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Review Article

Contacting Smart Textiles by Welding of Electronics to Textiles

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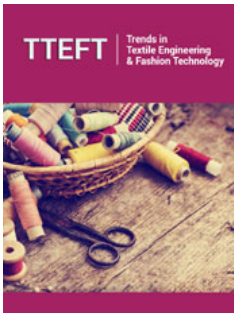

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Abstract

Despite all the growth forecasts for the smart textiles market, a stable automated manufacturing process to apply classic electronics to textiles does not exist. Indeed, the large number of manual production steps causes high production costs, which slow down market growth. During the production process, the contacting step offers the greatest potential to reduce manual tasks and lower costs. For this reason, we analyzed different contacting methods for the integration of electronic parts on textiles, which may enable automation during the smart textiles production. In this chapter we focus on ultrasonic-, laser- and resistance welding to integrate electronics to textiles.

Keywords: Smart textiles; Wearables, Welding, Bonding, Integration of electronics

Introduction

Current studies confirm a significant growth of the smart textiles market in the coming years. Smart textiles are able to sense stimuli from the environment, to react to them and to adapt to them by the integration of functionalities in the textile structure. The stimulus and the response can have an electrical thermal, chemical, magnetic or other origin. The additional intelligence is divided in three groups [1-3].

Sensors

Passive smart textiles can only sense the environment.

Actuators and sensors

Active smart textiles can sense stimuli from the environment and react to them

Very smart textiles

Adapt their behaviour to the circumstances

Smart textiles can realize additional functions of textiles, which were not textile before, such as higher efficiency through textiles (load measurement in lightweight construction e.g. logistics, architecture). Several functions are, therefore, integrated in one component. The usage will spread to the areas of fashion and sport, in addition to the current applications in the medical, military and occupational safety field [4]. Especially the health monitoring sector will increase. There are several other fields of application like smart home solutions. But at the moment there is no actual market breakthrough of smart textiles as there are a few factors hindering the process i.e. a high share of manual tasks, high prices due to the manual processes and the washability of the electronic textiles [5]. Furthermore, the high proportion of manual production steps ensures high prices, which slow down market growth. Hence a lot of research institutes are currently working intensively for automatable techniques, especially in the field of welding conductors to electronics. The most important criteria for integrating electronics to textile is the retention of textile properties. The contacting should have at least a similar lifetime as the textile itself.

The production process of bringing electronics to textile consists of three steps. At first the wires are automatically striped by laser. Then, the main contacting process between the electronic and the conductors starts [6]. This chapter only focuses on metallic textile integrated wires, because only with these wires it is possible to implement welding processes for metals. The wires are inside the textile, meaning it is possible to join components from both sides. In order to protect the electronics from environmental influences, the components are encapsulated in an injection moulding machine [7]. Other joining methods used so far have major disadvantages compared to welding. During soldering, a lot of solder enter the strands due to the required flux. The solder also flows into areas outside the joint due to the capillary effect of the strands. The solidified solder has much more brittle properties than the strands. This leads to weak points in the joint, which cause rapid failure by putting mechanical stress on the components. It is also possible to embroider electronics with conductive yarns. In this case, however, the conductor tracks themselves and the contact points have relatively high resistances. These resistances increase even further after washing the textiles. This limits the durability of the textiles.

Welding Basics

Welding is a joining process that creates a continuity of materials by heating and or by pressure, and with or without any additional joining materials. During soldering only the filler material is melted, whereas welding also partially melts the joining partners. Therefore, soldered joints are especially suitable for joining partners with differing melting points, while welded joints have very high mechanical strength. Furthermore, welding processes are also used for coatings or remitting. Welded joints are substance-to-substance bonds, thus, they are inseparable connections and can only be separated by destruction. The metal grid structure of the joining partners must be brought together during the welding of metals so the metal ions can bond. The requirements for a welded joint depend on the chosen procedure, surface and interface properties. Due to many years of experience with welded joints, they can be easily automated. In addition, some welding processes do not need any filler material, which also leads to easier automation. A further point is that the process has very low running costs. The welding process can be categorized in two main groups: Solid-state welding and fusion welding [8].

