Design and Analysis of Methods to Connect Microelectronics to Smart Textiles

Entwicklung einer Methode zur Integration von Mikroelektronik in Smart Textiles

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Sebastian Micus

Abstract

The smart textiles market shows a high growth potential during the next ten years. However, the integration of conventional electronics in textiles requires a lot of manual work. As a result, the products tend to have very high prices, which inhibits the success. During the production processes, the joining step offers the greatest potential to reduce manual manufacturing, but a suitable connection method for the automated production of E-textiles does not exist, yet. For this reason, this thesis analyses different connection methods for joining electronic components to textile integrated litz wires. The selected processes show a high potential for automation. The chosen methods are thermode soldering, insulation displacement connections (IDCs), anisotropic conductive adhesives (ACA), laser soldering, ultrasonic soldering and ultrasonic welding. Various test methods were developed and used to evaluate the samples in order to ensure the reliability of the joinings, such as direct optical observation of the microstructure, a peeling tensile test, and a four-wire contact resistance measurement.

The thesis consists of four peer reviewed paper. Each paper focuses on one or more connection methods. In the first paper, hot bar soldering, IDCs and ACA was investigated. The second paper focuses on the ultrasonic soldering. The third paper presents the development on laser soldering and the final paper shows the results of ultrasonic welding.

Hot bar soldering initially showed great results. However, solder was drawn into the strands, which was not possible to prevent. Drawn-in solder has a clear negative effect on the textile properties close to the contact point. IDCs have good preconditions for an automated smart textiles production. The strands can slip into the IDCs even under a certain deviation in position. However, thin wires are important to ensure the textile properties of the smart textile, but the available connectors were not suitable to connect AWG 32 or thinner strand. At the current stage of development, anisotropic conductive bonding methods are only conditionally suitable for the usage in automated production. The bonding process has weaknesses due to inadequate contacting and process time.

Ultrasonic soldering works with flux-free solder, which avoids embrittlement of the textile integrated wires trough drawn in solder. The influencing factors of the connection and the corresponding solder parameters were determined. The contact strength increases by reducing the operating temperature and the ultrasonic time. A lower operating temperature and a reduced ultrasonic time cause a more homogeneous metal structure with less defects, resulting in an improved mechanical strength of the samples.

Contactless laser soldering is considered to be a good contacting method to reduce the joining zone on the textile. An ytterbium-doped fibre laser (1064 nm) was used and different sets of parameters were investigated by means of different designs of experiment.

The copper strands in the textile tape were stripped by the laser and soldered to the printed circuit board (PCB) without any transport. Unfortunately, some conductors were poorly-wetted by solder.

The connection between flexible textiles and stiff electronic components has always been a structural weakness and a limiting factor to establish smart textiles in our everyday life. Therefore, the next chapter focuses on reliable connections between conductive textiles and conventional litz wires by ultrasonic welding. It shows a promising approach. The electrical and mechanical performance of the samples were investigated after both 15 and 30 wash and dry cycles in a laundry machine. The resistance of the joints increased by more than 300 %, because the silver coated wires suffered under the laundry cycles. While the mechanical strength during the peeling test decreased only about 20 % after 15 cycles and remained the same after 30 cycles. Ultrasonic welding showed good results for connecting conductive textiles to litz wires, which enables the production of smart textiles with textile sensors.

Kurzfassung

Der Markt für intelligente Textilien bietet in den nächsten zehn Jahren ein hohes Wachstumspotenzial. Die Integration herkömmlicher Elektronik in Textilien erfordert jedoch zum aktuellen Zeitpunkt viel Handarbeit. Dies führt dazu, dass die Produkte in der Regel sehr teuer sind, wodurch der Markterfolg gehemmt ist. Bei der Herstellung weist das Fügen von Elektronik und Textil das größte Potenzial zur Kostenreduktion auf, jedoch existiert hierfür noch keine geeignete Verbindungsmethode. Aus diesem Grund werden in dieser Arbeit verschiedene Verbindungsverfahren zum Fügen von elektronischen Komponenten an textilintegrierte Litzen untersucht. Die ausgewählten Verfahren besitzen ein hohes Automatisierungspotenzial. Hierbei handelt es sich um: Thermodenlöten, Schneidklemmverbinder (IDCs), anisotrop leitfähige Klebstoffe (ACA), Laserlöten, Ultraschalllöten und Ultraschallschweißen. Um die Zuverlässigkeit der Verbindungen zu untersuchen, wurden verschiedene Prüfverfahren entwickelt und zur Bewertung der Proben eingesetzt. Dazu zählen die optische Analyse von Schliffbildern aus der Fügezone, ein Schälzugversuch und eine Vier-Leiter-Kontaktwiderstandsmessung.

Die Dissertation besteht aus vier Publikationen. Jede Arbeit befasst sich mit einer oder mehreren Verbindungsmethoden. In der ersten Publikation wurden das Thermodenlöten, Schneidklemmverbinder und anisotrop leitfähige Klebstoffe untersucht. Der zweite Beitrag untersucht das Ultraschalllöten. Die dritte Publikation stellt die Entwicklung des Laserlötens in Zusammenhang mit Smart Textiles vor und der vierte Beitrag zeigt die Ergebnisse des Ultraschallschweißens.

Das Thermodenlöten zeigte zunächst gute Ergebnisse. Allerdings wurde das verwendete Lot in die Litzen gezogen. Das eingezogene Lot führt zu einer Versprödung der Litze in diesem Bereich. Dies hat einen negativen Einfluss auf die Eigenschaften des smarten Textils in der Nähe der Kontaktstelle. IDCs haben gute Voraussetzungen für eine automatisierte Smart Textiles Produktion. Durch die V-förmige Öffnung kann eine gewisse Lageabweichung der Litzen beim Eindrücken toleriert werden. Allerdings waren keine Steckverbinder für die Verwendung von AWG 32 Litzen oder dünneren Litzen verfügbar. Zum derzeitigen Entwicklungsstand sind anisotrope leitfähige Klebeverfahren nur bedingt für den Einsatz in der automatisierten Produktion von Smart Textiles geeignet. Das Klebeverfahren hat Schwächen durch seine unzureichende Kontaktierung und lange Prozesszeit.

Das Ultraschalllöten arbeitet mit flussmittelfreiem Lot, wodurch das Einziehen des Lots in die Litze gehemmt ist. Hierdurch kommt es zu einer geringeren Versprödung der textilintegrierten Drähte im Bereich der Kontaktstelle. In der Untersuchung wurden die Einflussfaktoren auf die Verbindung und die entsprechenden Lotparameter ermittelt. Die

Kontaktfestigkeit erhöht sich durch Reduzierung der Applikationstemperatur und der Ultraschallzeit. Eine niedrigere Betriebstemperatur und eine reduzierte Ultraschallzeit bewirken ein homogeneres Metallgefüge mit weniger Defekten, was zu einer verbesserten mechanischen Festigkeit der Kontaktstellen führt.

Das kontaktlose Laserlöten reduziert die Größe der Fügeeinflusszone im Textil. In der vorliegenden Untersuchung wurde ein Ytterbium dotierter Faserlaser mit einer Wellenlänge von 1064 nm verwendet. Anhand eines vollfaktoriellen Versuchsplans wurde ein passender Parametersätze ermittelt. Die Kupferdrähte im Textilband wurden mit dem Laser abisoliert und ohne Transport auf den Leiterplatten angelötet. Hinsichtlich der Qualität der Fügestellen konnten keine konstant reproduzierbaren Ergebnisse erzielt werden.

Die letzte Veröffentlichung untersucht Verbindungen zwischen leitfähigen Textilien und metallischen Litzen durch Ultraschallschweißen. Um die Qualität der hergestellten Verbindungen zu untersuchen und eine praxisnahe Beanspruchung nachzustellen, wurden die Proben sowohl nach 15 als auch nach 30 Wasch- und Trockenzyklen in einer Waschmaschine hinsichtlich ihrer elektrischen und mechanischen Eigenschaften untersucht. Hierbei stieg der Widerstand der Verbindungen um mehr als 300 %, da die silberbeschichteten Garne einen Teil ihrer Beschichtung während des Waschens verloren. Die mechanische Festigkeit während des Schältests nahm nach 15 Zyklen jedoch nur um etwa 20 % ab und blieb nach 30 Zyklen konstant.

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List of Abbreviations

ACA ..... Anisotropic conductive adhesive
AWG ..... American wire gauge
DIN ..... Deutsches Institut für Normung
DITF ..... German Institutes of Textile and Fiber Research Denkendorf
DoE ..... Design of experiments
E-textiles ..... Electronic textiles
ECG ..... Electrocardiogram
ICA ..... Isotropic conductive adhesive
IDC ..... Insulation displacement connection
ITFT ..... Institute for Textile and Fiber Technologies
LED ..... Light emitting diode
NCA ..... Non-conductive adhesive
Nd ..... Neodymium
PCB ..... Printed circuit board
SAC305 ..... Sn96.5Ag3Cu0.5
SEM ..... Scanning electron microscope
SMD ..... Surface-mounted device
TPU ..... Thermoplastic polyurethane
TSL ..... Textile signal lines
TWP ..... Tailored wire placement
YAG ..... Yttrium aluminium garnet ($Y_3Al_5O_{12}$)

List of Symbols

n .... Empirical value

n_f .... Number of factors

n_l .... Number of levels

n_{wire} .... Number of wires with the test length of 100 mm

$R_{contact}$ .... Contact resistance in Ω

R_{total} .... Total resistance in Ω

R_{wire} .... Wire resistance in Ω

1 Introduction

1.1 Smart Textiles

The integration of different functionalities into one system is a current trend in product development processes as well as in the textile industry [1]. Textiles can get an additional function through the use of a special material, their composition or structure. Functional textiles can have one or more of the following attributes:

- Electrically conductive
- Thermally conductive
- Heat radiation emitting
- Optically conductive.
- Fluorescent
- Phosphorescent
- Releasing substances

Smart textiles are functional textiles which interact reversibly with their environment and react or adapt to changes in their environment. They offer the advantages of a textile structure with an additional functionality. Smart textiles can have the following properties for this interaction:

- Chromogenic
- Phase change
- Active ingredients
- Shape memory
- Superabsorbent
- Auxetic
- Dilatant shearing
- Piezoelectric
- Thermoelectric
- Photovoltaic
- Electrolytic
- Capacitive.

Smart textiles are part of smart textile systems which are classified in terms of their energy demand (with / without an externals energy source) and their ability to communicate (with / without communication) (Tab. 1.1). [2]

Tab. 1.1 Categories of smart textile systems and examples for the categories [2].

	Without communication	**With communication**
Without external energy	Textiles with a phase change material	Textile with a photo chromogenic paint to detect the temperature
With external energy	Textiles with a photovoltaic module and no communication	Textile with a sensor and an information system

Smart textiles can also be differentiated according to their degree of integration. Initially, electronics can only be applied onto the textile. The next higher degree of integration is the partial implementation of electronics during the textile manufacturing process or the use of the textile structure as electric circuit and the subsequent attachment of further parts. The next higher level is the complete integration of electronics during the manufacturing process. The use of the textile structure as electronic element or sensor represents the apex of this development (Fig. 1.1).

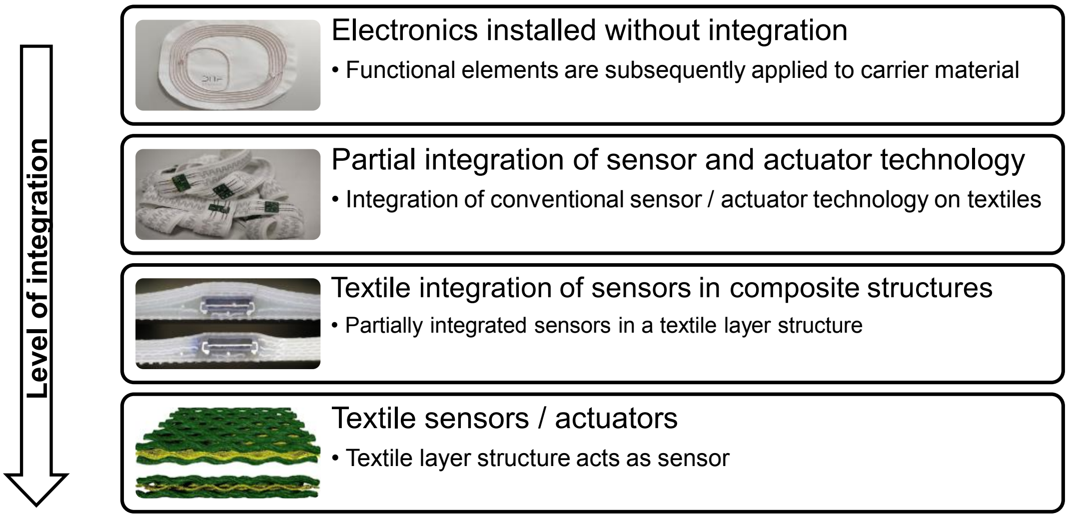


Fig. 1.1 The diagram shows different levels of integration of electronics in smart textiles.

According to current studies, the market volume of intelligent textiles will grow significantly in the coming years. Smart textiles are part of future high-tech materials. Hereby smart textiles will have a wide range of applications in many different industries. The functional plus makes the textiles ready for innovative special solutions. Examples can be found in smart home applications, in the smart city sector, applications for living walls and medical textiles. In addition to the current medical, space and military applications, the usage will expand into the fields of fashion and sports [3–6]. Clothing will be equipped with actuators or sensors. In the future, controllable functions such as actively cooling or self-luminous, will make them suitable for sports- and workwear as well as medical products. Other areas of application could be the automotive and construction industries, including consumer electronics as well as the digitalized production and logistics of the future.

The overall target of most of the research and development activities is to fully integrate sensors / actuators, energy sources, processing and communication within the clothes [7]. The full integration of electronics is also one of the main issues to ensure a dynamic wearability and high acceptance for smart textiles [8]. Here, fully integrated EKG Shirts for the sports and medical sector are one of the first areas of application [9].

The development is driven by the trend towards small and portable electronic systems as well as the increasing demand on miniaturized and flat packaging. The miniaturization of electronic components will make it possible to build useable smart textiles [10]. Their processability in textile machines will boost the smart textiles market even further. This potential has also been recognized by large German companies such as Lufthansa and Telekom [11]. The objective of these companies is to expand their market penetration in the field of smart textiles (Fig. 1.2).

(a) (b)

Fig. 1.2 Applications of smart textiles: (a) Firefighters and (b) Sports.

1.2 Motivation

However, currently there is no real market breakthrough. One of the challenges in the smart textiles production is to obtain the usual textile properties such as haptic, washability, wearing comfort and drapability. At the same time, the textile must be able to endure changing environmental influences and high mechanical and chemical load during a laundry process [12]. In many cases this unavoidable stress leads to the development and usage of hybrid products, which consist of textiles and electronics [13]. At the moment the production of these hybrid products is still limited due to the lack of cost-effective integration methods and the high proportion of manual steps during production [6]. In addition, the high proportion of manual production steps results in high prices, which slow down market growth.

Therefore, this thesis focuses on an automated contacting process with textile integrated insulated wires. These wires are located inside the textile. Components can be connected from both sides. Automated methods for connecting PCBs to insulated wires have not been sufficiently investigated in the literature, yet. Gopalsamy et al. already recognized that the connection between textiles and electronics is the most challenging part of the production [14].

Moreover, connecting electronics and stretchable textiles automatically is a challenging task: Macroscopically, the textile structure is produced very homogeneously, but none of the sections resemble each other, thus the mechanical behaviour of the textiles always differs during processing. The varying properties lead to problems in the positioning between the stretchable textile and the electronic. Further, the durability of the contacts is another big problem regarding the expected high mechanical stress on the textiles.

All current processes have difficulties due to one of the following aspects: Mechanical strength, durability of the contacts, fatigue resistance and implementation on an industrial scale. The transition between solid conventional sensor technology and the soft, flexible textile is the main weak point in the design of smart textiles. In particular the connections between the textile and the electronic are the points of weakness.

2 State of the Art

2.1 Production Methods for Smart Textiles

There are several forms of smart textiles, so every element has its own production process and different levels of integration require different raw materials. When looking at the integration of conventional sensors to conductive textiles, there are various possibilities to produce conductivity in textiles. Smart textiles can be distinguished between enabling conductivity during and after die textile manufacturing process. Afterwards they can differentiate between different kinds of conductive material (Fig. 2.1). This thesis covers only conductive textiles with metallic conductors, which were inserted during the manufacturing process.

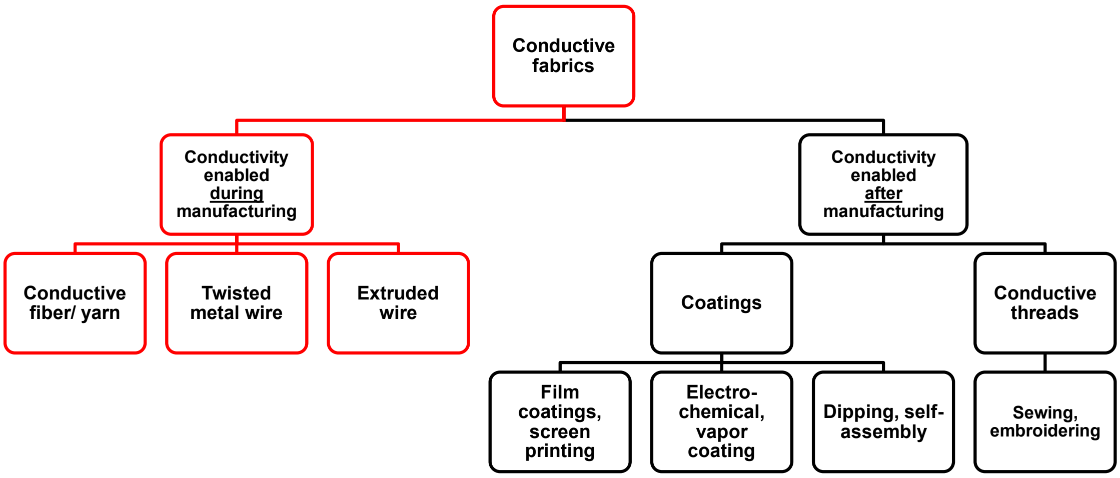


Fig. 2.1 Techniques to enable conductivity in textiles following [15]. This thesis only considers conductive textiles with metallic conductors and conductive yarns, which were both inserted during the manufacturing process (red).

The manufacturing process typically consists of three steps (Fig. 2.2). First, the wires are automatically stripped by a laser [16]. Afterwards, the connection process starts. In a final production step, the electronics are locally over-molded with polymer to protect the PCBs from environmental influences like water, chemicals, gas and mechanical stress. An automated silicon injection through an injection molding machine enables shorter cycle times and higher, reproducible quality. Another crucial factor during production is the position of the electronic in the mold. Moreover, high temperatures and pressure can damage the PCBs [4, 17].

