It is also clear that the pad (although consisting of different materials) will have a positive temperature coefficient and will expand with temperature. However, evaluating the overall thermo-mechanical behavior becomes delicate especially when taking the pierced fabric substrate into account. Therefore, it is interesting to build a simplified model of the contact consisting only of a yarn loop on a rigid and temperature independent substrate. This will be presented after the analysis of the electrical and thermo-mechanical behavior of the yarn. For didactic reasons the test conditions will be defined at first.

Test Conditions

There is no standard for testing electronics-in-textiles for reliability. This is due to the fact that electronics-in-textiles perceive very different environmental stresses depending on their field of application, e.g. automotive, medical or fashion. This makes it impossible to develop a single test standard for all applications. However, also application-specific test standards have not been developed until now. Therefore, researchers and companies have chosen their own tests. A collection of tests that have been used by different researchers and companies has been published previously in [4].

The JEDEC JESD22 A104 C temperature cycling test is an industry standard for testing electronics (without textiles) [5]. The standard contains a number of different temperature ranges for various applications. For consumer electronics test condition N may be appropriate. It describes a cycle with a low temperature of -40°C and a high temperature of +85°C. One cycle takes usually less than one hour. Typically tests run for one thousand cycles.

Since the goal of this paper is not to simply test the reliability but to understand causes for resistance changes during temperature variations, this standard test has been adapted. The test has been slowed down to one cycle per two hours, allowing all changes to reach equilibrium. An isothermal line at 20°C has been introduced between each transition to observe the behavior at room temperature. All dwell times and all transition times are 15 minutes each. The number of cycles has been limited to 20 cycles as this was sufficient for this purpose. Figure 4 shows the temperature curve of four such cycles.

To best observe the resistance change an in-situ four point measurement has been applied. One end has been connected to the conductive pad and the other one has been connected to the first knot outside of the pad (left side in figure 1).

Electrical Characteristics of the Yarn

The average resistance of the yarn as received from the manufacturer is 348mΩ/mm (at RT) with a standard deviation of 16mΩ/mm. Generally, the silver coating has a positive temperature coefficient causing the resistance to instantly rise or fall proportionally with temperature. However, when the yarn is annealed at increased temperatures the resistance (at a reference temperature) first falls and after a longer period of annealing rises again. This is due to agglomeration of silver particles on the surface which first leads to a healing of gaps and later to a creation of holes between the agglomerates as found by one of our students [6]. The speed of this process increases with temperature. For this paper the resistance change was tested during the above described temperature cycles. The result is illustrated in figure 3. The effect of the temperature coefficient is best observed when resistance is plotted over temperature (right plot). The effect of annealing which occurs in the hot phase of the temperature cycle can be observed in the plot over time (left plot). However, the overall cycling time (at this temperature) is too short to observe the mentioned resistance rise due to annealing.

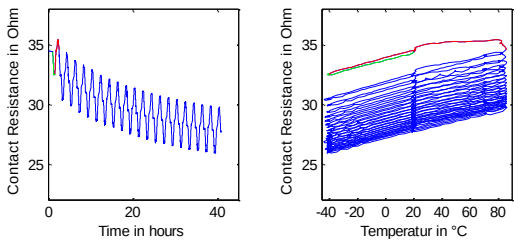

Figure 3. Resistance of *Shieldex117/17 twine* during 20 temperature cycles. Refer to the temp. profile in figure 4 to identify first cooling phase (green) and first heating phase (red). Yarn sample length: 10cm.

Thermo-Mechanical Characteristics of the Yarn

Polymer molecules in fibers are oriented along the fiber axis. This is a result of drawing which is always a part of the fiber manufacturing process. Due to the particular molecular orientation fibers (and consequently also yarns consisting of fibers) will contract on heating (unlike most other materials). Part of this contraction is irreversible and appears in the first heating cycle. As long as the maximum temperature of the first cycle is not overcome in the following cycles all subsequent contractions are mostly reversible with temperature.