Fusion welding and solid-state welding

The joining partners are locally heated above the melting point without any application of force. Depending on the welding process, work is carried out with or without filler metal. Fusion welding processes differ in terms of heat input. The joining process within the metallurgical structures takes place by coalescence. A similar melting point of the two joining partners is required for weldability. Fusion welding processes are often used to join metals of the same type. Solid-state welding differs from fusion welding in two main effects: Diffusion processes at room temperature and the presence of metallic surfaces. The material is not or only partially melted and often the melting temperature is not reached. Depending on the process, there is even no heat input at all. The application of pressure on the joining partners is necessary for all solid-state processes. Still, the plastic deformation only takes place in the micro scale. Diffusion processes and grain growth start by bringing the metallic surfaces together In the case of compounds of austenitic and ferritic steels, the grain size in the joining zone can be influenced by a change in pressure. A higher pressure leads to larger grains, whereby these are distributed in homogeneously beyond the joining zone [9].

Larger grains lead to a reduced ductility. The joint already acquires a similar strength to the original material, even if diffusion has not taken place at every point in the joint gap. Solid state welding processes immensely reduce the formation of pores through gas inclusions [10]. Furthermore, there is no erosion or embrittlement. Because different metals can also be welded together, the melting point of the connection corresponds approximately to the joined materials. In addition, several joints can be welded simultaneously. The following processes belong to solid state welding processes:

A. Ultrasonic welding

B. Explosion welding

C. Friction welding

D. Magnetic pulse welding

E. Friction stir welding

Ultrasonic welding or wire bonding

Ultrasonic Welding and wire bonding are often used to describe different manufacturing processes but are actually based on the same physical principle. In wire bonding applications, the established joint is made between an additional wire and the components to be connected, whereas ultrasonic joints are often made directly between the components without additional material. Both procedures belong to the category of solid-state welding. On a microscopic level, they can be seen as a combination of friction welding and cold welding [11].

To establish a connection between metals, pressure is exerted on the parts to be welded and these are moved relatively to each other by ultrasound. This leads to a static normal force and an oscillating shear stress in the joint gap. The contact pressure remains far below the yield point. The relative movement destroys the oxide, foreign layers and levels the surface. The impurity layer on the surface is torn open by small plastic deformations, so that the bare surfaces are welded together even at low pressure [5]. The crystal lattices approach each other at such high intensity so strongly that atomic lattice forces (1st order) are exerted. The joining partners are not melted, the temperature in the joint remains below the melting temperature of the materials at all times [6,12]. On this way, the bare metal surface is weld at low pressure and the joining partners are welded together [5,11]. Greases, oils or metals with a lower melting point than the joined parts must not be present in the joint; otherwise the friction in the joint is reduced[12].

Many soft metals and their alloys can be joined by ultrasonic welding. Also many combinations of these metals are possible. It is also possible to weld insulated conductors to other conductors without removing the sheathing. In this case, the insulation is removed locally by the normal pressure and the relative movement of the conductors [5]. The electrical conductivity of the connections is very good, because no recrystallization occurs. However the mechanical strength of the connection is not particularly high [6]. But there are also non-weldable metals for ultrasonic welding, such as lead. Here the oxide layer on the surface does not crack, so that the joining mechanism is inhibited [5].

An ultrasonic welding system consists of the following components:

Ultrasonic generator (frequency converter): Generates a voltage with the required frequency, in most cases between 15kHz and 70kHz. The power needed depends on the components to be welded and is usually between 100W and 4000W, so the welding time usually takes only a few seconds [5,6,8,13].

Converter: Converts the high-frequency voltage provided by the generator into a mechanical vibration. This is usually done using piezoceramics or due to the electromagnetically applied voltage of a ferromagnetic body (amplitude approx. 10μm). The frequency corresponds to the generator frequency [6,8].

Booster: Modifies the amplitude. Often used for magnification in ratios between 1:1 and 1:3 [8].

Sonotrode: Establishes contact between the ultrasonic part of the welding machine and the work piece. It transforms the amplitude and transmits the vibration energy and contact pressure into the work piece [14].

Anvil: Fixes and does not move with the ultrasonic vibrations [14].

For more than 60 years, ultrasonic welding has been used productively [11]. It is one of the most common welding techniques for thermoplastics. However, the technique is also used for joinings in the textile sector (filters, felts, shower curtains, underwear, outdoor clothing, vehicle interiors, surgical drapes), for metal foils, for joining and compressing strands and wires, on metal rails, and for attaching conductors (wires, moulded parts) to various components (sensors, batteries) [15].