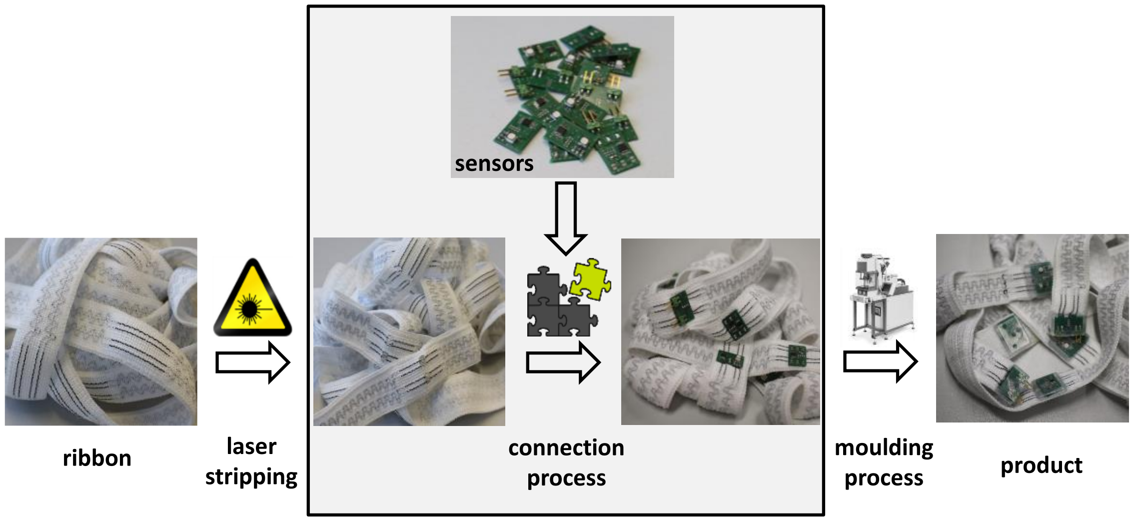


Fig. 2.2 Schematic production process for joining electronics to textile integrated, insulated wires.

2.2 Connection Methods for Smart Textiles

There is a large number of different ideas, which were tested to integrate electronics into fabrics. Some consider the fabric only as a carrier for electronic equipment, while others connect the electronic with standard cables. All try to use electronic functionality in an unobtrusive and comfortable way. In any case, there are several approaches for the integration of electronics into fabrics [15]. In this thesis, however, only those methods will be considered, which deal with the integration of conventional PCB electronics in textiles. Thus, all directly printing approaches on textiles (2D / 3D) are not considered. The PCBs may be equipped with different sensors or actuators to bring the function into the textile [17].

The integration of electronics to smart textiles built two connections: The mechanical connection to the textile and the electrical connection to a conductive structure. The function of the smart textiles is only guaranteed if both connections are reliable. In this thesis, connection methods are distinguished between their types of fitting: Substance-to-substance, form-fit and force-fit connections (Fig. 2.3). Procedures, which belong to more than one type of fitting are mapped to the more reasonable category.

Apart from the above mentioned, also other mapping possibilities exist. For instance, Castano et al. distinguished between types of bonding: Mechanical, physical, chemical or electrical bonding [4].

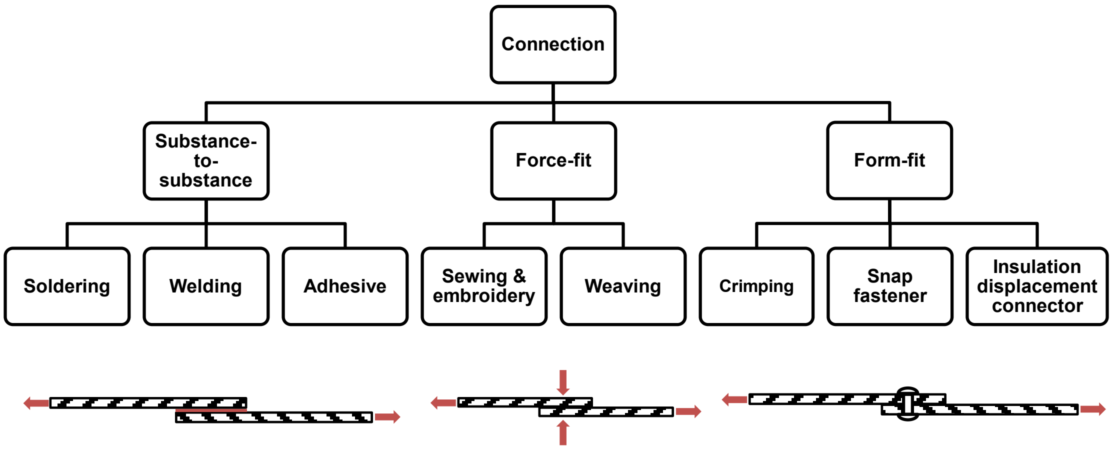


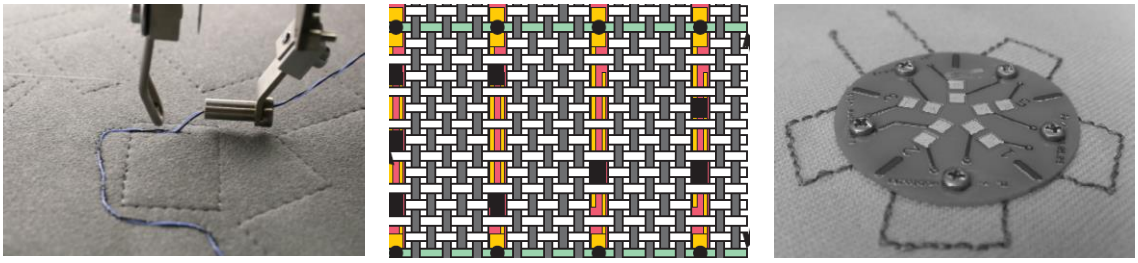
Fig. 2.3 **Different joining methods, which are suitable for the connection of electronics to textiles assigned to fitting method.**

2.2.1 Force-Fit Connections

The movement of binding partners with a force-fit connection is prevented by static friction. Friction requires normal forces, which mean forces perpendicular to the surfaces of the components (Fig. 2.3). The normal forces generate static friction, which counteracts the movement. Examples for these connections are knotted ropes but also any kind of clamp, press-fit or screwed connections.

There were different approaches for the attachment of electronics to textiles by using force-fit connects. In 1998 the first institutes started to embroider and sew PCBs on textiles (Fig. 2.4). Linz et al. investigated embroidered connections to flexible electronics with conductive yarns. This investigation enabled a connection with different modules, like sensors or batteries. They encapsulate the connections to improve the electrical contact and to support the reliability of the entire system. It was found that triple stitched contact pads were more conductive than individually sewn pads. They tried to define design rules for the embroidered interconnections. Therefore, four different contact pad designs were tested. Yet all of them had problems with conductivity after different reliability tests [18].

Weaving is another force-fit production method for smart textiles. Varga et al. developed a concept for the integration of electronic to textiles by weaving. The electronic can be placed between two conductive layers. They do not use an additional connection method. The complexity of the electronic and the number of in- and outputs determine the number of conductive threads in the woven textile. Currently it is only suitable for regular orthogonal structures [19].



(a) (b) (c)

Fig. 2.4 Force-fit connection methods for smart textiles: (a) Embroidery, (b) Weaving [20], (c) Screwing [21].

Another force-fit connection method is to screw the electronic on the textile. Simon et al. developed and integrated a force-fit interconnection, which was screwed into the textile. Therefore, they clamped a resistive textile between two circuit boards and screwed them together. Subsequently, they investigated the influence of the applied force and the used strips or yarns on the contact resistance. This method is not suitable for automated mass production. Thus, it should not be investigated any further in this study [21].

2.2.2 Form-Fit Connections

Form-fit connections have the advantage that they can form electrical and mechanical connections without thermal stress on the substrate. Form-fit connections open up a wide range of different electrical connectors. At least two connection partners usually interlock on a larger surface, which makes them predestined for the connection of electronics and textiles. Textiles can be clamped over a longer section or a wider surface. The deformed connection partner can typically only be used once. Other connections consist of two joining partners, which are attached through a connector. The connector links the joining partners perpendicular to the surface and applies a compressive force. The force prevents most of the movement directions between the joining partners and creates a form-fit as well as a force-fit connection (Fig. 2.5). In this context, snap fasteners are usually used in terms of textile technology. Snap fasteners allow the placement of larger evaluation units on textiles and the reversible removal of the units during a possible wash cycle. Snap fasteners are not an option for the integration of miniaturized electronic components, such as sensors or actuators to textiles. Only one connection can be made and a snap fastener usually has the dimensions of a complete sensor. However, a bus system usually requires three or more connections, thus sensors usually cannot provide the necessary space for installation. [9, 22–25]

Crimp connections are robust, reliable, low-cost, fast and easy to process. Simon et al. developed multi-terminal crimp packages to integrate them into large-area smart textiles

(Fig. 2.5). The woven textiles had integrated conductive yarns inside and, therefore, special forming tools were designed. These tools were able to bend eight pins at the same time, so they were able to applicate adjacent crimp terminals much faster than with serial production steps. [26]

Insulation displacement connections (IDCs) are a technique based on making an electrical connection by clamping a conductor into a contact (Fig. 2.5) [27]. In contrast to crimped contacts, the conductor and the connector are plastically deformed. Lehn et al. used insulation displacement connectors, especially ribbon cable connectors, for the integration of PCBs to textiles. The connections were made within the housing of the connector through the use of a sharp V-shaped contact that cuts through the insulation to connect the conductor [24, 28].

(a) (b) (c)

Fig. 2.5 Form-fit connection methods for smart textiles: (a) Crimping [26], (b) Snap fasteners, (c) Insulation displacement connections.

However, an assembly with cutters, sockets, pins, PCBs, and electronics provides a big block on the textile without any protection against environmental influences. A significant problem with these connectors is the potential of cutting the wire during mounting.

2.2.3 Substance-to-Substance Connections

Substance-to-substance bonds are the most common compounds in the electronic industry. This type of bond offers a very diverse and broad field for connections. They are characterized by the fact that under normal circumstances they cannot be dissolved without destroying them. The compounds are produced with or without an additive of the same or different type of material. The advantages are the high transmission of forces and moments as well as the small space requirements. However, not every material is suitable for all connections. High temperatures during production can cause internal tensions in the connection.

Adhesive Bonding

Non-conductive adhesives (NCA) bond the two contact points without additional fillers to each other (Fig. 2.6). Linz et al. presented a new technology to connect conventional electronics with conductive textiles. They introduced flip-chip connections with NCA as a reliable method for contacting rigid electronic modules to fabric substrates. They used thermoplastic polyurethane as non-conductive adhesive. During the process, they tried to bring the PCB and the adhesive in contact. Afterwards, they used load and temperature to melt the adhesive. If the isolation of the textile integrated wires has a lower melting point than the thermoplastic polyurethane (TPU) adhesive, wires with insulation can be connected [29]. The curing time of NCA connections is a limiting factor in raising productivity. Furthermore, it is difficult to ensure a reliable connection rate in mass production.

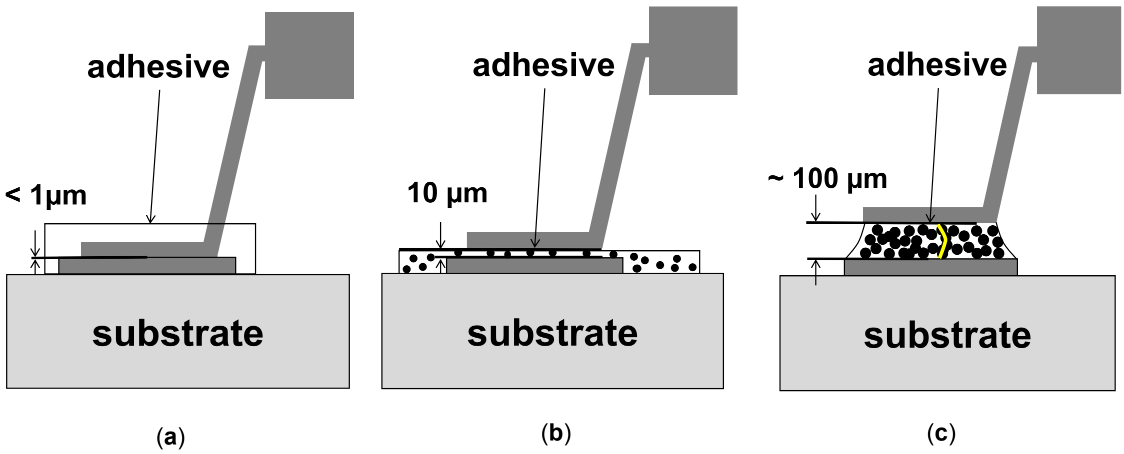


Fig. 2.6 Substance-to-substance connection methods for smart textiles: (a) Non-conductive adhesives, (b) Anisotropic conductive adhesives, (c) Isotropic conductive adhesives.

Anisotropic conductive adhesives (ACA) have a significantly lower filler content than isotropic conductive adhesives (ICA). The distance between the particles in the insulating polymer matrix is so large that no contact between the particles takes place. This prevents short circuits (Fig. 2.6). Moreover, the particle size (10 – 15 µm) of the filler is smaller than the filler size of ICA. The joining of the contact points occurs under pressure. The pressure compresses the adhesive layer to the particle diameter. The specific resistance in the direction of the line is low (10^{-4} Ωcm). The resistance across the line is sufficiently high to prevent short circuits in many applications (10^{14} Ωcm). Therefore, ACA is especially suitable for the connection of many contacts, which are located in a confined space. [30, 31]

ICA are characterized by a high degree of conductive fillers (Fig. 2.6). Specific resistances are between 10^{-3} – 10^{4} Ωcm. The particle size is between 10 – 50 µm. Silver and gold offer the best conductivity. Oxides (foreign layers) on the conductive particles (especially on silver) have a significant negative influence on the specific resistance [30, 32]. Areas of application for isotopically conductive adhesives include, for example, the contacting of components that are particularly sensitive to heat, and the creation of conductive connections in the high-temperature range [33].

Soldering

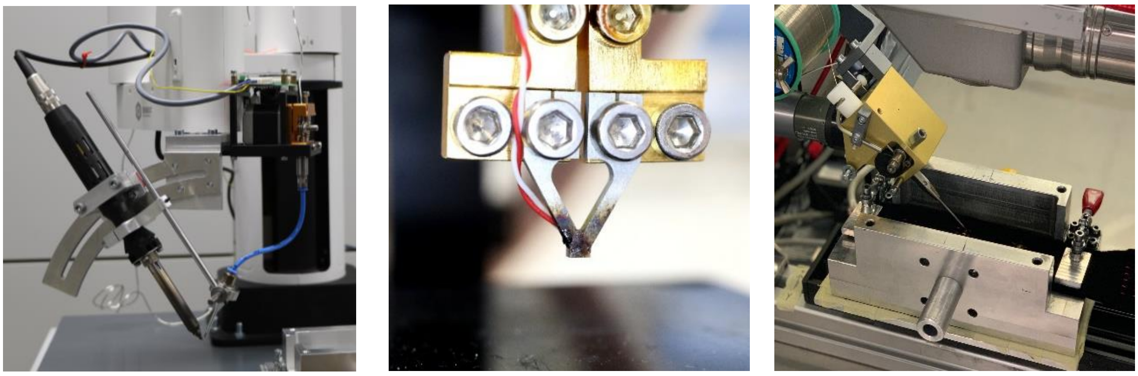
Soldering is the most common joining technology in the electronics industry. Two metallic materials are joined by soldering, using an additional material (solder) and the application of heat to create a mechanically sealed and electrically conductive joint. The melting temperature of the filler material is always below the melting point of the base material. Liquidus temperatures of up to 450° C are used for soft-soldering. At higher working temperatures, the process is referred to as brazing. Due to the long-term use of the technology, problems during production and the possibility of errors can be kept to a minimum. The suitability of the materials, the applicability of the soldering process and the solder-safe design are the prerequisites for proper soldered joints. This thesis will only present the most promising soldering techniques for the automatic integration of electronics to textiles (Fig. 2.7):

- Hot bar soldering (chapter: 4.1)
- Ultrasonic soldering (chapter: 4.2)
- Laser soldering (chapter: 4.3)

Laser soldering provides a defined heat input, which can prevent highly sensitive components from being destroyed. The technique has already been applied in the production of electronics on PCBs [34–36]. Laser soldering offers several advantages to conventional soldering techniques [35]:

- Contactless, locally limited energy application
- Well-controlled energy input
- Low thermal stress
- Reduced intermetallic compound formation
- Fine grain size due to rapid cooling
- Low maintenance

Different types of laser are suitable for soldering [37]. Nd:YAG lasers are solid state lasers. They use yttrium aluminium garnet (YAG) doped with neodymium (Nd) as a lasing medium. They emit at a wavelength of 1064 nm. Beam energies of 10 – 20 W are normally used for soldering [38]. The emitted spectrum of Nd:YAG lasers is absorbed by metallic surfaces.



(a) (b) (c)

Fig. 2.7 Substance-to-substance connection methods for smart textiles: (a) Ultrasonic soldering, (b) Hot bar soldering, (c) laser soldering.

Diode lasers offer a wavelength between 790 nm to 980 nm. The wavelength can be adapted by varying the Al-doping of the $Al_xGa_{1-x}As$ semiconductor [39]. Comparing diode lasers with Nd:YAG lasers, diode lasers offer many technological advantages for laser soldering. The shorter wavelength has a high absorbance on metallic surfaces, which makes the process more flexible and powerful.

Welding

Welding is a joining process that creates a continuity of the material by heating and or by pressure, and with or without any additional joining materials. Welded joints are substance-to-substance bonds. Thus, they are inseparable connections and can only be separated by destruction. 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. The welding process can be categorized in two main groups: Fusion welding and solid-state welding [40].

Fusion Welding: The joining partners are locally heated above the melting point without any application of force. Fusion welding differs in terms of heat input. Depending on the welding process, the joining process is carried out with or without filler metal. The joining process takes place within the metallurgical structures by coalescence, which requires a similar melting point of the two joining partners for weldability. Fusion welding processes are often used to join metals of the same type.

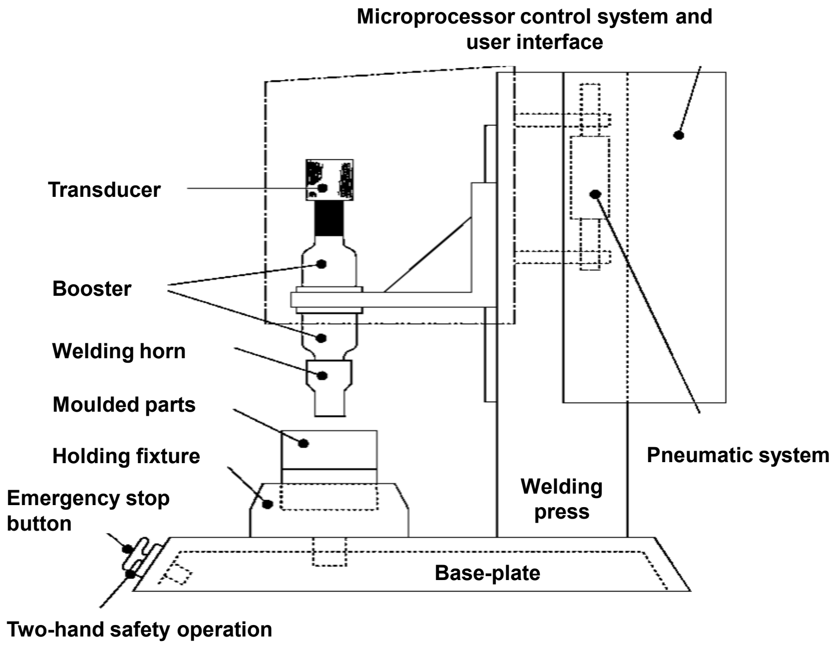


Fig. 2.8 Substance-to-substance connection methods for smart textiles: Ultrasonic welding [41].