Unfortunately, literature discusses this effect for Nylon yarns only for temperatures above 60°C (e.g. [7]). Therefore, a thermo-mechanical analysis (TMA) of the

yarn was made with the proposed temperature cycle. Figure 4 shows one of several measurements. The measurements were made on 10mm specimens using a TMA/SDTA841e. The pre-tensioning was set to 0.05N. Prior to measurement the yarn was dried for 48 hours at 20°C and less than one percent relative humidity.

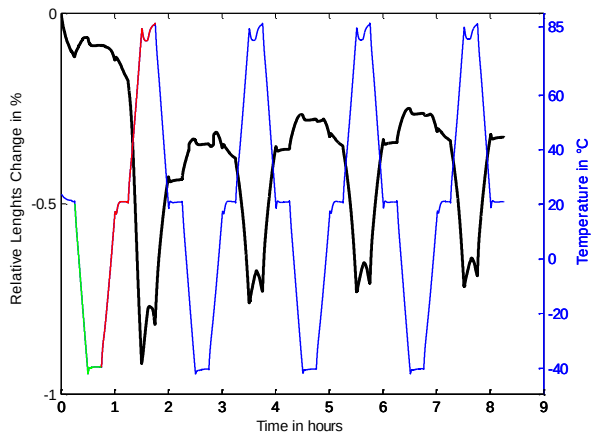

Figure 4. TMA of conductive yarn *Shieldex 117/17 twine*. The black curve is the free relative length change in percent. The blue curve is the temperature profile. The green colored part of the blue curve is the first cooling phase and the red colored part of the blue curve is the first heating phase. This temperature profile was also used for all other experiments in this paper but with 20 cycles.

Embroidered Contact Test Vehicle

The test vehicle is a rigid-flex printed circuit module of size 26mm x 36mm. The thickness of the rigid part is 580µm and was only necessary as this test vehicle was also used for wash tests which are not discussed here. The embroidered pads shown in figure 1 have the dimensions 2mm x 3mm and are built from 45µm flexible polyimide substrate. For symmetry reasons the pads are metalized on top and bottom. The bottom side is 45µm copper-nickel-gold plus 10µm solder resist. The top side (where the thread is laid) is made in two variants to test the influence of different contact metals: a) 27µm copper-nickel-gold or b) 22µm copper-silver. Hence, the total thickness of the embroidery pad is about 125µm.

This electronics substrate is laminated onto the embroidery ground by means of a 100µm thermoplastic polyurethane film. The lamination temperature of the film is roughly 200°C. The embroidery ground is a 200g/m^2 twill weave fabric made from meta-aramid yarn. Aramid stands for aromatic polyamide fibers. It shows good chemical fastness, has a high tenacity and resists high temperatures. This will make sure that neither the lamination temperature nor the testing temperature will alter the material in any way.

Finally, the test circuit and the contact have been embroidered with a professional embroidery machine (*ZSK JCZ 01*). The conductive yarn was used as needle thread and as bobbin thread. Initially the contact pads had no hole. The needle pierces each pad once and lays the thread over the pad. The stitch distance is 3mm. The way the loop is formed over the pad the parallel resistance of top and bottom thread calculates to about 260mΩ.

The circuit is designed such that the precise resistance of the above described contact resistance $R_{contact}$ can be measured with the four point method.

Simplified Model of the Embroidered Contact

As proposed in the theory chapter, the influence of the yarn loop's thermo-mechanical behavior on the electrical contact should be investigated separately. All other elements of the assembly should be eliminated in a simplified model of the embroidered contact.

Ideally, the loop would be wound around a tube that does not change its dimensions with temperature. Quartz glass comes sufficiently close to this ideal. Its coefficient of thermal expansion is $+0.5 \cdot 10^{-6}$/K. This means the circumference lengthens by only 0.003% when heated from room temperature to 85°C. Compared to the length changes of the yarn presented in figure 4 this can be neglected.

For practical reasons the diameter of the tube had to be much larger than in the real contact. The diameter is 30mm. The wall thickness is 2mm thin to provide a quick cooling and heating during the cycling.

To model the contact pad a 2mm wide stripe of gold was sputtered onto the tube. The film thickness is about hundred nanometers and therefore does not influence the mechanics.

To fix the yarn on the pipe in a defined way, 20g weights were knotted to the ends of a small piece of yarn and laid around the pipe with the weights hanging down on each side and the gold film facing down. In this position the yarn was glued to the pipe. After curing the weights were removed.