The ultrasonic application differs depending on the joining partners. Longitudinal waves are used in most technical applications [8,14]. Metals are applied horizontally to the joint. Subsequently the joining partners rub in the joint. Ultrasonic welding of plastics is different. Here, the ultrasonic vibration is not introduced parallel, but orthogonally to the joint gap [10,13].

Laser beam welding

For laser welding, the energy is introduced by means of a laser beam. Usual wavelengths are in the range of approx. 450nm to 1060nm. In special cases, they may also be significantly different. In general, the wavelengths of non-ferrous metals tend to be lower than those of iron [16]. In addition, lasers can operate in pulsed or continuous mode and have outputs of 100W up to several kW. Laser welding is characterized by its low heat input compared to conventional methods, as this is only done very locally [11]. It is also possible to combine laser welding with other welding processes, such as gas-shielded arc welding in so-called hybrid welding processes [17]. Another special form of laser welding is laser deep penetration welding: Here, the ratio of weld seam width to weld seam depth is large [18].

During welding, a vapour capillary is often formed, which can lead to a recoil due to the vapor pressure or ensures that the absorption is increased and the energy input is greater for the same power [11]. On the other hand, no vapour capillary can be formed due to insufficient power input. In this case, heat conduction welding is used (no load beam deep penetration welding). This means that the molten pool penetrates less deeply. Heat conduction welding is therefore only suitable for thin materials. Micro ring welding is a further development of simple laser beam spot welding. It increases the connection cross section in relation to the welding depth [18]. In terms of construction and connection technology, the areas of application for contacting are also diverse: On the one hand, it can be used for welding SMD components (contact area 0.5mm²) by means of micro ring welding. It can also be used for wire contacting [19], or for connecting copper strands and cable connectors [20].

Electric resistance welding

The required heat for resistance welding is generated by electric current flow. The joining partners are formed in such a way that the wire cross-section is smallest in the contact point (e.g. “projection welding”). Due to the increased electrical resistance, most of the heat is generated here. This leads to melting of the parts in the contact zone and the partners can be joined [11,21]. For the classification of welding processes, a distinction must be made between pressure welding processes and resistance fusion welding.

In the case of pressure welding processes, the application of an external force causes plastic deformation of the surfaces to form a welding curtain. On the other hand, in resistance fusion welding, the application of an electric current is responsible for the melting at the joint surfaces. A filler material can also be added [22]. If a high force is applied, the weld becomes weaker than the contact resistance and thus the heat development decreases [23].

The current frequency is often above 1kHz. This results in a pulsed high and well controllable energy input in a short time [11]. One of the most frequently used processes is cross welding [24,25]. It is mainly used for larger positioning tolerances and small contact surfaces. Another process of small parts resistance welding is gap welding [23]. Here, both electrodes are fed to the joining partners from above. The distance of the welding lens and the electrodes must be large enough being able to connect both joining partners [10].

During hot staking, welding with a welding fork or resistance hot upsetting, the electrodes are contacted with a specially shaped fork. The joining partners are located in the fork without direct contact to the electrodes [23,26]. Welding with welding flaps is very similar to hot staking, but it has a different fork shape. Furthermore, strands are also compacted into a rectangular format by means of resistance welding, in order to be able to weld on additional parts afterwards.

A requirement for resistance welding is the electrical conductivity of the parts to be joined [21,25]. If the electrical conductivity is very high, it is difficult to produce a large-area, cohesive welded joint because then the resistance is too low to melt. In addition, precipitation forming copper alloys ($CuNi^3SiMg$, $CuFe^2P$) is not suitable [11]. Furthermore, the materials must be wieldable in the wrought state [25]. The force transmitted by the electrode to the work piece, as well as the power supply, often follows a program specifically defined for the work piece [13]. The size of the resulting welding lens depends on the contact area and shape of the electrode, as well as the applied force [22,23]. The transfer of electrode material to the work piece poses a risk of surface contamination [11]. Influencing factors on the quality of the weld seam are: welding current, welding time, electrode force and resistance of the joint. A supplementary (contact grease) is often added to the joint to maintain the metallic condition of the contact points [6]. In special cases, combinations of press connection and resistance welding processes in the form of thermal crimping / hot crimping are also possible.

Other welding processes

Vertical wire welding is used for welding contact wires onto components. The contact material must be in wire form and is clamped in a collet. The principle is similar to resistance welding. Platelet welding is used for welding contact plates onto carrier parts. In ball welding, balls are first welded on the joining parts and then formed into a contact form. In flash butt welding, an arc is ignited between the contact and the carrier part [11].