Solid-state welding differs from fusion welding in two main effects: Diffusion happens at room temperature and at metallic surfaces. The material is not or only partially melted and often the melting temperature is not reached. Depending on the process, there even can be no heat input at all. The application of pressure on the joining partners is necessary for all solid-state processes. Diffusion processes and grain growth start by bringing the metallic surfaces into contact. A higher pressure leads to larger grains, whereby these are distributed in homogeneously beyond the joining zone [42]. Larger grains lead to a reduced ductility. The joint acquires a similar strength to the original material, even if diffusion has not taken place at every point of the joint gap. Solid state welding processes immensely reduce the formation of pores through gas inclusions. Furthermore, erosion or embrittlement does not occur. 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. Ultrasonic welding belongs to the category of solid-state welding (Fig. 2.8). On a microscopic level, it can be seen as a combination of friction welding and cold welding [43, 44].

3 Research Gap, Working Hypotheses and Approach

3.1 Research Gap and Working Hypotheses

Several research projects proposed to connect PCBs or other electronic components to conductive textiles. The focus of most of these research projects was so find a connection method between electronic components and silver coated conductive polyamide yarns. But these yarns have disadvantages due to their mechanical and electrical properties. These connections have a lack of reliability and potential for mass production. In this case, the use of metallic conductors and conventional electronic components offers a remedy.

Comparing textile integrated metallic strands and textile conductive yarns, similar fine structures can be achieved, which do not influence the textile character of the fabrics. Moreover, metallic strands have many advantages due to isolation, conductivity and reliability. For the use of metallic conductors, textile-specific joining methods have not yet been sufficiently investigated. Therefore, a textile-specific joining process for contacting textile-integrated metallic conductors with conventional electronics and textile sensors will be identified and analysed. Promising processes will be studied and developed for textile-specific use. Attention is paid to the fact that all the processes are suitable for the automated assembly of textiles with sensors or actuators.

Currently, there is no suitable method for contacting PCBs to litz wires in smart textiles. The contacting processes developed in this thesis are analysed and developed specifically for use in smart textiles. Impact parameters will be investigated and put in relation to target parameters, which focus on the reliability of the contact. Electrically the contact resistance and mechanically the peel strength are the most important parameters. A scientific model will be derived from this. Therefore, this thesis is based on the following working hypotheses:

1. Adaption of joining processes from the electronic industry: Hot bar soldering, ultrasonic soldering, laser soldering, IDCs and ACA to join PCBs to textile-integrated metallic conductors.
2. The adapted joining methods enable secure connections between the textile integrated litz wires and PCBs.
3. The developed and adapted joining processes enable an automated integration of PCB sensors to textile-integrated metallic conductors.
4. Ultrasonic welding is suitable to connect full textile sensors to insulated metallic litz wires.

3.2 Objectives

This thesis aims to solve one of the most challenging topics in designing and constructing electronic textiles (e-textiles): The automated integration and connection of conventional electronic hardware components to textiles, while ensuring the textile properties: Drapability, flexibility, handling and feeling. The integration of PCBs to smart textiles enables various functionalities (chapter 1.1). Thereby the measurement accuracy is comparable with conventional electronic sensors. Moreover, many functions can be realized in very small units. The **first objective** focuses on the evaluation of the most promising integration method of PCBs to conductive ribbons using established processes from the electronic industry and adopt them to smart textiles: The Adaption and development of connection processes, which are applicable to integrate PCBs to smart textiles.

Smart textiles are exposed to high loads, during use. At the same time highly, conductive connections between the electronic components are elementary for the transmission of energy and data. In the **second objective**, the focus is on developing reliable connections between the textile integrated litz wires and PCBs and to evaluate these connections due to their mechanical and electrical properties. For this purpose, measuring methods have to be developed, which are suitable to evaluate the mechanical and electrical properties of the connections.

Due to the high proportion of manual tasks during the production of smart textiles, they tend to have high prices. A large portion is generated during the bonding process and the associated work steps. At the same time, high costs reduce the market success of smart textiles. The **third objective** is to adopt a suitable process for the automated production of smart textiles and to partially automate the process.

The full integration of sensors in textiles is advancing. A direct cable connection between textile sensors and a central evaluation unit is desirable for a valid data transmission. A robust connection between textile and wire makes it possible to produce smart textiles with both textile and conventional sensors. The **fourth objective** was to connect conductive textiles to litz wires trough ultrasonic welding.

3.3 Approach

The already given overview of the wide range of problems and objectives shall act as the motivation for the presented study. It focuses on investigating and finding a reliable, cost and time efficient as well as automatable way of connecting electronic components to conductive textile structures. In this study, various processes will be analysed, regarding their textile-specific adaptability for the integration of electronics to textiles. Processes that may be particularly suitable for joining electronics to textiles are subsequently modified for textile-specific applications. After development and several textile specific modifications, the processes will be investigated in terms of their mechanical, metallurgical and electrical properties. For this reason, the mechanical properties of the connections are analysed in self-developed peeling test. The test allows to determine whether the connection is strong enough for further production steps. The electrical properties are analysed in a four-wire resistance measurement test. The four-wire resistance measurement allows to eliminate resistances from the connected wires and to investigate the joining itself. The scientific studies include aspects of contacting, the use of joining aids, their effect on the joint as well as their adaptability for textile-specific use and the possibility to automate the production.

Initially, the use of force-fit connections for the automated integration of electronics into textiles was virtually rejected and the most promising connection methods were considered to be in the area of form-fit and substance-to-substance connections. Therefore, hot bar soldering, IDC and ACA were chosen to investigate regarding their suitability for the application of PCBs to smart textiles. IDC proved to be too large for microelectronic application and sufficient miniaturisation cannot ensured. ACA were not strong enough and had poor conductivity. In hot bar soldering, an additional work step is necessary to apply the solder paste. When soldering with flux, more solder enters the stranded wire. The solder stiffens the stranded wire also outside the soldering point and makes it brittle. Flux-free soldering with ultrasound reduces this problem.

Therefore, ultrasonic soldering was developed and optimized for the automated manufacturing of PCBs to smart textiles. Additional ultrasonic movement of the solder tip removes boundary layers on the surface, which ensures solderability without flux. Due to the absence of flux, less solder penetrates into the wires and they become less brittle. The entire textile retains with a higher flexibility.

But contactless joining processes enable significantly smaller treatment zones around the contact points, so the textile is weakened less through the process. For this purpose, laser soldering is predestined. Hence, the parameter of a pulsed Neodymium Yttrium aluminium garnet ($Y_3Al_5O_{12}$; wavelength: 1064 nm) laser for the integration of electronics to smart textiles were investigated and automated. A special diode laser for soldering with a wider focus and a wavelength of 940 nm was installed in the final automation system.

The Ultrasonic welding technology makes it possible to connect insulated micro cables directly to textile sensors and to evaluate their signal. For this purpose, different parameter sets were examined and their functionality was also tested after 15 and 30 washing cycles.

The development of connection methods between textile-integrated conductors and microelectronics as well as textile-integrated conductors and textile sensors enable the flexible construction of smart textiles (Fig. 3.1).

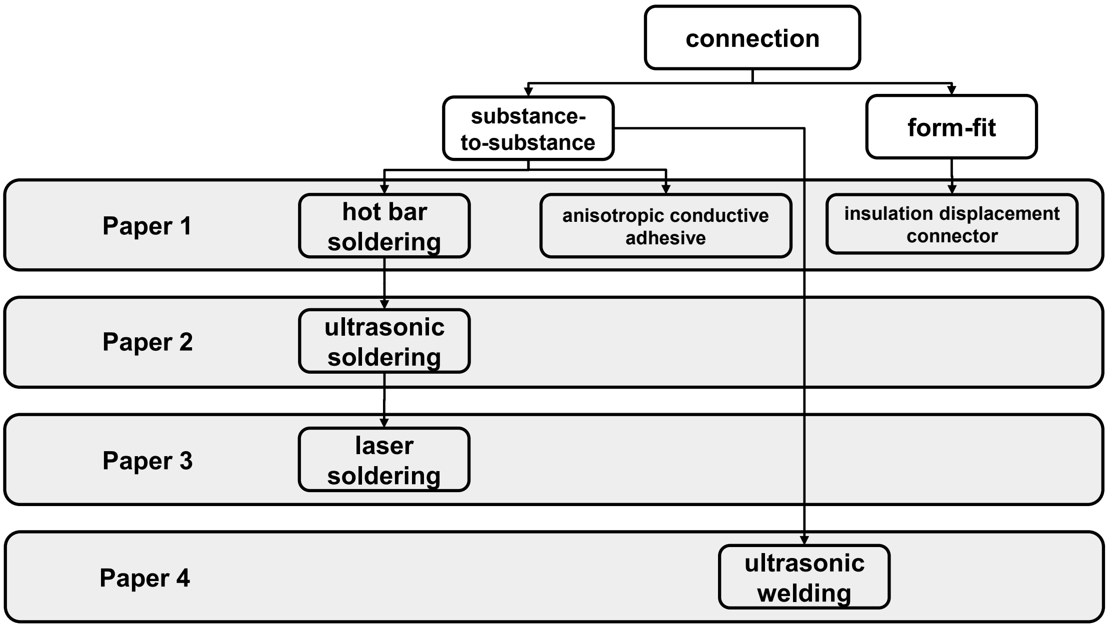


Fig. 3.1 Approach for developing methods to connect microelectronics to smart textiles.

4 Publications

4.1 Analysis of Hot Bar Soldering, Insulation Displacement Connections (IDC), and Anisotropic Conductive Adhesives (ACA) for the Automated Production of Smart Textiles

Publication Date: 18. December 2019

Authors: Micus, S.; Kirsten, I.; Haupt, M.; Gresser, G.T.

In: MDPI Sensors 2020, 20(1), 5;
https://doi.org/10.3390/s20010005

Within the first paper three different connection methods with high potential for automated integration of electronics on textiles are analysed: (1) hot bar soldering, (2) insulation displacement connections and (3) anisotropic conductive adhesives.

These connection methods showed only conditionally suitable results for their use in an automated production line for smart textiles. The adhesive bonding process had weaknesses due to inadequate contacting. The contacting of the thermode soldering initially showed greater success. However, it was not possible to prevent the solder from being drawn into the strands by varying the soldering parameters. In addition, the used IDC connectors are not suitable in practice. Available connectors for AWG 32 were not found, which would allow to connect the original strand size without breaking the wires. Furthermore, the investigation showed that an automated positioning of the textile ribbon is another challenge on the way to an automated production line for smart textiles.

Summary of the individual contribution:
Sebastian Micus developed the idea for the presented investigation and leaded the investigation himself. He evaluated the results of the series of experiments and wrote all paragraphs of the publication. As part of the presented research, he also developed a four-wire resistance test stand for the electrical characterisation as well as a peel test stand for the mechanical characterisation.

sensors

MDPI

Article

Analysis of Hot Bar Soldering, Insulation Displacement Connections (IDC), and Anisotropic Conductive Adhesives (ACA), for the Automated Production of Smart Textiles

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Abstract: Despite all the growth forecasts of the smart textiles market, there is no stable automated manufacturing process for attaching classic electronics to textiles. The great amount of manual production steps causes high prices, which slow down market growth. During the production process, the contacting step offers the greatest potential to reduce manual manufacturing steps. For this reason, we have analyzed various contacting methods for electronic parts on conductive yarns that have a high potential for automation. The chosen methods were thermode soldering, insulation–displacement connectors and anisotropic conductive adhesives. In order to ensure reliable mechanical contacting, the samples were tested in a peeling experiment. The examination of the contact resistances took place in the context of a resistance test using four-wire measuring technology.

Keywords: smart textiles; joining method; joining technique; joining processes; soldering; bonding; integration of electronics

1. Introduction

Current studies confirm that the market volume of smart textiles will grow significantly in the coming years. In addition to the current medical and military areas of application, as well as occupational safety application will spread to the areas of fashion and sport [1]. At the moment, however, we cannot see a real market breakthrough. One of the reasons for the low market penetration of electronic textiles is the high share of manual tasks during their production [2]. Furthermore, the high proportion of manual production steps ensures high prices, which slow down market growth. This is the reason why the German Institute of Textile and Fiber Research (DITF) has searched intensively for automatable contacting methods. In this paper, we have focused on isolated wires. These are inside the textile, meaning it is possible to join components from both sides. Automated methods for contacting printed circuit boards PCBs to isolated wires have not yet been sufficiently investigated in the literature. The production process typically consists of three steps. At first, the wires are uninsulated automatically by a laser. After this, the main contacting process starts, which is investigated in this paper. In order to protect the electronics from environmental influences, the components are encapsulated in an injection molding process [3]. For this reason, we have investigated the mechanical properties of the contacts in a peeling test. This makes it possible to determine whether the connection is robust enough for further production steps.

1.1. Hot Bar Soldering

Hot bar soldering is one of several solder processes for contacting PCB to textiles [4]. A pulsed heat thermode is used to join two pre-tinned parts. This technology is suitable for mass production and involves reliable processing conditions and results. It is a very cost-effective process because multiple connections can be made simultaneously and it has a fast temperature ramp-up and cool-down rate [5]. Hot bar soldering was developed for simultaneously soldering many wires (Figure 1a) [6]. It is a re-flow process using a thermode made of titanium [7] or molybdenum. For a defined force application a linear guide with a force gauge is used. By measuring the sinking path, correct positioning of the component and the melting of the solder can be determined [5,6,8,9]. The contacting process of the hot bar soldering system starts by pressing the thermode with a defined force on the contact point. For many processes a force of less than 20 N is sufficient. The thermode heats and cools according to the reflow profile [7]. Overall, thermode soldering is relatively easy to automate. The automated positioning of the contact partners is one of the challenges which can be simplified through positioning pins. Woznicki [10] describes problems with very small pad pitches [10].

1.2. Insulation Displacement Connection (IDC)

Insulation displacement connection is a technique based on making an electrical connection by clamping a conductor into a contact [11]. In contrast to crimping, only the conductor is deformed, not the contact. Lehn et al. [12,13] use insulation displacement connectors, especially robbon cable connectors, for the integration of PCDs in textiles. The connections are made within the housing of the connector through the use of a sharp V-shaped contact that cuts through the insulation to connect to the conductor. An assembly with cutters, sockets, pins, PCBs, and electronics provides a big block on the textile without any protection against environment influences. A significant problem with these connectors is the potential of cutting the wire. Lehn himself makes the suggestion to mount IDCs directly on PCBs to obtain a smaller package [12,13]. Martin et al. [14] present a case study of a prototype sensor jumpsuit for motion capture. They integrated isolated wires to the textile. The different sensors were connected to the wires in special areas. The sensors and wires were connected by IDCs [14].

1.3. Adhesive Bonding Methods—Anisotropic Conductive Adhesive (ACA)

Linz et al. [15] investigated non-conductive adhesive (NCA) bonding to integrate electronics to textiles. They introduced NCA as a reliable method for contacting rigid electronic modules to embroidered fabric substrates with metal-coated polymer yarns [15]. Furthermore, Linz et al. [16] performed investigations with laser-structured conductive fabrics laminated onto non-conductive fabrics. In the following, they used harsher reliability test conditions and more detailed investigations of non-conductive adhesives to confirm the advancement of this technology [16]. Krshiwoblozki et al. [17] used mechanical reinforced litz wires with and without insulation. They showed the interconnection to woven highly conductive metal-coated polymer yarns. In addition, the selection and investigation of a suitable thermoplastic insulation material was investigated [17]. Hence, the total potential of adhesive bonding methods has not yet been fully realized [18].

2. Materials and Methods

In this paper we selected three different contacting methods for which we perceive a high potential for automated integration of electronics on textiles:

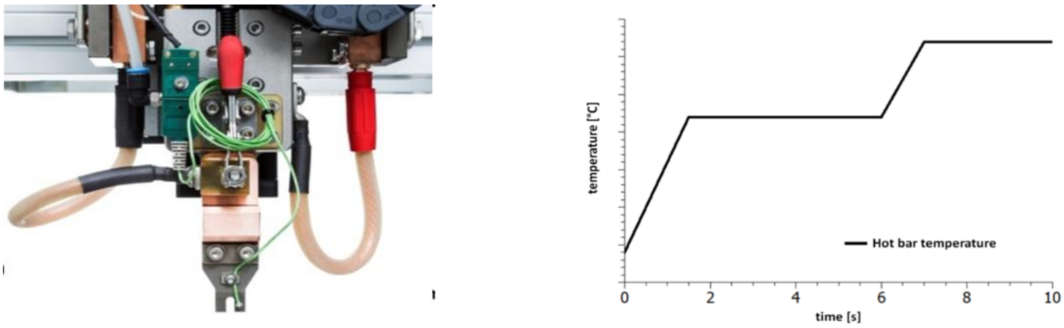
- Hot bar soldering has high potential for the automated production of smart textiles due to the parallel application of pressure and temperature as well as the simultaneous soldering of several places.
- Insulation displacement connections compensate for poor manufacturing accuracy and the associated positioning problems of textiles with their V shape.

- Anisotropic conductive adhesive prevents short circuits during the simultaneous curing of nearby contact points and has a much lower thermal impact on electronic parts [19].

In order to be able to compare the possible methods, 30 samples of each contacting method were prepared. The process was carried out on one-layered test boards which were optimized for contacting. The test boards were attached to a knitted tape of polyester fibers (synthetic fibers) with a width of 24 mm and a thickness of 1 mm. Four comparatively large contact points were used for contacting. A gold-plated male connector was manually soldered (Sn96, 5Ag3Cu0, 5 and 3, 5% flux) for minimization of contact resistance.

2.1. Hot Bar Soldering

For the sample preparation a hot bar soldering system from Nippon Avionics Co., Ltd. was used. The thermode used had a square solder surface with an edge length of 1.6 mm. The soldering profile had been developed in a previous test series (Figure 1b). The soldering took 10 s. In this test series, two-sided laser processing of the textile tape was used to strip the wires. The processing on both sides reduced residual insulation in the solder joint and significantly improved the wetting behavior. For every contact point 0.05 g solder paste which contained Sn96.5Ag3Cu0.5 with a metal content of 87.5% and grain size 3 was applied.