A four point resistance measurement was chosen to measure the contact resistance most precisely. Figure 5 demonstrates the final setup.

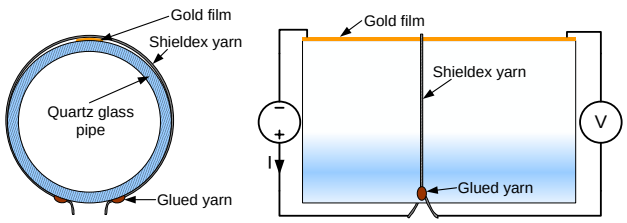

Figure 5. Simplified model of embroidered contact that elimates all elements except the conductive yarn to test the influence of its thermo-mechancial behavior on the contact resitance. Tube diameter is 20mm.

Results

First, the initial contact resistances were measured at room temperature. Five samples of each type of contact have been measured. The following table shows mean and standard deviation.

type of contact	*mean*	*st.dev.*
gold pad	652mΩ	76mΩ
silver pad	565mΩ	70mΩ
contact model	340mΩ	157mΩ

During temperature cycling - inversely to the yarn resistance - the contact resistances in all three contact types were high at low temperatures and low at high temperatures. Moreover, the first cooling showed almost no effect in all contacts while the first heating always lead to a contact improvement.

In the following cycles contact resistances always returned to low values at high temperatures (in all contact types). Furthermore, during the high temperature the embroidered contacts further improved causing the high temperature resistance to improve slightly from cycle to cycle.

At the low temperature all of the simplified contact models had strong resistance increases after a few cycles (4 out of 5 even increased beyond the measurement range of 1kΩ; in two of them this appeared already in the second cycle). The strong rise appeared at around 50°C. Figure 6 shows a typical plot.

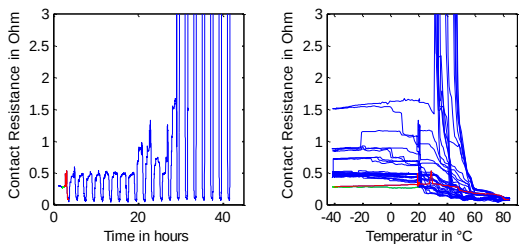

Figure 6. Typical resistance change of simplified contact model during 20 temperature cycles. Refer to the temperature profile in figure 4 to identify first cooling phase (green) and first heating phase (red). [8]

This behavior has also been observed in some embroidered contacts. One silver contact and three golden ones rose beyond the measurement range (1kΩ) during the cold phase. Furthermore, one of each type roughly doubled its resistance at low temperatures compared to the high temperatures. Unlike in the model, the transition between high and low resistances appeared around 0°C. Figure 7 shows a typical plot of this type of behavior in embroidered contacts.

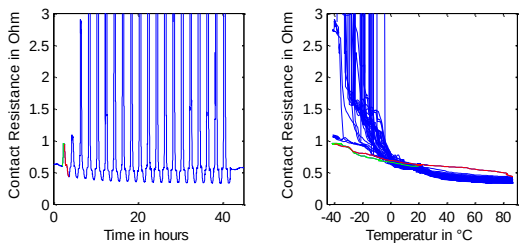

Figure 7. Typical resistance change of embroidered contact that had failed during 20 temperature cycles (in this case a gold contact). Refer to the temperature profile in figure 4 to identify first cooling phase (green) and first heating phase (red). [8]

However, the remaining embroidered contacts (one golden one and three silver ones) did not rise above their initial values. Figure 8 shows a typical graph for such embroidered contacts that did not fail in the cold phase.

Beyond these measurements it was observed in the simplified contact model that the yarn loop had lengthened during the cycling test. After the test the loop was less tight around the tube than before the test. This observation was made at room temperature.