Contacting of E-Textiles

Current studies confirm that the market volume of smart textiles will grow significantly in the coming years. There are several requirements to preserve the textile properties of the final product when contacting electronics to textiles. Especially haptics, drapability and elasticity of textiles are elementary properties. Textiles differ in terms of their manufacturing processes. Fabrics have lower elastic properties than knitted or warp-knitted fabrics. Depending on the requirements, the textile manufacturing process can be selected.

Different levels of Integration

Smart Textiles can be differentiated according to their degree of integration. This ranges from the subsequent application of electrical conductors to the use of the textile structure as a sensor (Figure 1). Subsequently, conductors are often applied by embroidery. Here, an electrical conductor is fixed to the carrier material by a thread. Such structures have currently the deepest market penetration in the form of seat heating elements in passenger cars.

As a further form of integration, sensors or actuators can be applied to textiles in which the electrical conductors have already been integrated during the textile manufacturing process. With this form of integration, therefore, only sensors and actuators are applied subsequently. The entire range of available microelectronics can be used as sensors. By using conventional sensors, this form of application has the widest range of possible use cases. In addition, measuring accuracies can be achieved that are impossible to reach with textile sensors. This type of sensors can also be integrated into fibre composite structures. Conventional sensors, however, always present a point of interference, which weakens the composite.

The highest form of integration is to use the textile structure as a sensor. Here, different physical functional principles can be deployed. One widely used principle is the piezo resistivity. In this case, the electrical resistance between two electrodes changes, which is detected by a subsequent electronic system. This means that even large area sensors can be designed. It should be noted, however, that a conventional control unit has to be integrated to evaluate these sensors. The integration procedures explained in This article are elementary for this (Figure 1).

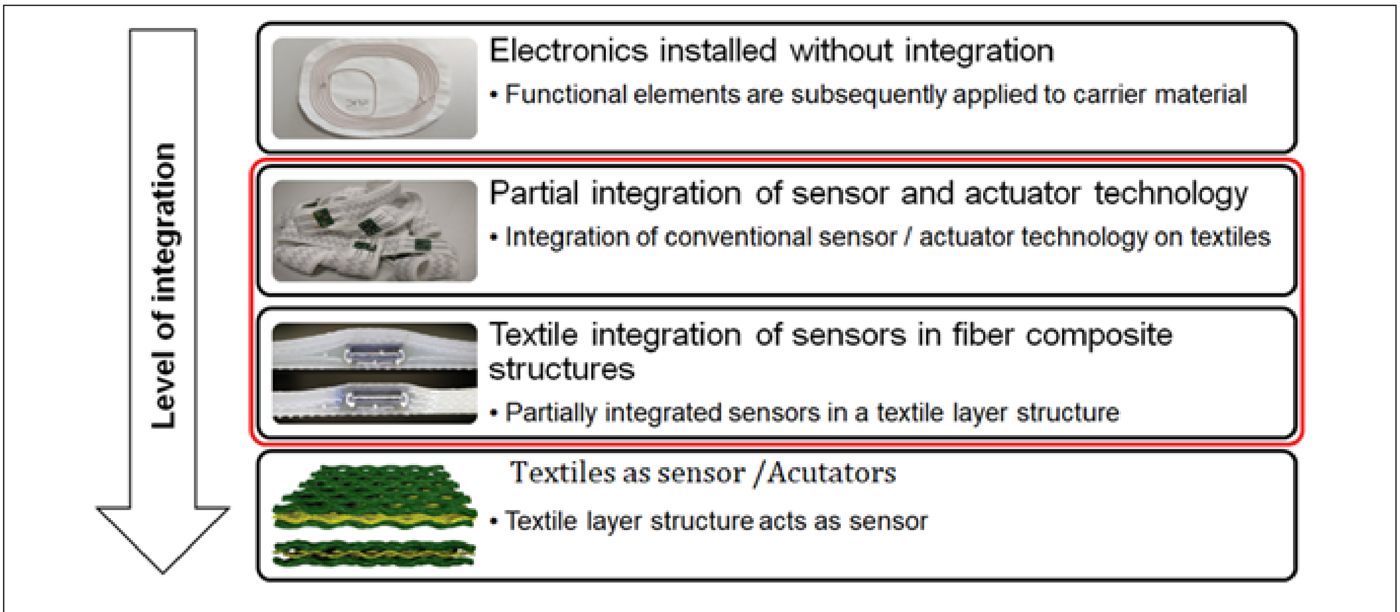

Figure 1: Smart textiles: Level of Integration.