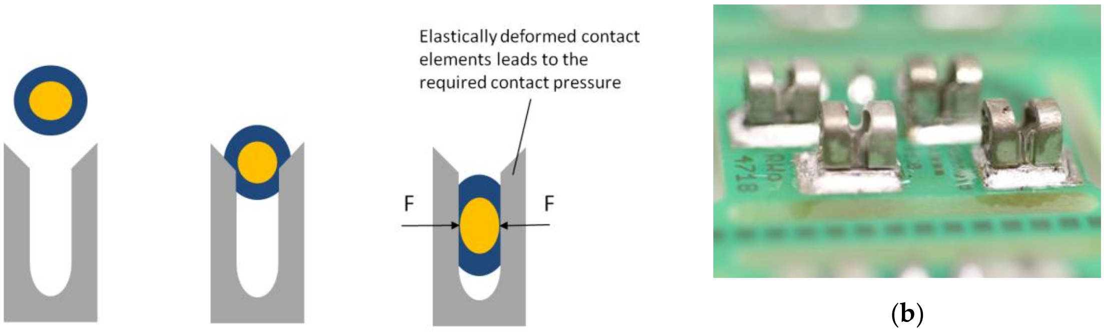


(**a**) (**b**)

Figure 1. (**a**) Picture of a hot bar soldering system with a 3D thermode and two contact points [17]. (**b**) Temperature profile of a thermode soldering process with a two-phase process; first step: heating and holding to activate the flux, second step: melting the solder and cooling down.

2.2. Insulation Displacement Connections

For contacting, an insulated conductor was pressed from above into a V-shaped terminal (Figure 2a). This process cuts open the insulation of the conductor and the conductor comes into direct contact with the clamp. The clamp deforms the conductor elastically and plastically by spring forces [20]. The elastic deformation of the conductor leads to the contact force required at the terminal to produce a gas-tight connection. Contact forces can be varied by the material thickness, shape, and the material used for the terminal contact. If the contact force is too low, this can result in an increased contact resistance and the formation of foreign films [21]. American Wire Gauge (AWG) 30 were used for IDCs because IDCs were not available for thinner conductors. We selected IDCs with the designation 1235 from Zierick. The height of the connector was 3.05 mm. The IDCs were conducted with solder (Sn96.5Ag3Cu0.5, 3.5% Flux ROL0) onto the contact pads of the test board (Figure 2b). We used a special press-in tool to connect the IDCs to the textile tape. All contacts could be made in a short time.



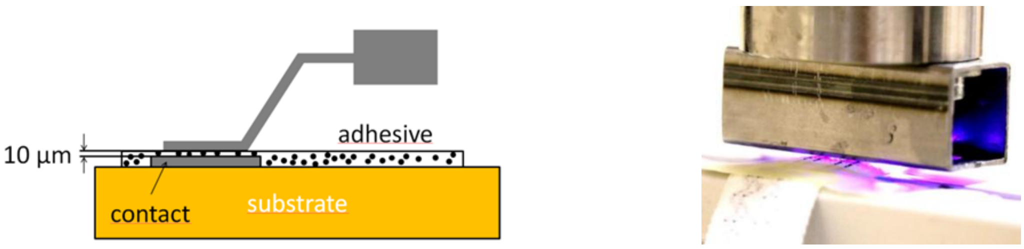
(**b**)

(**a**)

Figure 2. (**a**) Schematic drawing of the assembling of insulation displacement technology: before assembling (left), during assembling (middle), and after assembling (right) in style of Kirstein [4]. (**b**) Prototype of insulation displacement connections (IDCs) placed on circuit boards to integrate the boards in the textile.

2.3. Anisotropic Conductive Adhesive

ACAs have significantly lower filler content than ICAs (Figure 3a). The distance between the particles in the insulating polymer matrix is so large that no contact between the particles takes place. This prevents short circuits. At 10–15 µm, the particle size of the fillers is smaller than that of the ICA. The joining of the contact points occurs under pressure, which compresses the adhesive layer to the particle diameter. The specific resistance in the direction of the line is low (10^{-4} Ωcm). Across the line it has a significantly higher resistance (10^{14} Ωcm) which is high enough for many applications [22,23]. The adhesive samples were prepared with an anisotropic conductive acrylate-based adhesive. The contact surface area was measured to be 90 mm^2, so a force of 135 N was applied. Five UV-light-emitting diodes (395 nm LEDs) were installed into the tool to cure the adhesive (Figure 3b). For curing, a constant light intensity of 400 mW/cm^2 was used. The amount of adhesive was approximately 0.05 g on each test board. We assumed a shadow by the wires so that the adhesive could not cure completely by irradiation. This is why all adhesive samples were post-cured in an oven at a temperature of 100 °C for 20 min.



(**a**) (**b**)

Figure 3. (**a**) Schematic drawing of the contacting mechanism of an anistropic conductive adhesive (ACA); (**b**) stamp for load application and UV curing of the ACA.

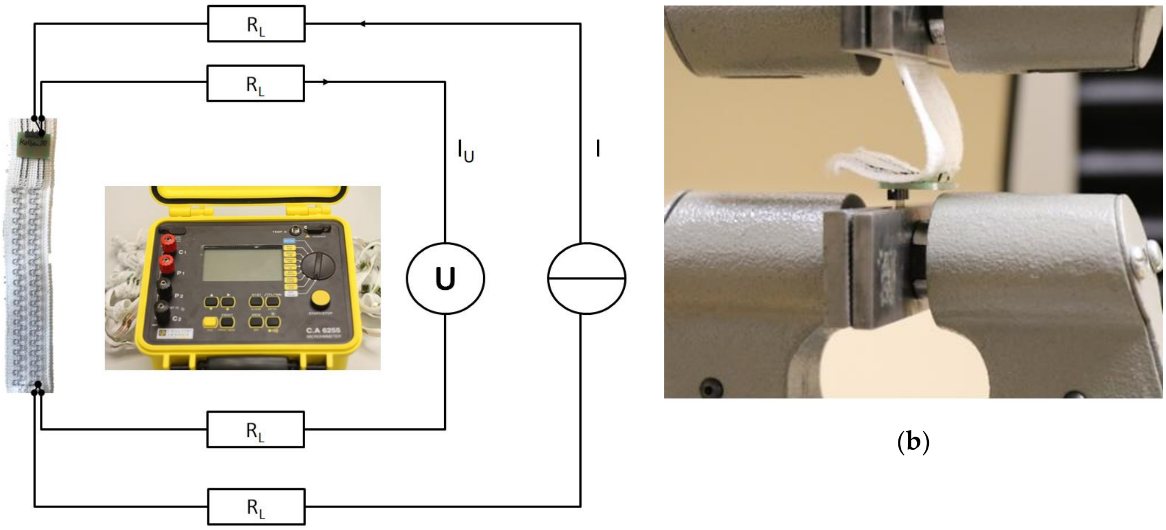
2.4. Standard Test Methods for Smart Textiles and Their Connections

2.4.1. Continuity Test Before and After Washing

Contact resistance measurement shows the quality of the contact itself. A four-wire measuring instrument, in this case a micro ohmmeter, is used to eliminate connection and line resistances (Figure 4a). The falling voltage at the resistor is measured with a voltmeter over the two remaining conductors. Based on Ohm's law it is possible to calculate the resistance of the contact. The contact resistances are in the range of only a few milliohm [24]. In order to generate a measurable voltage, high currents of up to 10 A are required.

2.4.2. Peeling Test

A peeling test was carried out to determine the mechanical strength of the joint for further processing. A self-developed peeling test is ideal for inspecting joints between PCBs and conductive textiles. The test boards previously attached for the contact resistance test were clamped into the tensile testing machine in such a way that the conductors peeled off the board at a 90° angle. The force was applied perpendicular to the board (Figure 4b). A load cell with a maximum force of 1000 N was used at a travel speed of 100 mm/min.



(**a**) (**b**)

Figure 4. (**a**) Measuring setup for determining the contact resistances using four-wire measuring technology. (**b**) Peel test setup in which the samples were clamped to the blank and pulled on the attached textiles with a speed of 100 mm/min.

3. Results and Discussion

Assessment of the contact quality was carried out using several tests. An initial assessment of a successful contact was provided by a visual inspection during a continuity test. A bearable maximum force was determined with a tensile test.

3.1. Continuity Test Before and After Washing

Contact resistance provides information about the quality of the contact points. To calculate the contact resistance, a four-wire measuring technique was used by way of the measuring setup from Section 3.4. The wire resistance as well as the contact resistance can be calculated using the formula

$$R_{ges} = R_1 + n \cdot R_L \approx 2 \cdot R_K + n \cdot R_L \quad (1)$$

where R_K = contact resistance, n = number of wires with the test length of 100 mm, and R_L: = wire resistance

According to the data sheet, the line resistance for hot bar soldering is 100 mΩ per conductor length (length 100 mm, AWG 32) and 25 mΩ (length 100 mm, AWG 32) for IDC. The line resistance can be determined by measuring different conductor lengths. Due to unreliable contacts the samples with adhesive joints could not be examined in all tests.

Figure 5 shows the nearly identical contact resistances of the soldered and the interlocking contact points. At the same time, information on the line resistances from the data sheets was able to be confirmed by the measurement procedure. After confirming that our measurement method was reliable we needed to simulate a mechanical, thermal, and chemical stress like that which occurs during the use of smart textiles. A resulting load was applied as an example for environmental influences. The samples were washed in a commercial washing machine at 40 °C and retested again. The washing process employed a heavy load because normally the contacts are molded in silicon. If the contact points are unprotected, the loads will be greater than expected during operation. After washing, 75% of the solder samples were faulty. Failure occurred mainly due to the breaking of wires near the soldered joint. This was caused by the solder being drawn into the wire. The drawn solder made the wires crumbly, brittle, and tend to break quickly under mechanical stress. Sixty-seven percent of the specimens with conductive adhesive came loose. This was possibly because of mechanical stress due to the high acceleration forces during the washing process which could not be eliminated due to a faulty bond. Samples with IDCs withstood the washing process. Only one out of 40 contact points failed. The stranded wire broke directly in front of a connector.

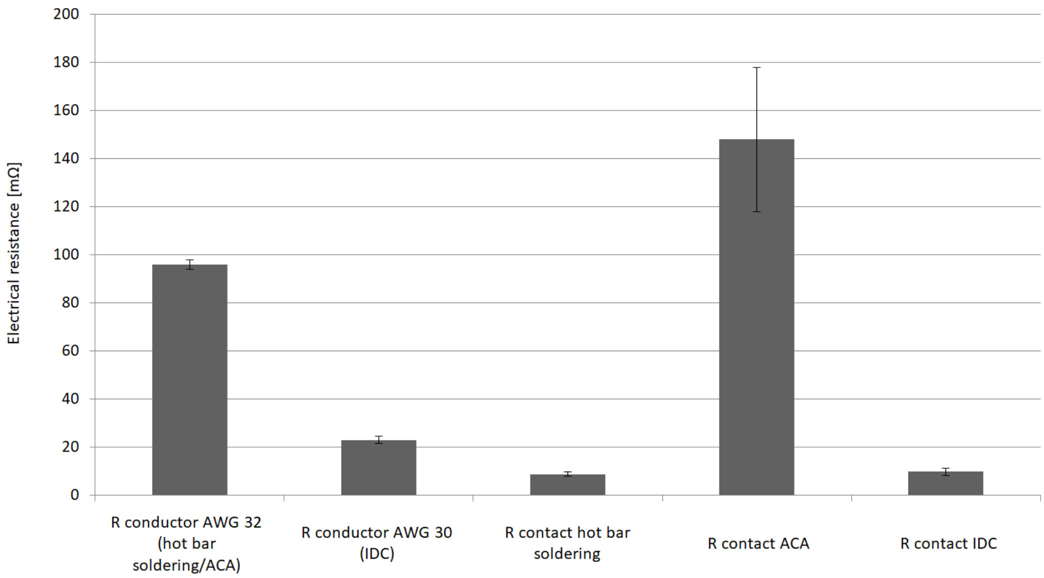


Figure 5. Electrical resistance of hot bar soldered contacts and conductors (AWG 32) compared to IDC contacts and conductors (AWG 30). The contact resistance of hot bar soldering and IDCs is nearly the same. The measured resistance and the resistance from the data sheet correspond, so the measurement method might be reliable.

Figure 6 illustrates the electrical resistances of hot bar soldering and IDCs after washing. It shows a massive scattering and increase of the contact resistances, especially in case of the soldered joints. In contrast the scattering of the IDCs' contact resistances can be observed to have increased only slightly. The resistors of the electrical conductors largely remained constant. Observations were:

1. Massive scattering and increase of the contact resistances after washing, especially for the soldered connections.
2. Washing does not influence the wire resistance.

3.2. Peeling Test

After examining the contact resistances, the interesting aspect of mechanical strength inspection was considered. We needed sufficient strength of connections for further processing. If the strength was insufficient, the joints could have been damaged before the subsequent spraying process. However, the maximum strength has very little effect on the final strength of the product. The potting compound and the strip structure represent a kind of strain relief for the electrical connection.

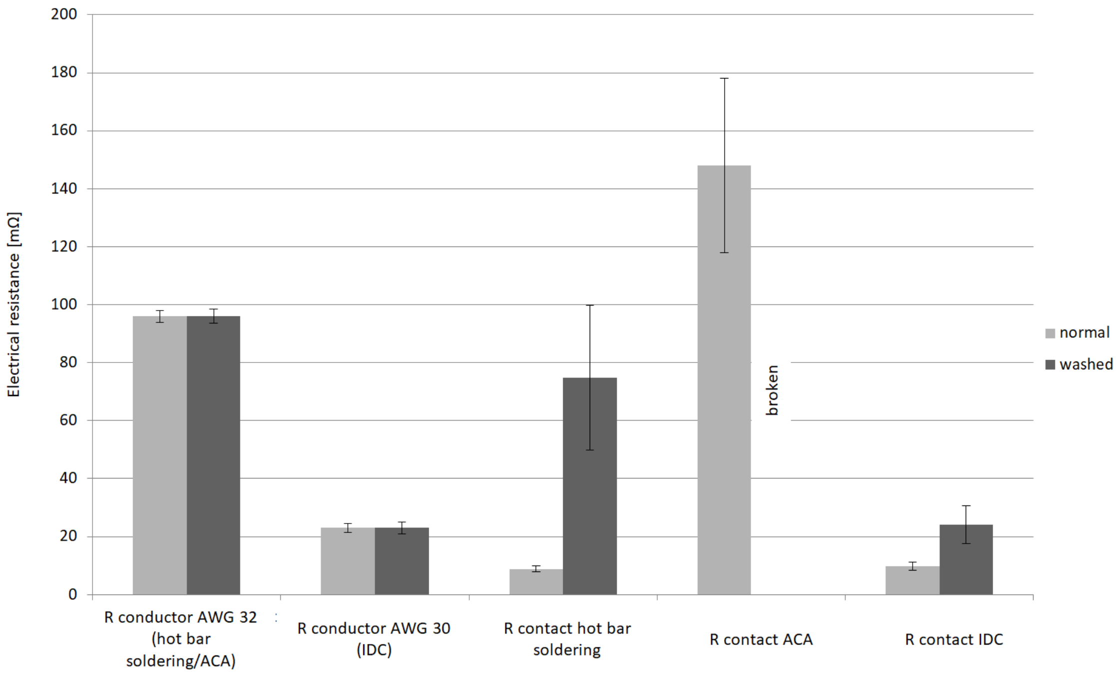


Figure 6. Electrical resistance of hot bar soldered contacts and conductors (AWG 32) compared to IDC contacts and conductors (AWG 30) after washing. The results show a massive scattering of the contact resistances, especially for the soldered connections, while the wire resistance is not really influenced by the washing process.

3.3. Hot Bar Soldering

During the tensile test, three types of failure were observed:

1. Micro cable pulled off at the soldered joint.
2. Micro cables broke off directly at the contact point.
3. Micro cables broke off at the point where the strand draws tin during the soldering process.

In Figure 7, the first force peak indicates the failure of the contacting and the second the removal of the micro cable from the knitted fabric. This occurred when the strands broke up on the side when force was introduced into the textile. On the opposite side they were still connected to the contact points. When the textile was further removed from the circuit board, the strands remained connected to the contact point and were pulled out of the textile. A travel of 50 mm was necessary until all samples were completely cut open. The highest forces and failures of contacting occurred up to a maximum travel of 20 mm, with a comparatively high dispersion of the measured values.

3.4. IDC

In most cases the force measurement showed two high points (Figure 7). The connectors were detached in pairs, meaning that with each detachment an increase in force was recognized. When samples were detached from the crimp connection, no strand was cut through. In this case, the failure of one sample did not affect the other units on the textile. Compared to the hot bar soldering test series, the absence of flexible areas in the textile reduced elongation. A movement path of 15 mm was sufficient.

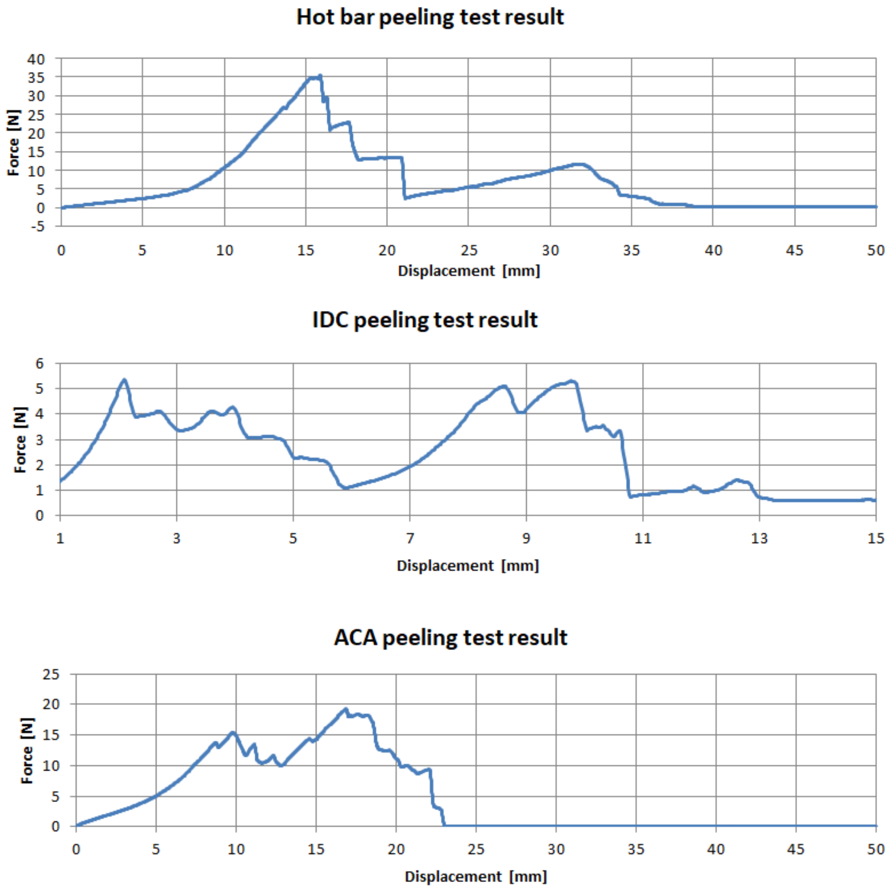


Figure 7. Force-displacement during the peel test. Hot bar soldering (**1**) shows three different failure mechanisms sequentially. In the case of the IDCs (**2**), the contacts failed in pairs. The samples with ACAs (**3**) showed no clear failure mechanism.