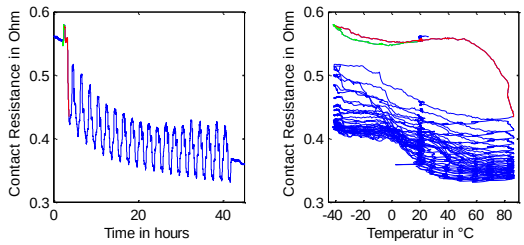

Figure 8. Typical resistance change of embroidered contact that had continuously improved during 20 temperature cycles (in this case a gold contact). Refer to the temperature profile in figure 4 to identify first cooling phase (green) and first heating phase (red). [8]

Discussion of Results

The contact model seems to be little influenced by the yarn resistance. It shows no resistance reduction during the hot phase. This is not a surprise since the four point resistance measurement of this contact does not include a 3mm piece of conductive yarn like the embroidered contact. Yet the contact improves during the first heating from room temperature upwards and always returns to this low resistance value. It can be explained with the contraction of the yarn with temperature. Contraction leads to an increase of contact force which again leads to a better contact.

In the same way the extension of the yarn at decreasing temperatures explains increasing resistances at low temperatures. It surprises though that a total contact loss occurs. After all, the length change in the TMA at low temperatures is still negative compared to the original length. However it must be considered that the TMA shows a free length change. In the model the yarn loop is not free. It is tensioned from the start and most likely tension further rises at the high temperature. Apparently, a free shrinkage with rising temperature does not directly translate to a tension rise if the length is fixed. The observation of the loop lengthening supports this.

Possibly irreversible relaxation occurs at high temperatures. As the glass transition of Nylon is reported to be between 30°C and 90°C this is not unlikely [9]. The extension at falling temperatures may then lead to lengthening beyond the original length as visualized in figure 9. However, this explanation is just speculative and needs further investigation.

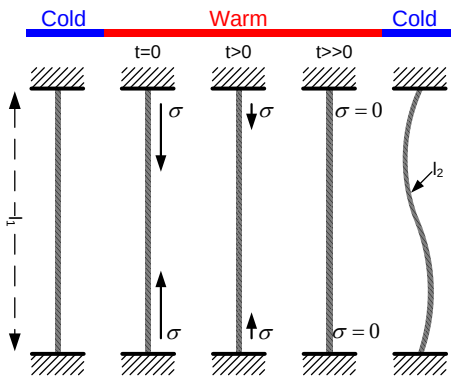

Figure 9. Visualization of a possible explanation of the observed yarn loosening. A yarn that is fixed in length (tension free) perceives a rise in tension as the temperture rises. Over time this tension may decay due to relaxation. Cooling may then result in a yarn length larger than original.

In embroidered contacts, very similarly the strong shrinkage during the first heating leads to a significant resistance drop. Also in following cycles the thermo-mechanical behavior dominates the hot-cold behavior of the resistance.

However, during the 85°C isothermal phase a resistance drop can be observed that is due to agglomeration of silver particles in the yarn surface. This effect also becomes smaller with time like in the yarn (figure 3). In figure 8 this effect is very obvious as it causes the resistance to drop equally over the whole temperature range. In figure 7 the effect is equally there but at low temperatures it is masked by dominating thermo-mechanical effects.

Although the transition to higher resistances appears at lower temperatures in figure 7 than in the contact model, the parallelism is evident. In the contact model everything has been eliminated but the thermo-mechanical influence of the yarn. Therefore it can be concluded – even though the mechanism is not fully understood – that the failure in figure 7 has to do with the thermo-mechanical behavior of the yarn which is an important result.

At this point it is still unclear why some embroidered contacts fail and others do not. Extended tests with up to 1000 cycles have shown that there are some contacts that never fail.

Conclusions

For the first time a theory has been developed that explains key elements of embroidered contacts and their behavior during temperature cycling stress. The thermo-mechanical behavior of the Nylon based conductive was found to be a source of contact instability during cycling. Understanding the polymer-physics leading to this behavior is the next challenge which could possibly explain why some contacts remain stable and others do not. In the best case this will also lead to an answer how to assure that contacts do not fail. This could eventually boost the embroidered circuit technology which until now lacks a reliable interconnection technology.

Acknowledgments

The authors would like to thank the Federal German Ministry of Education & Research (BMBF) and the VDI/VDE-IT for funding this research within the project TePat. Furthermore, we would like to thank Christoph Greve for making numerous TMAs of the yarn for us.

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