This article is about integrating conventional sensors or actuators to integrated electrical conductors. To produce such e-textiles, insulated wires, strands or even coated yarns are inserted into the textile (Figure 2). Wires and strands have great advantages in terms of conductivity and electrical insulation. However, due to their different mechanical properties, they slightly limit the textile properties. Coated conductive yarns usually consist of polyamide with a thin silver layer on the surface. The use of these yarns hardly changes the textile properties of the end product, as they have similar properties to the rest of the textile product. In the manufacturing of e-textiles, small sensors or actuators are often contacted very locally. For this purpose, the sensors or actuators are contacted with the conductors introduced in the textile manufacturing process. Various connection methods are available for contacting these sensors or actuators.

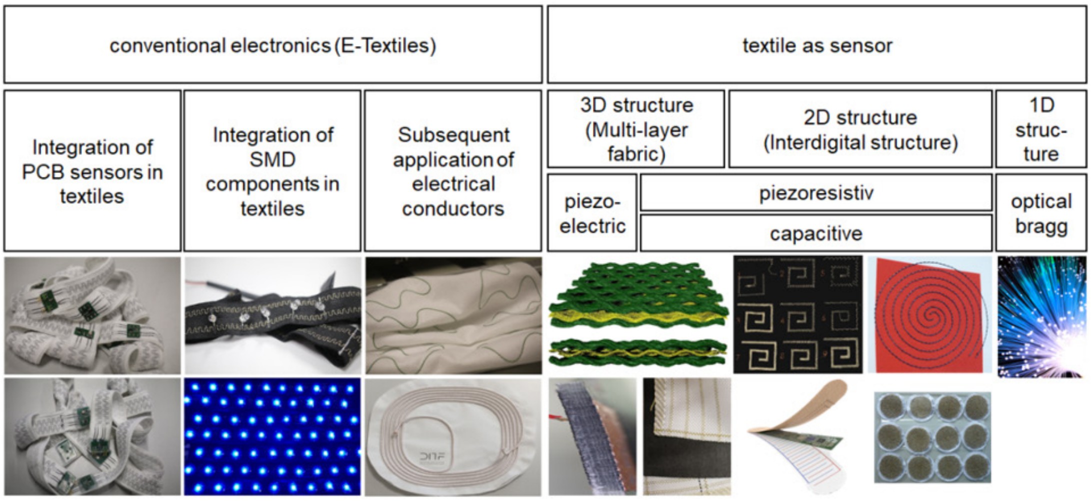

Figure 2: Classification for different smart textiles.

Contacting methods for E-Textiles

Numerous processes for contacting sensors and actuators to smart textiles exist including various soldering processes such as piston soldering, laser soldering, ultrasonic soldering or hot bar soldering. These processes also have the potential for stable automation in the production of smart textiles (Figure 3). However, the solder additive causes embrittlement at the contact point [27]. The embrittled contact points represent a weak point in the component and are the first points of failure, especially under mechanical stress.