3.5. ACA

Specimens with conductive adhesive did not show reliable results in the tensile test. The force increased unstably and constantly to a maximum and then decreased rapidly. Due to the delay in the release of the adhesive, several samples showed force peaks after the first maximum force was applied. Since the adhesive not only bonded the strand at the contact point but also the textile tape with the printed circuit board, it can be assumed that the failure of the contact was already probable before maximum force was reached.

Figure 8 illustrates the maximum forces during peeling tests of test bodies of hot bar soldering, IDCs, and ACAs. In the beginning, it was determined that a force of 5 N was sufficient for further processing of the components. The soldered samples show the highest maximum forces but also the highest dispersion. The form-fit connections failed with the lowest force applied and have minimal scatter. With regard to both parameters, the glued samples lie in between the soldered and pressed samples.

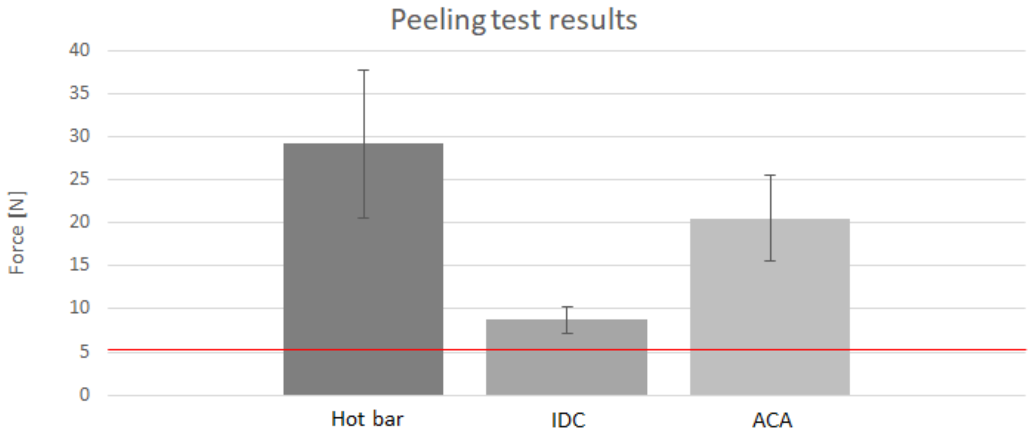


Figure 8. Peace force during peeling tests of hot bar soldered, IDC, and ACA, connections. Hot bar soldering has the highest peak force but also the highest scattering rate.

There were clear differences in behavior and bearable strength. Insulation displacement connectors withstood the lowest force average of 8.6 N. The contacts were detached individually. The failure of individual contact points could have occurred before the maximum force was reached. Samples contacted with the conductive adhesive failed on average with a maximum force of 20.53 N. Since the adhesive not only bonded the strand but also the textile to the circuit board, it can be assumed that the contacts failed even before the maximum force was reached. On average, samples from the thermal soldering process withstood the highest load. They failed at an average maximum force of 29.22 N. Since the force curve was continuous up to the maximum force, it can be assumed that the contacting failed in the range of the maximum force. This behavior could be due to elastic elongation and flow at the contact point. All maximum forces determined by the tensile test were found to be satisfactory for further processing.

It can be concluded that the process stability of the IDCs is the highest but that only low strengths were achieved. The large dispersion of the material-locked samples indicates that the process could be further improved.

4. Conclusions

The automated contacting of conductors in textiles with an electronic assembly to so-called smart textiles is a technical challenge which needs to be solved by electronic and textile manufacturers. Solution strategies were demonstrated in this work on the basis of a model test for the automated integration of electronic components into a textile. The three most suitable processes from different categories were selected for further investigation, i.e., hot bar soldering, anisotropic conductive adhesive bonding and insulation displacement connection. All of the selected processes are suited for automation. The insulation displacement joint process was the easiest to handle while the hot bar soldering and anisotropic conductive bonding required a significant amount of effort. Process times for contacting ranged from a few seconds for the insulation displacement joint to 30 s per PCB for the adhesive to cure. Hot bar soldering took about 15 s. Insulation displacement connectors have an advantage due to the fixing and the independent positioning of the wires in the connector before the contacting process. At the current stage of development, contacting methods are only conditionally suitable for use in automated production. The bonding process had a weakness due to inadequate contacting. However, it offers high optimization potential with few modifications of the equipment curing. A modified stamp shape and a higher energy density for curing are currently possibilities which could be used to achieve a higher contact rate with a shorter curing time. The contacting of the thermode soldering initially showed greater success. However, it was not possible to prevent the solder from being drawn into the strands by varying the soldering parameters. Drawn-in solder has a negative effect on the textile properties near the contact point. More complex solutions, such as ultrasonic compacting before soldering, have not yet been considered. A greater difficulty than the contacting itself is the correct and automated positioning of the conductors above the contact point. Due to its flexibility and deformability, the outer dimensions of the textile cannot be used to precisely determine the position of the inner conductors. As already described, the strands of the IDCs slip into the contact point itself up to a certain deviation. However, the connectors used are not suitable in practice. No available connectors were found that would allow the original strand size of AWG 32 to be contacted without breaking it up. However, the textile tapes used in the test, which were manufactured with AWG 30 strands, do not exhibit the required textile properties as previously assumed. The development of suitable IDCs is costly but promises the greatest success on the basis of the measurements carried out.

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4.2 Automated Joining of Electrical Components to Smart Textiles by Ultrasonic Soldering

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The following paper mainly focuses on the integration of electronics to textiles using the ultrasonic soldering technique. Ultrasonic soldering was chosen to solve the problems with soldering described in chapter 4.1: Preventing solder from being drawn into the strands through the absence of flux in the soldering alloy. The aim of the investigation was to understand the influencing factors affecting the connection and to determine the corresponding solder parameters. Therefore, a robot-assisted ultrasonic soldering process was developed.

Various test methods were used to evaluate the samples, such as a direct optical observation of the microstructure, a peeling tensile test and a four-wire contact resistance measurement. The contact strength increases when the operating temperature and the ultrasonic time were reduced. The lower operating temperature and the reduced ultrasonic time cause a more homogeneous metal structure with less defects. A lower number of defects improves the mechanical strength of the sample.

Summary of the individual contribution:
Sebastian Micus share of this study consists in the idea for this technique. He developed the concept of this investigation and led the investigation himself. He evaluated the results and wrote all sections of the publication.

sensors

Article

Automatic Joining of Electrical Components to Smart Textiles by Ultrasonic Soldering

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Abstract: A suitable connection method to automatically produce E-textiles does not exist. Ultrasonic soldering could be a good solution for that since it works with flux-free solder, which avoids embrittlement of the textile integrated wires. This article describes the detailed process of robot-assisted ultrasonic soldering of e-textiles to printed circuit boards (PCB). The aim is to understand the influencing factors affecting the connection and to determine the corresponding solder parameters. Various test methods are used to evaluate the samples, such as direct optical observation of the microstructure, a peeling tensile test, and a contact resistance measurement. The contact strength increases by reducing the operating temperature and the ultrasonic time. The lower operating temperature and the reduced ultrasonic time cause a more homogeneous metal structure with less defects improving the mechanical strength of the samples.

Keywords: smart textiles; wearables; ultrasonic; soldering; joining; integration of electronics

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1. Introduction

According to current studies, the market volume for intelligent textiles will grow significantly in the coming years. In addition to the current medical and military applications, the usage will expand to the fields of fashion and sports [1].

The challenge is to ensure the usual textile properties for the customer, such as textile feeling, washability [2], wear comfort, and drapability. At the same time, the textile must be able to withstand changing environmental conditions.

However, we currently do not see a real market breakthrough due to the following reasons. One of the reasons for the low market penetration of electronic textiles is the high proportion of manual activities during production [3]. In addition, the high proportion of manual production steps results in high prices, which slow down market growth. Therefore, the German Institutes for Textile and Fiber Research (DITF) have intensively researched on automated contacting processes. In this work we focused on textile integrated insulated wires. These wires are located inside the textile enabling to connect components from both sides. Automated methods for contacting printed circuit boards (PCBs) with insulated wires have not yet been sufficiently investigated in the literature. The manufacturing process typically consists of three steps [4]. First, the wires are automatically uninsulated with a laser. The contacting process starts afterwards, which is investigated in this article. To protect the electronics from environmental influences, the components are overmoulded by an injection molding machine [5]. For this reason, we investigated the mechanical properties of the connections in a peeling test. This allows us to determine whether the connection is strong enough for further production steps.

The challenges in contacting electronics to textiles are as follows. Macroscopically, the structure is very homogeneously produced. None of the sections resemble each other, thus the mechanical behavior of the textiles always differs during processing. This leads to problems in the positioning step between the textile and the electronic. The durability of the contacts is also one of the problems regarding the expected high mechanical stress of e-textiles.

However, there is a challenge due to the processes used so far. Each of these processes has the following difficulties: Mechanical strength (durability of the contacts), fatigue resistance and the implementation on an industrial scale.

1.1. Force-Fit Connections

The integration of electronics to smart textiles by force-fit connections needs two steps: The mechanical connection to the textile and the electrical connection to a conductive structure. The function of smart textiles is only guaranteed if both connections are reliable. Force-fit connections have the advantage that they can form both connections without thermal stress on the substrate. Simon et al. [6] developed and integrated a force-fit interconnection and investigated the influence of the applied force and the used strips or yarns on the contact resistance [6]. In the end, the required effort to produce the screwed connections is clearly too high and no automation could be realized.

1.2. Form-Fit Connections

Crimp connections are robust, highly reliable, low-cost and fast and easy in processing. Simon et al. [7] developed multi-terminal crimp packages to integrate them into large-area smart textiles. The woven textiles had integrated conductive yarns inside. Therefore, they designed special forming tools. These tools were able to bend eight pins at the same time, so they were able to applicate the crimp terminals much faster compared to with serial production steps [7] These methods did not become generally accepted. Due to the inhomogeneity of textiles, the difficult positioning especially with large textiles and the low adaptability of the tools between different products.

Klink et al. [8] used printed isoplanar and anisotropic conductive adhesive (ACA) flip chip connections for the integration of thin chips into textiles. The printed isoplanar connections showed high resistances and none of the samples failed during a temperature reliability test. These results confirm the thermomechanical stability of the assembly. The ACA contacts with pure copper are susceptible for degradation. The absence of this effect in silver plating indicates that the origin of these failures is not mechanical fatigue but due to the degradation of the copper and the ACA contact interface.

Linz et al. [9] developed a theoretical model of the contact mechanism underlying embroidered contacts. They used the model to identify potential failure mechanism and exposed temperature cycles as a reliability test. Additionally, they encapsulated the contact zones with different thermoset plastics. As a result, they determine a quickly lose in conductivity during their temperature cycle tests. Only the combination out of epoxy adhesive in the contact zones and subsequent encapsulation with hot melt showed good results [9].

In the field of Smart Textiles, snap fasteners are often used for ECG measurements. They allow the placement of larger evaluation units on textiles and their reversible removal during a possible wash cycle. Examples for the application can be found in [10–14]. For the integration of miniaturized electronic components such as sensors or actuators this is not an option. Only one connection can be made and a snap fastener usually has the dimensions of a complete sensor.

1.3. Substance-to-Substance Bonds

Furthermore, Linz et al. [15] present a new technology to connect conventional electronics with conductive textiles. They introduced nonconductive anisotropic adhesives (NCA) as a reliable method for contacting rigid electronic modules to fabric substrates. They used thermoplastic polyurethane as non-conductive adhesive. The technology brings the PCB and the conductive adhesive in contact. Afterwards, they use load and temperature to melt the adhesive. If the isolation of the textile integrated wire has a lower melting point than the thermoplastic polyurethane (TPU) adhesive, they can also contact wires with insulation. In the following, they used harsher reliability test conditions and more detailed investigations of non-conductive adhesives to confirm the advancement of this technology [15].

Hirman et al. [16,17] focused in their research on connecting SMDs onto textile ribbons by UV curable NCA. The ribbons had silver coated copper threads inside. Even after several washing, temperature and load cycles they dedicated a reliable connection between the electronics and the ribbon [16,17].

Atalay et al. [18] used different stainless-steel and different silver-plated yarns to create a signal transmission lines resistant. Therefore, they used the ultrasonic welding technology. The conductivity of the stainless-steel yarns changed slightly, while the silver-plated yarns were more affected by the ultrasonic welding technology. Furthermore, the electrical resistance of the silver-plated yarns showed huge variations. Thus, they considered to use stainless-steel yarns for the proposed technology [18].

Shi et al. [19] investigated the bonding mechanisms of ultrasonic welding in fabrics. Therefore, they used different natural and synthetic fabrics with and without polyurethane adhesive. They studied the influence of the three important welding parameters: amplitude, welding time and welding pressure. Furthermore, the temperature inside the connection was measured during processing [19].

Leśnikowski et al. [20] welded textile nickel coated, fabric signal lines (TSLs) between non-conducting textile layers by using ultrasonic welding technology. He analysed the usability of ultrasonic welding for the integration of TSLs. Unluckily, the resistance of a direct welded TSL increased [20].

Buechley et al. [21] built up a construction kit for e-textiles, on which they soldered an IC socket to a fabric PCB or metal crimping beads to surface mount LEDs and motors. The resistance of the solder joints increased a bit but remained below 1 Ω even after washing [21].

Kallmayer et al. [22] developed a solution for the integration of passive silicon transponder labels in textiles. These flexible chips can overcome high mechanical load but the integration required new integration technologies because of their dimensions and the possible tolerances between the microelectronic and the textile. As a solution, they soldered the transponders to conductive yarns with a low melting alloy. The connections survived conventional washing process without any failures after encapsulation [22].

Hot bar soldering has several advantages, which makes it particularly suitable for contacting PCBs on Smart Textiles. The process offers the possibility of contacting several contact points on textiles at the same time [23]. Furthermore, pressure and temperature are applied. This allows the conductor and PCB to be fixed to each other. The thermode is usually made of titanium [24] or molybdenum. Furthermore, such a system offers the advantage to use it for curing conductive adhesives. As described by Woznicki [25], hot bar soldering has problems with very small pad pitches. A lot of textile has to be removed to connect single contacts.

Another connection method is conventional piston soldering. It always uses solder with flux. Flux is necessary to activate the surface of the solder joints and to remove impurity layers. Flux in particular removes oxidized metal from the surfaces of the solder joint, it seals out air, thereby preventing further oxidation, and it improves the wetting characteristics of the liquid solder to facilitate amalgamation. It allows the solder to flow nearly in the same way as lead-containing solders, which are forbidden in most applications. Soldering with lead-containing solders is now only permitted under strict regulatory requirements and for special applications. When soldering with flux, the solder is drawn into the strand due to capillary effects. The solidified solder outside the soldering point itself causes an embrittlement of the otherwise very ductile strands. This results in weak spots close to the connection points, which cause the electronics to fail under cyclical load. The difficulty of conventional piston soldering is a high motivation for the investigation of ultrasonic soldering.

2. Materials and Methods

2.1. Ultrasonic Soldering

During ultrasonic soldering, the heat input occurs primarily through the temperature-controlled solder tip (Figure 1). In contrast to ultrasonic welding or wire bonding where the heat energy is generated by ultrasonic friction the temperature-controlled soldering tip melts the solder and the additional ultrasonic movement of the tip removes boundary layers on the surface, which ensures solderability without flux. The ultrasonic excitation leads to cavities in the liquid solder, which remove impurities (impurity layer) from surfaces similar to the principle of ultrasonic cleaning. Two main principles are common in ultrasonic soldering:

- Similar to dip soldering: The solder bath is heated and excited with ultrasonic. However, this application is not suitable for textiles as the textile comes into contact with solder and melt.
- Similar to piston soldering—soldering iron with an additional ultrasonic generator: The frequency power and temperature can be adjusted.

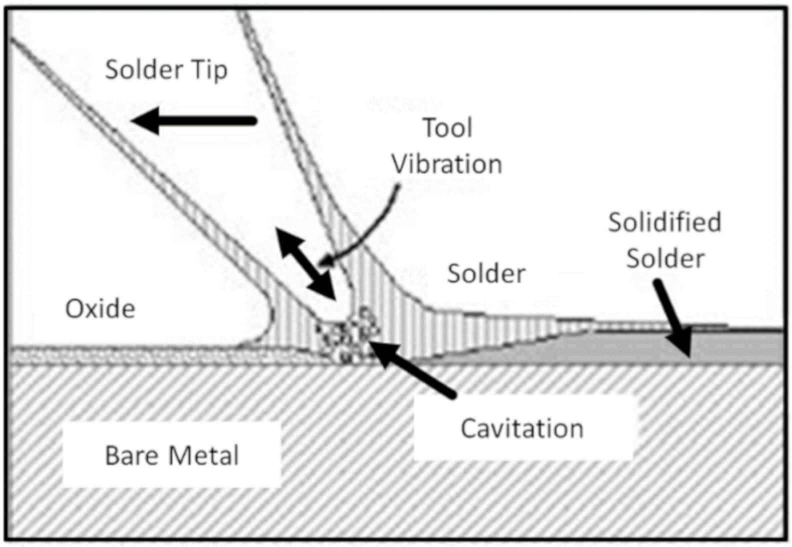


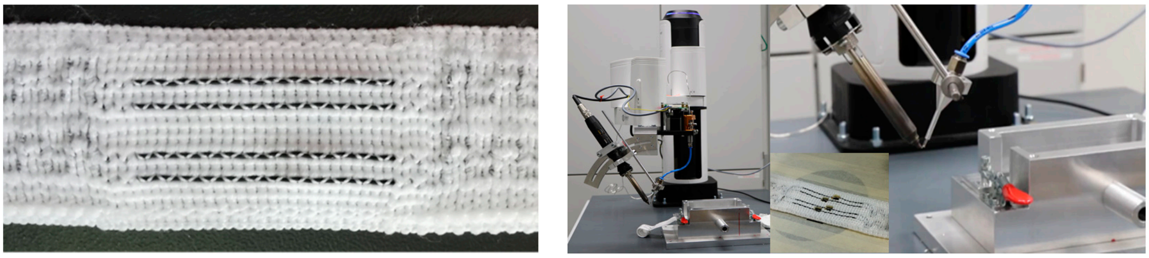
Figure 1. Schematic illustration of the cavitation mechanism in ultrasonic soldering [26].

Special solder alloy without flux must be used for ultrasonic soldering since soldering materials with flux inhibit the transmission of ultrasound. Due to the absence of flux, less solder penetrates into the strand though the wick effect. As a result, the strand becomes less brittle and the entire textile retains higher flexibility. In addition, the entire process can be easily automated and scaled. Due to years of use in the electronic industry, the soldering machines are well controllable and available in different dimensions. The contact points have a high strength and good electrical conductivity.

2.2. Experimental Setup

A warp-knitted textile tape was used, which is made out of polyester with four integrated polytetrafluoroethylene (PTFE) insulated AWG 32 strands (19 wires) and a diameter of 17 µm. The copper strands have a silver coating on the surface and no extra insulation around every wire. The tape consists of flexible (stretchable) areas and inflexible contact points. The flexible areas of the ribbon are achieved through the use of elastomers and the wrap-knitting technology. The ribbon was developed together with the company A MOHR Technische Textilien GmbH in Wuppertal and is now a commercial product of them. The isolation and small areas of the textile tape are removed locally at the contact points from both sides with a CO_2 laser (Alltec LC300). A USS-4200 from MBR Electronics with different widths of tips (1, 3 and 5 mm) was used. The temperature is adjustable up to 500 °C; the ultrasonic power is variable between 4 W and 12 W at 60 kHz.

A four-axis industrial robot arm (Dobot M1) was programmed to automate and ensure reproducibility in the production of test samples (Figure 2a). In addition, a special holder for the textile tape and the PCB was manufactured. The PCBs have a size of 18 × 12 mm^2. The ultrasonic soldering iron and the solder feed are carried out by the robot (Figure 2b). The soldering is done in two steps. First, the solder is melted at the tip of the soldering iron and, second, the tip of the soldering iron moves to the contact point. The tip of the soldering iron has a high carrying capacity for solder. We used three different solder alloys: Sn95.5Ag3.8Cu0.7, Sn99.7Cu0.3, and Sn97Ag3 without flux. These alloys are common in the electronics industry, in which flux-free solders are used.

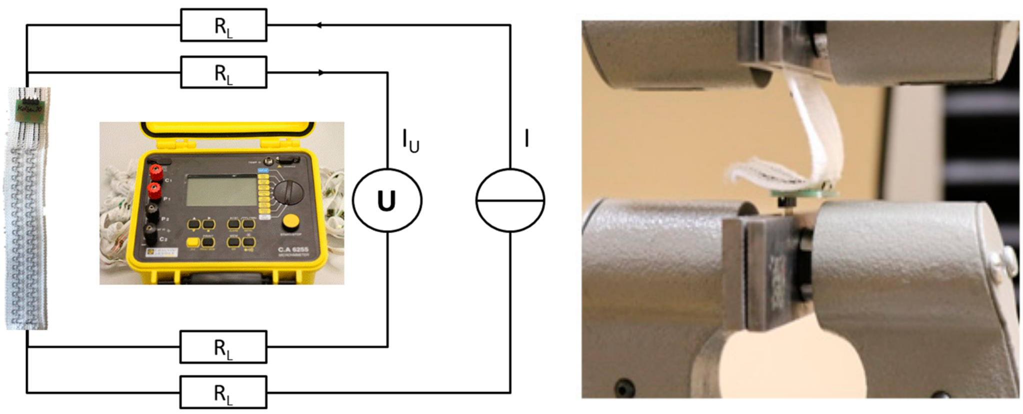


(**a**) (**b**)

Figure 2. (**a**) Textile tape with flexible and stiff sections. The ribbon is 26 mm width and the position of the wires is axially symmetrical to the centreline. The outer wires have a distance of 12 mm and the inner wires a distance of 6 mm; (**b**) Pictures from the experimental setup, with the four-axis robot and the ultrasonic solder iron and the textile tape after CO_2—Laser processing.

2.3. Test Procedures

To examine the samples, micrographs were first prepared and microscopically examined. The size and characteristics of the contact points can be examined under the microscope. By measuring the contact resistance, the quality of the joint can be examined. A four-wire measuring instrument is used to eliminate the line resistances (Figure 3a). The contact resistances are in the milliohm range [6]. High currents of up to 10 A are required to measure a measurable voltage drop at the contact point. Joints are usually characterized by a peel test. Peeling is usually the most unfavorable load direction for joints. In this case the peel strength is used to determine the mechanical strength of the joint for further processing. The force is applied vertically to the PCB (Figure 3b). Therefore, a load cell with a maximum force of 1000 N is used. The drawing speed is 100 mm/min. 10 samples were prepared for each test parameter.



(**a**) (**b**)

Figure 3. (**a**) Measuring setup for determining the contact resistances by using the four-wire measurement principle; (**b**) Peeling test set-up: The PCBs are fixed in the blank and pulled on the contacted textile bands with a speed of 100 mm/min [27].

3. Results and Discussion

3.1. Solder

Micrographs of the cross-section were made of all solder materials Sn95.5Ag3.8Cu0.7 (Figure 4a,d); Sn99.7Cu0.3 (Figure 4b,e); Sn97Ag3 (Figure 4c,f)). Sn99.7Cu0.3 (Figure 4e) shows significantly less pores compared to the samples (4d) and (4f). Sn95.5Ag3.8Cu0.7 (Figure 4a) has a needle-shaped micro-structure, which indicates that the metal alloy is brittle. The microstructures of Sn99.7Cu0.3 (Figure 4b) and Sn97Ag3 (Figure 4c) show a much more homogeneous picture.

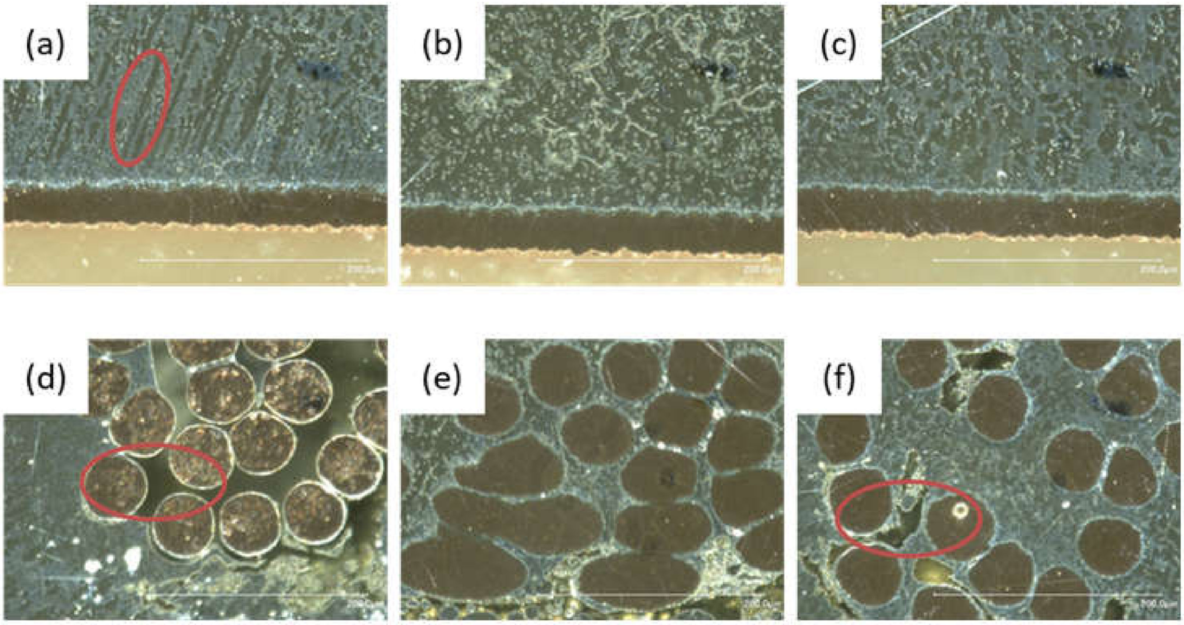


Figure 4. Microsections of various solder materials, (**a**,**d**) Sn95.5Ag3.8Cu0.7 with a needle-shaped microstructure in picture (**a**) marked with a red circuit, (**b**,**e**) Sn99.7Cu0.3, (**c**,**f**) Sn97Ag3; (**d**,**f**) not completely wetted electrical conductors also marked by red circuits.

This is also reflected in the results of the peeling test (Figure 5a). In the peeling test, the textile tape is pulled off at a 90° angle from the PCB. The contacting points usually fail one after the other. There are mainly two types of failure. One is the break outside the joining zone; the other is an adhesive breaking. In addition, other influencing variables and their effects were investigated. The used solder materials have effects on the contact resistance and the mechanical strength of the connection. Solder joints made of Sn97Ag3 had the lowest electrical resistance and low strength, Sn99.7Cu0.3 had the highest strength and also the highest electrical resistance (Figure 5b). In general, a higher silver content leads to a lower the resistance. In this case Sn95.5Ag3.8Cu0.7 represents a deviation from this. Furthermore, the degree of wetting of the electrical conductors has an impact on the resistance of the joints. Due to the high strength of Sn99.7Cu0.3 alloy and the hardly reduced contact resistance, the following tests were always carried out with this alloy. On the one hand the good wetting of Sn99.7Cu0.3 leads to high peel strength; on the other hand, the low silver ratio has not a high impact on the contact resistance.

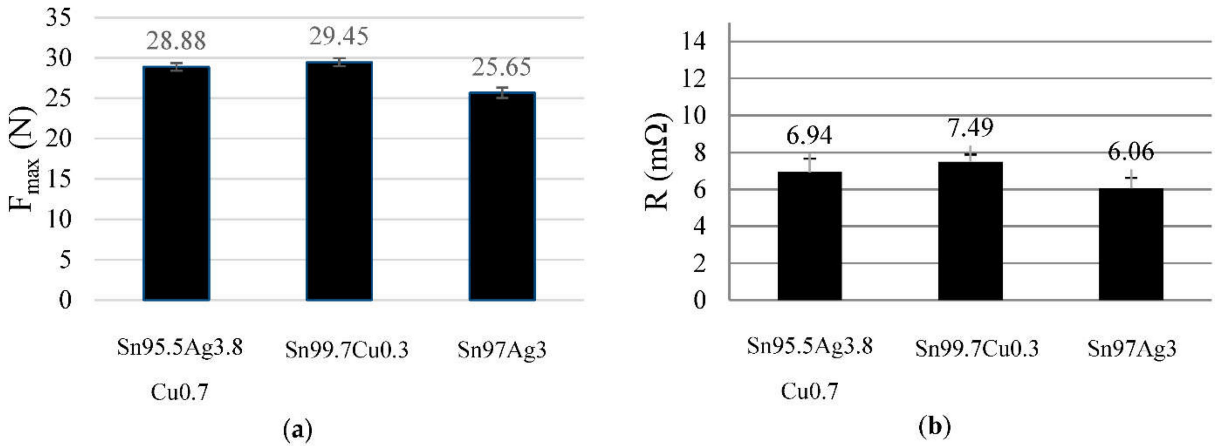


Figure 5. (**a**) Results of the peeling test and (**b**) resistances depending on the solder alloy.

3.2. Quantity of Solder

The amount of solder added has an influence on the electrical properties of the connection (Figure 6), while the mechanical properties in the peeling test remain the same. We used samples with 4.3 g and others with 8.6 g per contact point. Unfortunately, the automated solder feeding only allowed multiple quantities of this portion and 12.9 g was too much solder for one contact point. The more solder is used, the lower the contact resistance. Since the contact area has the same size for each sample, and all other parameter remains the same, the individual strands might be better wetted with more alloy. Regarding the high prices for flux-free solder alloys contact points with less solder might for most applications be sufficient.

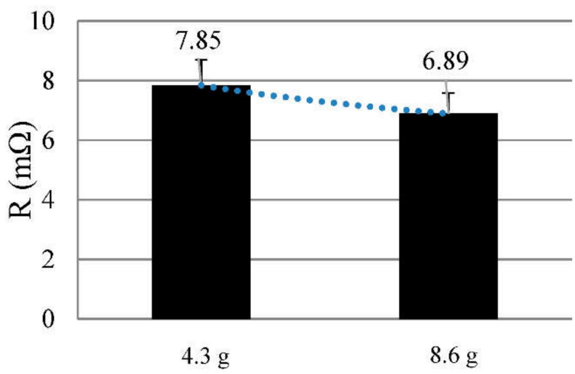


Figure 6. Contact resistance with different quantities of solder.

3.3. Temperature

The temperature at the soldering tip far above the liquidus temperature leads to lower strength. The samples produced with 370 °C show a bit lower strength than the samples made with 390 °C, but with a wider distribution (Figure 7a). A larger diameter of the soldering tip increases the heat capacity and thus facilitates faster melting of the solder. Furthermore, a larger soldering tip can lead to a resonance of the soldering tip with the solder. The different temperatures of the solder tip have no impact on the conductivity of the connection. The contact resistance is 7.65 mΩ +/− 0.23 mΩ. The strength increases by reducing the temperature. To further demonstrate the results, micrographs of the different samples were analyzed (Figure 7b). In comparison with contacting at 390 °C, contacting at 350 °C is optimized in two aspects. Due to the low heat input at 350 °C, the structure is more homogeneous and has fewer pores (Figure 7b (2)). Although there are some pores between the wire and the solder. This was also shown in the results of the tensile tests. The force during the peeling test of the 350 °C samples is greater than 32 N, which is about

20% more than with higher temperatures. The soldering process does not work at low working temperature like 320 °C, because the temperature does not liquefy the solder quickly enough.

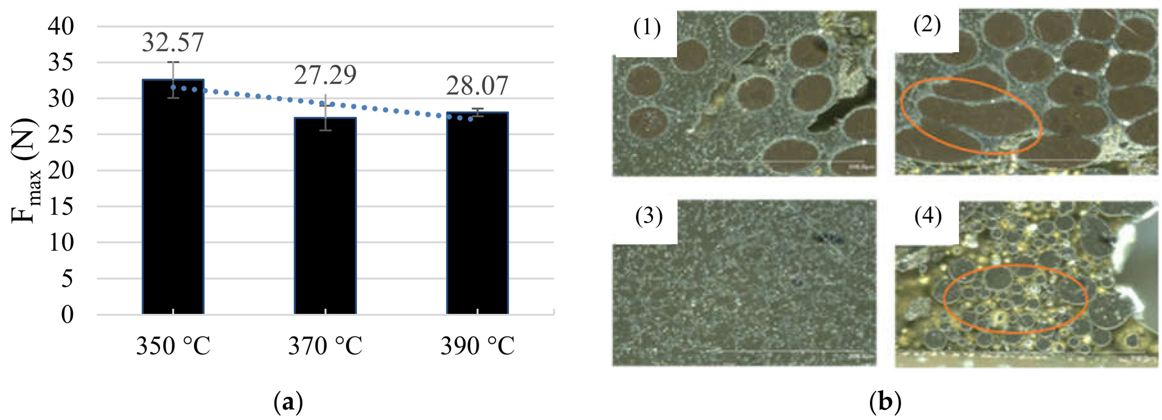


Figure 7. (**a**) Results of the peeling test with Sn99.7Cu0.3 depending on the solder tip temperature; (**b**) Microsections of Sn99.7Cu0.3 with different solder process temperatures: (1), (3) 350 °C and (2), (4) 390 °C; the red circuits show imperfections in the solder allow which reduce the mechanical strength of the connections.

3.4. Time of Soldering

Additionally, the influence of time on ultrasonic soldering was investigated. It was found that a longer soldering time in combination with the ultrasonic application has a negative influence on the strength of the samples during the peel test (Figure 8a,b). Samples that were treated for only 0.5 s showed a more than 40% higher peel strength than samples that were soldered for 10 s. So, the removal of foreign layers by ultrasonic application might be a very fast process.

Although the application of ultrasound causes larger grains to break up, thus reducing the crystal grains of the alloy, the higher heat input inevitably leads to a coarsening of the crystal grains [28]. In addition, the longer temperature effect during ultrasonic soldering leads to overheating of the solder joints, as well as to oxidation and charring. This reduces the mechanical properties of the solder joints [29]. However, the contact resistance between the samples does not differ.

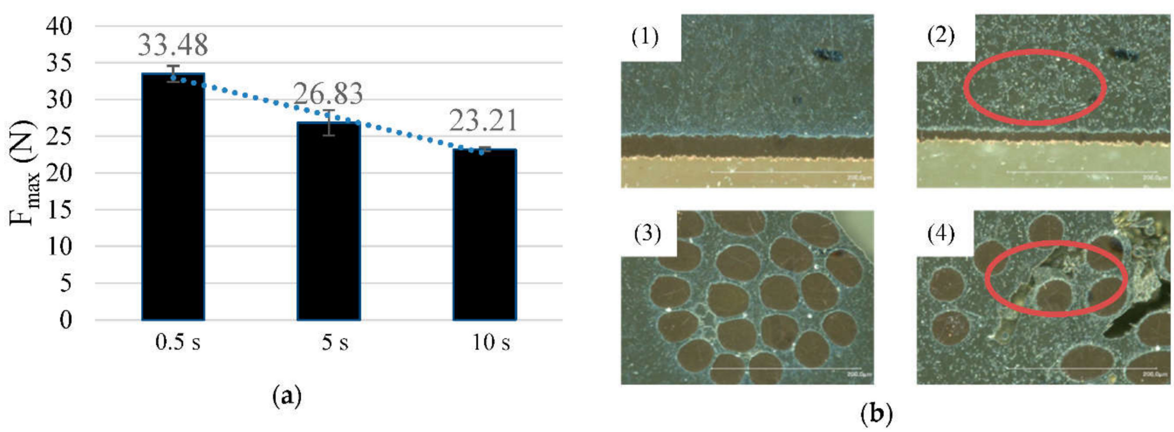


Figure 8. (**a**) The diagram shows the influence of the solder time and the mechanical strength. The lower the soldering time, the higher is the strength during the peeling test.; (**b**) Microsections of Sn99.7Cu0.3 samples, soldered with different ultrasonic solder times: (1), (3) 0.5 s solder time; (2), (4) 10 s solder time. The red circuits show imperfections in the allow after a longer ultrasonic soldering time.

3.5. Ultrasonic Power

The power mainly influences the variation of the amplitude during the movement of the solder tip under ultrasonic waves, and the adjustment range of our soldering machine is from 4 to 12 W. During our investigations, we found that the power has an important influence on the soldering process, especially for the melting process of the solder. At high power, the solder was quickly homogenized after melting and formed into droplets. This allows the tip to carry and feed more solder. During the soldering process, the spread on the soldering plate at high power was significantly better than at low power, which helps to increase the solder joint strength. However, there was also a maximum amount of power at which the strength was significantly reduced again. At an output of 10 W, the joint strength was 25% higher than at 12 W (Figure 9), because an increased ultrasonic power ensures a more homogeneous micrograph at the contact point. The contact resistances are almost identical. Due to the choice of the test device, no higher power than 12 W could be tested. Soldering was not possible at too low power levels because the solder did not spread fast enough and the impurity layers may not be removed.

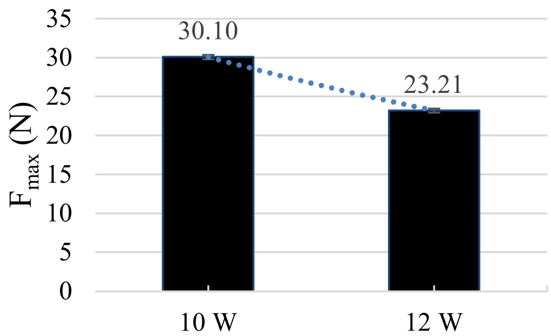


Figure 9. The Diagram illustrates a correlation between power and mechanical strength. A reduced ultrasonic power of 10 W leads to a higher mechanical strength.

3.6. Pretreatment

We also investigated the effects of pretreatment or surface with cleaners. We found that the additional pretreatment of the contact points with acetone has a negative influence on both the tensile strength and the electrical resistance (Figure 10). The tensile strength during the peeling test decreased from 25.5 N to 23.5 N, which means around 10%. In X-ray Spectroscopy (XPS) tests for surface cleaning, it was proven that acetone or other cleaning agents leave (carbon) residues on surfaces that negatively influence subsequent coating processes [30].