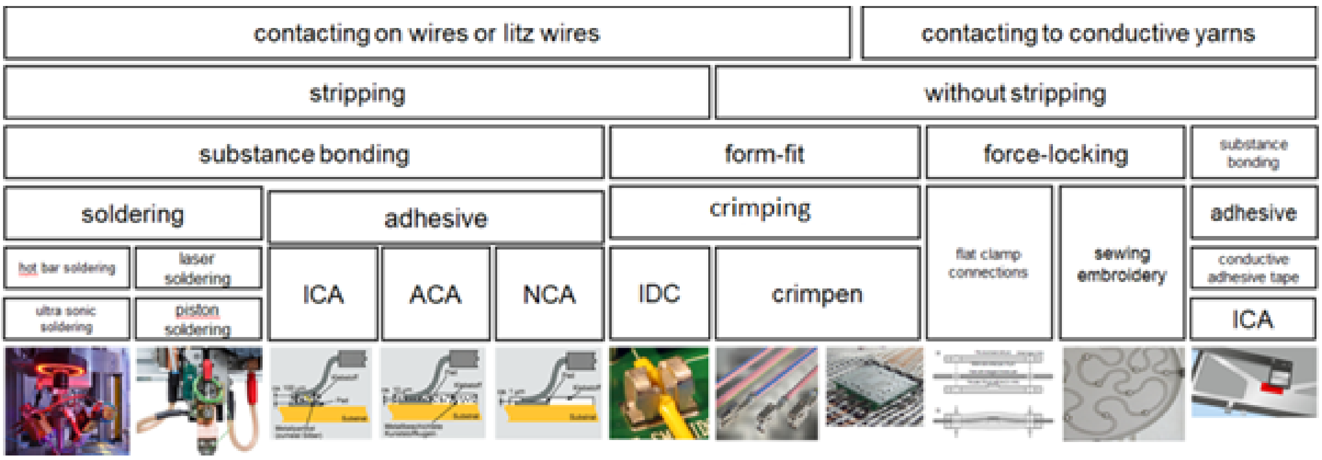

Figure 3: Different methods of contacting smart textiles.

Conductive adhesives also have the potential to be suitable as joining processes for Smart Textiles. They avoid embrittlement of the contact point. However, their conductivity is limited, especially at low filler concentrations. With increasing filler content, the already low strength is further reduced. That is why the sticking processes are divided into three different categories. Non-conductive adhesives (NCA) have no conductive filler. Anisotropic conductive adhesives (ACA) and isotropic conductive adhesives (ICA) have different proportions of conductive fillers and, therefore, have to be processed differently. Furthermore special curing processes are needed for every form of adhesive [17,20,21,25,27].

Form-fit connections show good electrical conductivity like soldered connections and avoid the embrittlement of the contact points. Often, however, their automation capability is severely limited, as conductors have to be threaded in. Despite all IoT approaches, threading is an activity that still cannot be solved.

Welding methods for E-Textiles

There are also numerous types for welded joints. Due to their material-closed metallic connection, they all have good electrical conductivity. The different welding processes have been automated in numerous applications, which might also be possible for the application of smart textiles. We evaluated various welding processes for the application of sensors and actuators in textiles and consider that ultrasonic welding, laser welding and resistance welding offer the greatest potential for automation. In addition, welding processes without filler material can prevent embrittlement of the soldered joint, as no brittle material is drawn into the strand by capillary action.

Ultrasonic welding (chapter 2.1) is suitable for contacting electronics to textiles for many reasons. On the one hand, very good electrical contacts are produced, because the metallic structure is retained, as with all welding processes. On the other hand, the joining partners are not melted above their melting temperature. This also means that there is no danger for the surrounding textile being damaged by the joining process. Furthermore, no additional soldering material needs to be added and the electrical conductors can be aligned on the contact points by means of a specially shaped sonotrode. This creates very reliable contact points. In addition, the insulated conductors can be contacted without removing the insulation before. The isolation is removed during the ultrasonic welding process. The already implemented wire bonding is also suitable for very small contact points in the micrometer range. This means that ultrasonic welding is also applicable for very filigree joints.

Laser welding processes (chapter 2.2) offer the possibility of producing contact points with very short and fine energy input. In addition, it is a contactless joining technique. This is also one of the disadvantages. Since no contact pressure is applied when contacting the conductors and the circuit boards, it cannot be guaranteed that the two joining partners will touch each other. Without contact, however, no connection can be made. Furthermore, it is possible that the joining partners are not in the focus of the laser, so that no adequate energy can be applied. A further point is that the joining partners have to be heated above their melting temperature. Since the melting temperature of the thermoplastic textile is significantly below the metallic conductors, the textile may be damaged.

The disadvantage, however, is that high temperatures are often required, which lie significantly above both, the melting temperature of the solder on the board and the decomposition temperature of the plastics in the textile. To counteract this problem, solid state welding processes or very short term welding processes offer a solution.

Resistance welding (chapter 2.3) is probably one of the most frequently used automated welding processes in the automotive industry. It has the advantage that a normal force acts on the conductors through the electrodes during contacting the electronic on the textiles. Thus, they are safely in contact with the circuit board and the conductors can be reliably contacted to the board. However, even with this welding process, the conductors have to be heated above the melting temperature. This can again lead to damage of the textile and contamination of the electrodes.

Conclusion

Unfortunately, the market penetration of Smart Textiles is lagging behind expectations. This is mainly caused by the high product's cost. Due to the low demand, none of the processes for automation has yet become industrially accepted. Still, ultrasonic welding has a good chance of establishing itself in the field of wires and strands because of its filigree contacting possibilities, the high conductivity and low embrittlement of the conductors.

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Conflict of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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