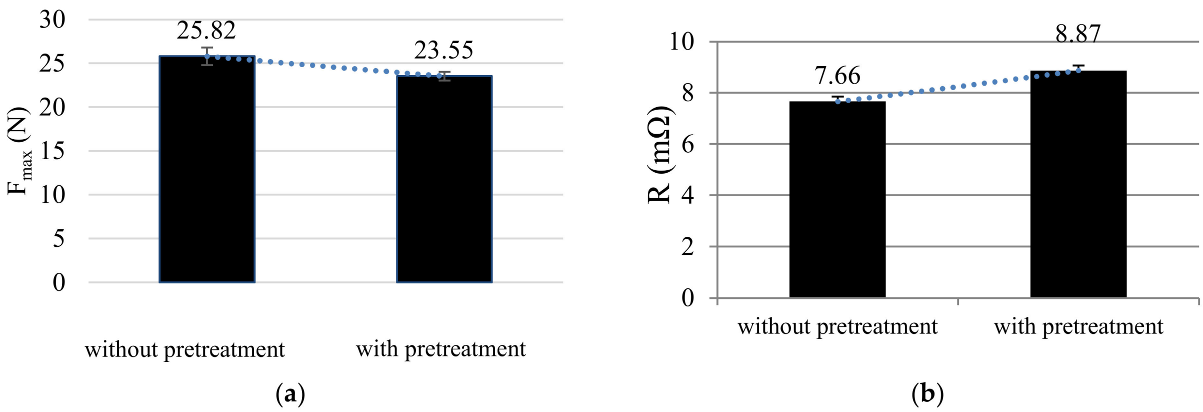


Figure 10. (**a**) With the reduced tensile strength during the peeling test after pretreatment; (**b**) with the increased contact resistance after pretreatment with acetone.

Related to our test setup and our equipment possibilities, we found the following soldering parameters as a compromise between shear strength and contact resistance: Sn99.7Cu0.3 at 350 °C, an ultrasonic working time of 0.5 s and a power of 10 W (Table 1). The results are based on the fact that the process is quite fragile and needs automation to be reliable. Using this technique manually leads to a many poor connections. A lot more parameter have been tried, but they were not successful.

Table 1. Results from this investigation.

Solder Material	Quantity	Time	Temperature	Power
Sn99.7Cu0.3	4.3 g	0.5 s	350 °C	10 W

4. Conclusions

This article focuses on the development of a contacting method by means of a partially automated ultrasonic soldering system to integrate PCB components on smart textiles. Three solder alloys were chosen: Sn95.5Ag3.8Cu0.7, Sn97Ag3 and Sn99.7Cu0.3 without flux. Subsequently, the mechanical and electrical properties of the soldered connection were analyzed as a function of the soldering parameters. Therefore, a contact resistance measurement and a peeling test of the connections were conducted.

We analyzed the influence of the solder alloy itself, the quantity of solder, the solder temperature, the time of soldering, the ultrasonic power and the pretreatment of the surface before soldering as a function of the contact resistance of the connections and their strength during the peeling test. One of the main problems is the durability of the electronics. The investigations of the peeling test showed that connections with solder made of Sn99.7Cu0.3 yield higher strengths due to connections with Sn95.5Ag3.8Cu0.7 or Sn97Ag3. The contact resistances ranged from 6 to 8 mΩ. For this reason, the alloy with the highest peel strength was chosen: Sn99.7Cu0.3. The quantity of solder also has only a limited influence on the strength and contact resistance, thus we recommend not to choose more solder alloy than necessary. Further, the solder temperature is also a very important influencing factor. In addition, too high or too low working temperature damages the contact. The ultrasonic power and the ultrasonic process time have a great influence on the formation of the microstructure. The shorter the ultrasonic treatment time during the soldering process, the better the properties of the solder connection. The reason for this is the better homogeneous microstructure with only few defects. Overall, the ultrasonic welding process looks very promising for the integration of electronics to textiles, because with the dispense of flux in the solder alloy less solder draws into the litz wire, which reduces the embrittlement of the wire. We found the following optimal soldering parameters as a compromise between shear strength and contact resistance: Sn99.7Cu0.3 at 350 °C and an ultrasonic working time of 0.5 s and a power of 10 W.

Author Contributions: Conceptualization, methodology, validation, investigation, resources, data curation, writing—original draft preparation, project administration, funding acquisition, S.M.; writing—review and editing, M.H.; supervision, G.T.G. All authors have read and agreed to the published version of the manuscript.

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4.3 Soldering Electronics to Smart Textiles by Pulsed Nd:YAG Laser

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Authors: Micus, S.; Haupt, M.; Gresser, G.T.

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The following article focuses on laser soldering with a wavelength of 1064 nm. Laser soldering is considered to be a suitable connection method, because it is a contactless process and enables smaller zones of influence in the textile ribbon. During the investigation, the textile integrated copper strands were stripped by the laser and soldered to the PCB without any transport of the ribbon. Therefore, different sets of parameters were investigated by using different designs of experiment (DoE). However, in some cases the conductors were poorly-wetted by the solder alloy. The joinings were electrically analysed using a four-wire resistance test. The microstructure of the samples was optically examined by using a scanning electron microscope (SEM). Finally, the samples were mechanically analysed with a peeling test. As a result, the mechanical strength as well as the electrical conductivity of the poorly-wetted contact points drop from the usual values for soldering.

Summary of the individual contribution:
Sebastian Micus developed the idea and the concept of the investigation and led the investigation himself. He evaluated the results and wrote all paragraphs of the publication.

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Article

Soldering Electronics to Smart Textiles by Pulsed Nd:YAG Laser

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Abstract: Experts attest the smart textiles market will have high growth potential during the next ten years. Laser soldering is considered to be a good contacting method because it is a contactless process. For this reason, it is intended to investigate the contacting process of printed circuit boards (PCB) to isolated conductive textile strips by means of a ytterbium-doped fiber laser (1064 nm). During the investigation, the copper strands in the textile tape were stripped by the laser and soldered to the PCB without any transport of the textile. Therefore, we investigated different sets of parameters by means of a design of experiment (DoE) for different types of solder pastes. Finally, the joinings were electrically analyzed using a contact resistance test, optically with a REM examination, and mechanically using a peeling test.

Keywords: smart textiles; wearables; laser; soldering; bonding; integration of electronics

1. Introduction

1.1. Smart Textiles Definition and Classification

Smart textiles are hybrid products with a functional add-on. They consist of intelligent or functionalized textiles and have an integrated sensor and/or actuator system [1]. This functional plus is distinguished between pneumatic-, light- and sound-textiles, climate control, and conductive e-textiles. They can also be used in passive, active, and very smart textiles [2].
Smart textiles can be divided into two categories (cf. Figure 1):

(1) E-textiles–these are textiles with conventional electronics where the textile works as carrier material, and;
(2) Textiles in which the textile structure itself acts as a sensor

The former category offers many more possibilities and functional principles. Furthermore, textile sensors are not able to measure as accurately as conventional electronics. They have a much stronger miniaturization, but the integration leads to local thickening. Conventional electronics added to textiles can be divided in terms of functionality. There are integrated cables for heating or charging inductively, followed by electrically-contacted SMD parts and sensors on PCBs. PCB sensors offer high accuracy at a small size.

Textile sensors have the advantage of structural integration, though a limited number of physical principles, which are optical, capacitive, resistive, and piezoelectric [3–5]. Structures are mostly in the millimeter range.

Current studies anticipate a high growth of the smart textile market in the upcoming years. Including the existing medical, military, and occupational safety markets, it will also be spread to the fashion and sports market [6]. However, at the moment there is no actual market breakthrough 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. Hence, there is currently a lot of research on automatable techniques assembling PCB to textiles.

In this paper, our main focus is on isolated wires, because they have low resistance and the insulation provides protection against electric shocks.

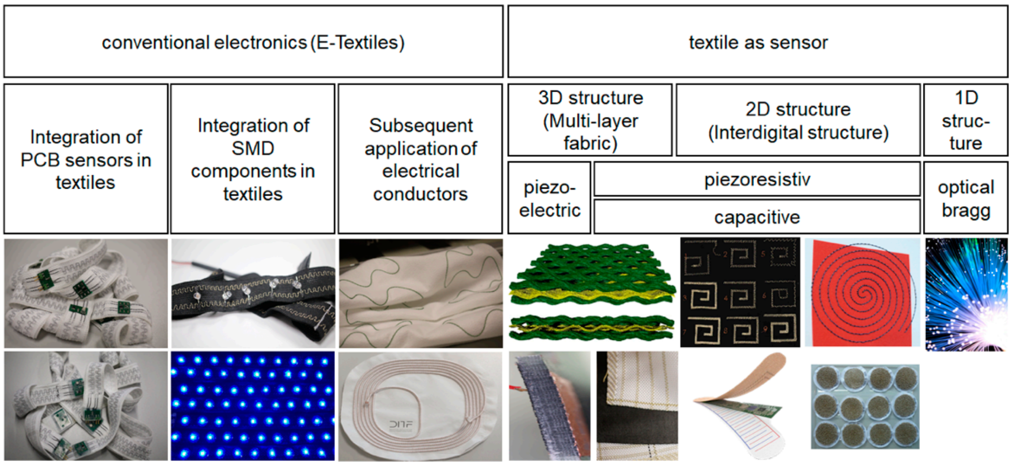


Figure 1. Classification of different smart textiles: E-textiles, where conventional electronics are integrated into textile and the textile structures which works as sensors.

The production process of e-textiles with PCBs and insulated wires consists of three steps. At first, the wires are automatically stripped by laser. Then, the main contacting process starts [7]. In order to protect the electronics from environmental influences, the components are encapsulated in an injection molding machine [8]. The first two steps are investigated in this paper.

1.2. Methods for Integration

A number of studies have already been conducted on the rational contacting of electronics on textiles.

1.2.1. Sewing and Embroidery

Linz et al. [9] developed an embroidery process for the efficient application of LEDs to textile surfaces requires prefabricated electronic substrates in the form of preassembled flexible electronic boards in sequin. The sequins are connected and contacted with non-insulated silver-coated conductive yarns. These yarns must survive the embroidery processes without damage, which limits the choice of material. However, these uninsulated conductors are sensitive to corrosion in washing processes, and subsequent insulation damages the textile feel.

Afterward, Linz et al. [10] used interposers for contacting, which made the contacting process much more efficient. However, the problem of contacts with a high resistance still exists.

Therefore, Afroj et al. [11] investigated a highly-conductive, scalable, and machine-washable graphene-based yarn for embroidery. Since the surfaces to be embroidered must be tensioned during the embroidery process, embroidering elastic structures is very difficult and time-consuming.

It has also been shown that the contact resistance of a sewn or embroidered connection deteriorates over time because the textile conductors relax [11]. For this reason, the connections must be elaborately reinforced by an additional process step, e.g., gluing or soldering [9].

1.2.2. Bonding

In Stoppa et al. [12], tissues with non-insulated conductors were fabricated at defined distances. In this work, μ-LEDs (200 μm wide) were placed on them and sprayed (jetted) with adhesive for fixation. However, their contact resistances increased significantly after the first washing cycles [13].

There are approaches to the production of flexible interposers. Meander-shaped copper tracks in elastic foils made of, e.g., polyurethane and PDMS are used. These can also be stretched [14,15]. Investigations with copper meanders in an elastomer (PDMS) showed that only 200 to 400 cycles can be endured at a cyclic elongation of 20% [13].

1.2.3. Crimping

Simon et al. [16] described how modules with SMD components can be connected to textile-integrated conductors via crimp contacts. However, the modules with 2 × 2 cm^2 are still too large and have to be specially manufactured. This method only becomes interesting for very large quantities of several million pieces.

Vanfleteren et al. [17], Simon et al. [18], and Vicard [19] worked on developing interposers with form-fit connections. The interposers are pressed between two parallel conductors until the conductors are fixed to recesses on each side of the interposer. The interposers are contacted with the conductors via these recesses.

Neudeck et al. [20] worked on interposers containing electrical components inside which are connected to the contact via bonding wires. However, the interposer must be manufactured separately for each SMD component or chip. Due to the interposer, the space required for small components such as a temperature sensor is approximately doubled, thus requiring large contact points. In addition, only two components can be contacted to one conductive yarn.

1.2.4. Soldering

Molla et al. [21] integrated LEDs into textile structures by soldering conductive uninsulated yarns. The LEDs could be soldered to the exposed conductors, but in particular, the solder wicking along the multi-filament affects the durability of the joint and added stiffness to the textile. The distinct effect of the solder especially has an impact on the stiffness of the textile. All work steps were performed manually and were not fast enough.

Additionally, the soldering of smart textiles was investigated in different public-funded German research projects. In these projects, conductors with and without insulation were used. The temperature sensors and LEDs could be soldered to the exposed conductors. The working steps were performed manually with a solder piston and automatically with a soldering robot, but tensioning and feeding of the strips were still done manually. Overall, the contacting processes, manually and automatically, were still too slow, and the conductors were not stretchable [22,23].

2. Materials and Methods

2.1. Different Types of Lasers

Lasers can be distinguished according to their laser-active material and their pumping. The laser-active media can be divided into three classes: gas lasers, dye lasers, and solid-state lasers. These are pumped either optically by light or electrically by gas discharge, electrical discharge, or a laser diode. The laser-active medium of solid-state lasers depends on the active crystal used, the doping material, and its shape (see Figure 2). In dye lasers, a fluorescent dye is used as the active medium. Various gases are available for the construction of a gas laser.

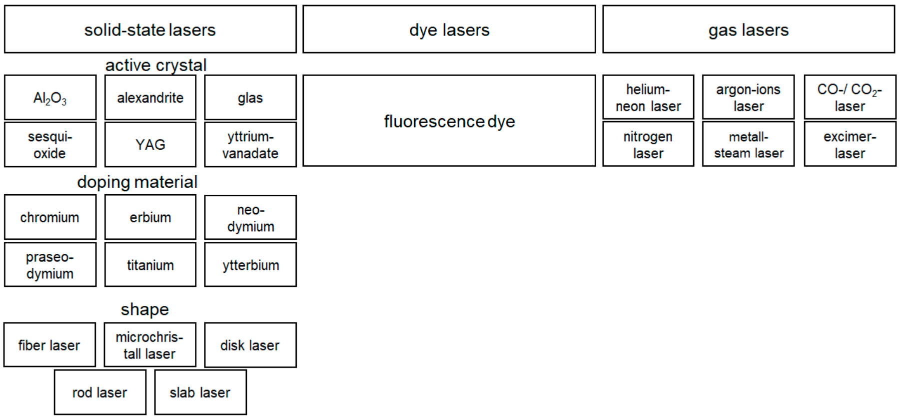


Figure 2. Characterization of different lasers using their active medium: solid-state lasers, color lasers, and gas lasers. Solid-state lasers can be distinguished by their active crystal, their doping material, and their shape.

The interaction of a laser-active medium and a resonator produces a monochromatic, coherent light beam with a very small divergence. The laser-active medium determines the wavelength of the laser beam and is able to influence the temporal behavior of the laser. The laser resonator determines other properties of the emitted laser radiation, such as beam divergence, beam diameter, intensity distribution, and pulse duration [24].

Active media with wavelengths between 940–1064 nm are used for laser soldering, since the ab-sorption coefficient of metals at these wavelengths is relatively high, and thus sufficient energy can be introduced into the material. The wavelength of Nd:YAG lasers is 1064 nm.

2.2. Solder Materials and Laser Soldering with Nd:YAG Fiber Lasers 1064 nm to Connect E-Textiles

The integration of PCB on textiles is usually divided into three process steps. First, the textile integrated wires have to be stripped. Afterward, the sensors/actuators can be contacted to these points. In a final work step, the applied sensors are protected from environmental influences and mechanical loads in the injection molding process. The use of a laser soldering process for the production of e-textiles is suitable for various reasons. On the one hand, the first two process steps in the production of e-textiles can be carried out in one machine bed; on the other hand, the laser soldering process ensures low heat input into the component [7]. Contactless soldering with high energy density enables short process times and low mechanical stress. This prevents damage to the surrounding textile. In addition, hard-to-reach areas can also be reached.

For laser soldering with solder paste, pastes with a grain size of 4 or 5 or larger should always be used. Smaller particles (larger grain size) have a larger surface to volume ratio. This promotes heat conduction between the particles. Heat conduction between the particles is important, as the laser energy can only be introduced optically via the surface. This means that the solder paste can only be melted by heat conduction. However, an enlarged surface also leads to increased oxide formation before and during the process.

Two different alloys in a near-eutectic composition were used as a solder paste. As a result, the alloys have a fixed melting point so that a rapid solid-liquid transition (phase diagram) takes place. This is elementary for a stable process and for determining the laser parameters. In one attempt popular in electronics manufacturing, Sn96.5-Ag3-Cu0.5 (SAC305) with eutectic point at Sn96.5-Ag3.8-Cu0.7 (SAC 387) and a melting temperature of 216 °C was used [24]. SAC alloys are characterized by very low electrical resistance and low melting points as well as high reliability in contacting. SAC 305 is more recommendable than the eutectic SAC387 because it has a lower tendency to solder defects [25]. In another attempt, the alloy Sn42-Bi57.6-Ag0,4 with a eutectic point at 43.47Sn-55.85Bi-0.68Ag and a melting temperature of 137.1 °C was applied [26]. We have chosen these two alloys because of their relevance to electronics manufacturing processes. Both alloys have a blend ratio close to the eutectic point, so that they have a rapid solid to liquid transition. Figure 3 shows the phase diagrams of the two alloys and their proximity to the eutectic point.

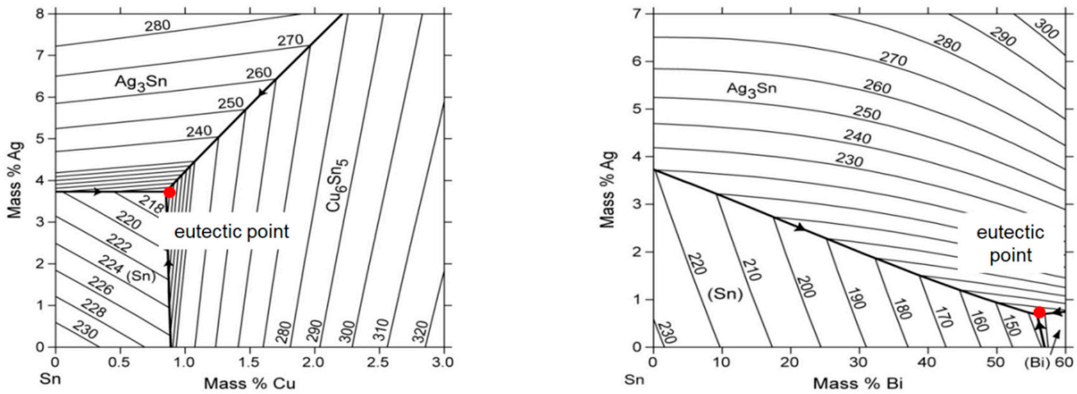
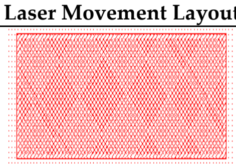


Figure 3. Phase diagram of SAC305 (**left**) [24] and Sn-Bi-Ag (**right**) [27] with eutectic points Sn96.5-Ag3-Cu0.5 (**right**) and Sn42-Bi57.6-Ag0.4 (**left**).

2.3. Wire Stripping

The laser (LPKF Laser & Electronics MicroLine 3D 160i, Garbsen, Germany) movement layout for stripping the micro cable is shown in Table 1. The red crossed lines in this frame represent the movement paths of the laser focal point. The distance between two lines counts only 45 µm. In order to completely remove the outer housing of the micro cables during stripping, the laser processing must be repeated. The optimum number of repetitions was set at 12, which leads to the best stripping result. The total process takes about 2.4 s.

Table 1. Wire stripping parameter.

Repetitions	Laser Power (W)	Processing Speed (mm/s)	Frequency (kHz)	Laser Movement Layout
12	16	1200	85	

The high transmittance (approximately 90%) of polyester means that only a very small proportion of the laser beam is absorbed by the polyester fibers [28].

2.4. Laser soldering of PCB to Textile

The hatch pattern of the test soldering surface reflects the movement pattern of the laser beam. The distance between the two lines of the hatch pattern is 45 µm, by a position accuracy of ±25 µm. The focus diameter of the laser beam is 80 µm (λ = 1064 µm) and a distance between Laser and PCB of 212 mm. The laser alignment and positioning are controlled by a camera. A range of 4 mm × 1.4 mm is traversed with this. This area is then processed for soldering with the parameters from the following Table 2. The parameters were selected on the basis of preliminary tests and varied by a suitable combination of parameters. Pneumatic clamping jaws are used to fix the textiles on the processing table. This means that the position of PCB and the textile can no longer change. The soldering paste is dosed by means of a robot. Also, 4–12 mg of solder paste is applied per soldering point.

Table 2. Parameters of the full factor plan: soldering of PCB to textile with four different alloys: Sn96.5-Ag3-Cu0.5 (T3, T4), 43.47Sn-55.85Bi-0.68Ag (T3, T4).

Full Factor Plan: Alloy:	S(1)	S(2)	S(3)
Laser power (W) Sn96.5-Ag3-Cu0.5	6	7	8
Laser power (W) 43.47Sn-55.85Bi-0.68Ag	4	5	6

Processing speed (mm/s)	95	100	105
Frequency (kHz)	95	100	105

Statistical Design of Experiments (DoE) is a methodology for the planning and statistical evaluation of test series. The DoE aims to obtain the most important influencing factors on the measurement results (outputs). The relationships between input and output can be determined and the influence of the input variables and their interactions on the output can be quantified. Statistical design of experiments has proven its worth for complex applications compared to other methods with multivariable data analysis. A full factor plan examines all combinations. The number of trials n_r is calculated accordingly as follows:

$$n = n_l^{n_f} \quad (1)$$

n_l represent the number of levels and n_f the number of factors.

2.5. Continuity Test

The measurement of the contact resistance is an indicator of the quality of the contact itself. For a reliable measurement, a four-wire measuring instrument is used. It eliminates the line resistances of the measurement cables (Figure 4b). The falling voltage at the resistor is measured with a voltmeter over the two remaining conductors. Based on the ohmic law, the resistance of the contact is calculated. Contact resistances are in a range of only a few milliohms [17]. In order to generate a measurable voltage, high currents of up to 10 A are required.

2.6. Peeling Test

The peeling test is used to determine the mechanical strength of the joint for further processing. The force is applied perpendicular to the circuit board (Figure 4a). Therefore, a load cell with a maximum force of 1000 N is used. The travel speed is 100 mm/min.

(a) (b)

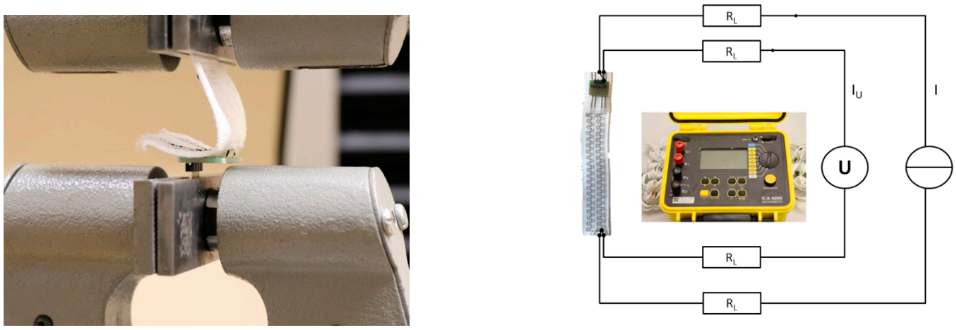


Figure 4. (**a**) Peeling test set-up: The PCBs are fixed in the blank and pulled on the contacted textile bands with a speed of 100 mm/min; (**b**) the measuring setup for determining the contact resistances by using the four-wire measurement technology.

3. Results and Discussion

3.1. Results of Wire Stripping

The textile-integrated lacquer-insulated copper strands were successfully and reliably stripped from both sides using the parameter set (12 repetitions, 16 W, 1200 mm/s, 85 kHz) and the hatch pattern (Table 1). The Nd:YAG laser (LPKF MicroLine 3D 160i with a wavelength of 1064 nm) is suitable for processing. This allows the electronics to be integrated locally into a textile tape without cutting off the integrated conductors. The insulation literally flaked off due to the high thermal energy of the laser (cf. Figure 5). The surrounding polyester knitted fabric was melted so that the copper strand could be contacted. It was still possible to find remains of the insulation on the conductors during microscopic examination of the stripped copper strands. Parts of the strands were always in the shadow of the laser beam, due to the 17-wire structure of the strands. That is why they probably were not removed.

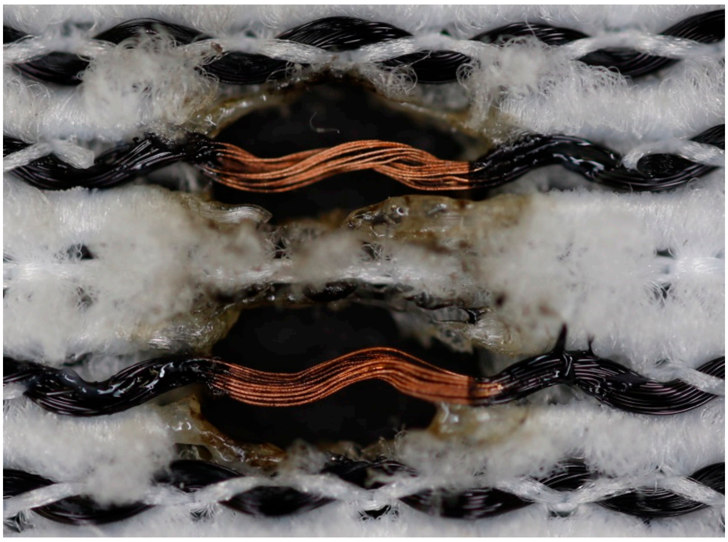


Figure 5. Laser wire stripping.

3.2. Results of Laser Doldering

After laser stripping, the PCBs can be soldered directly to the textile conductor tape. The direct processing of the samples eliminates the need for a further positioning step. This promotes the automated integration of electronics on textiles. Two established alloys (Sn96.5-Ag3-Cu0.5 and 43.47Sn-55.85Bi-0.68Ag) from electronics manufacturing were selected for the soldering pastes. For both alloys, a parameter set was first empirically determined, and then a Design of Experiment was carried out. Since there are 27 parameter combinations per material, only a few good examples are listed here (Table 3). An initial assessment of the successful contacting was provided by the visual inspection. The pictures show the resulting contact points after laser soldering.

Table 3. Parameter and results with Sn96.5-Ag3-Cu0.5 (SAC 305).

Sn96.5-Ag3-Cu0.5				
No.	**Laser Power (W)**	**Processing Speed (mm/s)**	**Frequency (kHz)**	**Results**
1	6	100	95	
2	7	95	95	
3	7	95	100	
4	7	95	105	
5	7	100	95	
6	7	100	100	

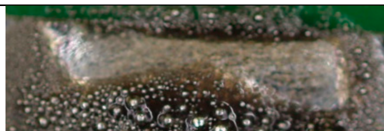
7	7	100	105	
8	7	105	95	
9	7	105	100	

Table 3 shows that the parameter set 7 W, 95 mm/s and 100 kHz produces the best optical result. The applied solder paste is completely melted and there is no solder ball formation. None of the appearances can be directly assigned to a parameter. However, it is noticeable that the amount of energy is always in a similar range.

The optical evaluation on the basis of shape, surface, and traces of smoke of the soldering results from Table 4 leads to an optimal parameter set of 4 W, 100 mm/s, and 105 kHz for the solder paste 43.47Sn-55.85Bi-0.68Ag. In general, solder balls are formed in all samples with this solder paste. This could not be prevented even with the DoE. As a result, the SAC 305 alloy shows clear advantages in handling and results. After determining an optimum parameter set for the two alloys, SAC 305 is selected for further processing. The wires are stripped and soldered directly to the PCB. The solder quantity, the grain size of the SAC 305 alloys used, and the number of laser processes were varied.

The repeated melting of the solder paste has a positive influence on the soldering result (Table 5, No. 1 and 2). The renewed short-term melting of the solder paste improves the soldering result, because the solder has more time to flow into the strand, and therefore it has a better wetting behavior. The solder is not damaged by the repeated short term melting. From observing the surface of samples 1 and 3, it can be assumed that the heat distribution in the solder paste with smaller grains (T4) is better than in the paste with larger grains. This is caused by the same ratio of the higher surface to volume ratio. More contact points between the grains improve heat transfer in the solder paste, resulting in more uniform heating. In addition, we evaluated the mass used. This results in an optimum between 6 mg and 8 mg. The amount of solder used in pattern 1 is not sufficient, while pattern 7 contained clearly too much solder paste. The contacting quality was carried out in several tests, including the investigation of the contact resistances between conductor and pad surface. In visual inspection, the quality of solder connection can be analyzed very well. The most promising samples were examined in mechanical and electrical tests. The samples were produced with the parameter combination 4 from Table 5 (T4, 6.8, 3).

Table 4. Parameter and results for 43.47Sn-55.85Bi-0.68Ag.

43.47Sn-55.85Bi-0.68Ag				
No.	**Laser Power (W)**	**Processing Speed (mm/s)**	**Frequency (kHz)**	**Results**
1	4	95	105	
2	4	100	105	
3	4	100	100	
4	4	105	95	

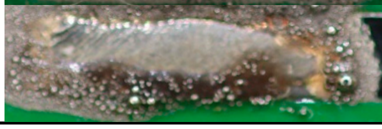
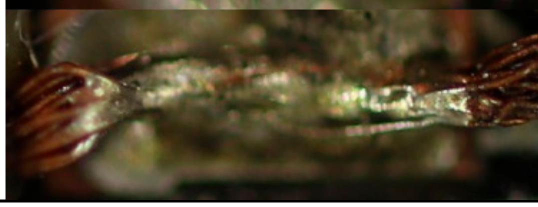
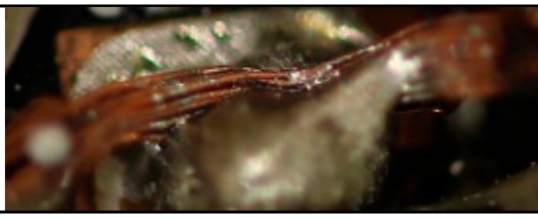
5	4	105	105	
6	5	95	105	
7	5	100	100	
8	5	105	105	

Table 5. Solder results depending on grain size and applied quantity.

No.	Grain Size	Solder (mg)	Laser Repetitions	Results
1	T3	3.4	3	
2	T3	3.4	4	
3	T4	4.1	5	
4	T4	6.8	3	
5	T4	8.7	2	
6	T4	11.1	5	

7	T4	19.9	2	

3.3. Continuity Test

The contact resistance provides information about the quality of the contact points. A four-wire measuring technique is used to calculate the contact resistance with the measuring setup from chapter 2.5. The contact resistance, as well as the wire resistance, can be calculated with the following formula:

$$R_{ges} = R_{1+n} \ldots R_L \approx 2\ R_{K+n} \cdot R_L \quad (2)$$

R_K = contact resistance; n = Number of wire (length 100 mm) and R_L = wire resistance

According to the data sheet, the line resistance is about 80 mΩ per conductor length (100 mm, AWG 32). Furthermore, the line resistance can be determined by measuring different conductor lengths.

Figure 6 shows the nearly-identical contact resistances of the soldered joints and insulation dis-placement connections [7]. Aside from that, adhesive connections show a much higher contact resistance. At the same time, the line resistances from the data sheets can be confirmed by the measurement procedure.

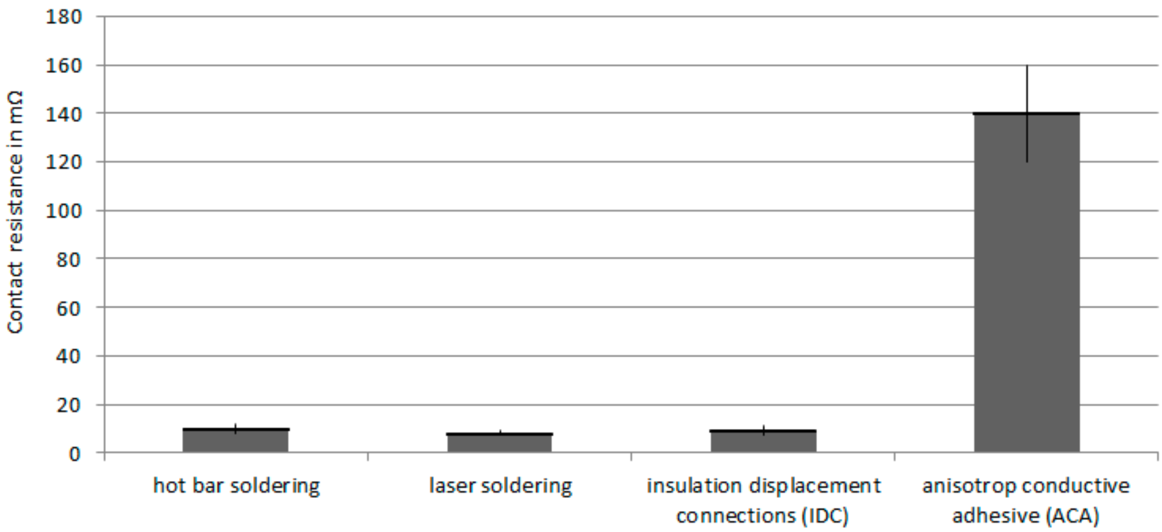


Figure 6. Contact resistance from hot bar, laser soldering, and insulation displacement connections (IDC). They all show nearly the same contact resistances, except for isotropic and anisotropic adhesive connections (ICA and ACA).

3.4. Peeling Test

The inspection of the mechanical strength is also interesting, after the examination of the contact resistances. The bearable maximum force was determined in a peeling test. During the tensile test (Figure 4a), three types of failure were observed in particular:

(1) Pulling the micro cable out of the solder joint
(2) Break-off of the micro cable directly at the contact point
(3) Break-off the micro cable at the point up to which the strand draws tin during the soldering process

When peeling the laser-soldered samples, the following picture can always be seen. In the beginning the first strand breaks off at the soldering point. In the second step, the stranded wire breaks off the board completely. Then the applied force only acts on the second contacted strand until it breaks off. Finally, the second strand is also peeled off the board. This results in the characteristic curve shown in Figure 7 compared to the contacting processes investigated so far: hot bar soldering, insulation displacement connections (IDC), and anisotropic conductive adhesives (ACA). The laser-soldered connections have rather low mechanical strength (Figure 8) [7].

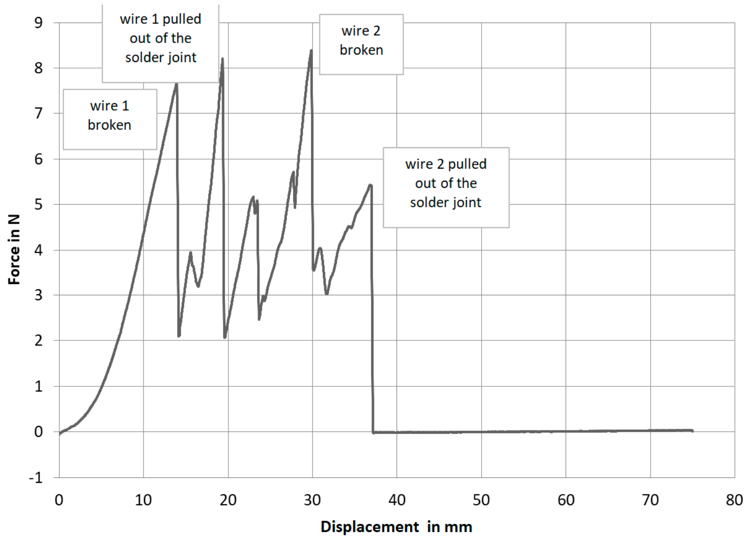


Figure 7. Exemplary force-displacement during the peel test.

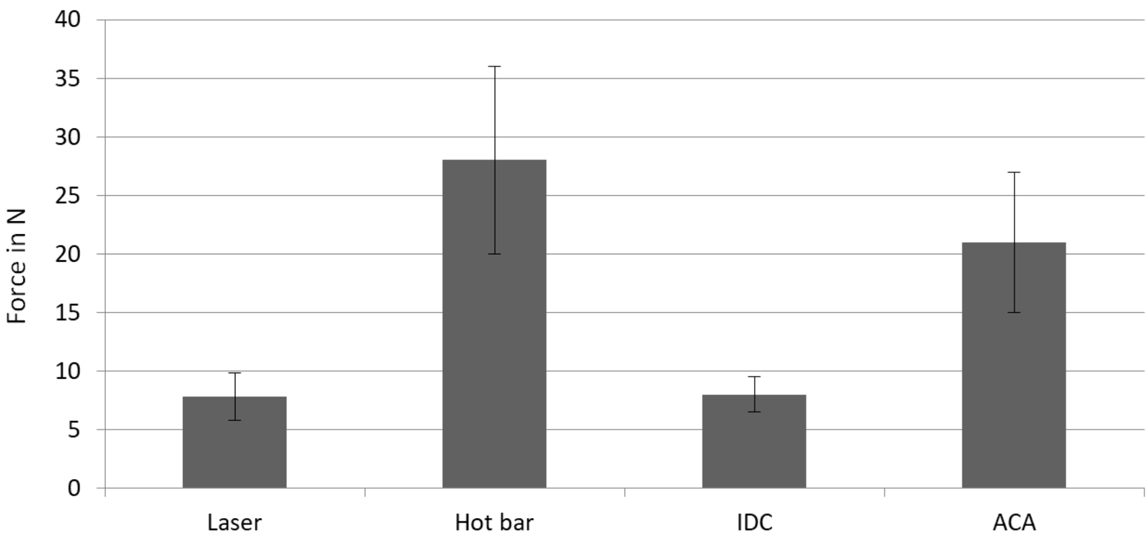


Figure 8. Peace force during peeling tests of laser soldering compared with the maximum peeling force of hot bar soldered, IDC, and ACA connections. Laser soldering shows a low peak force, with an acceptable scattering rate.

3.5. Metallography

Metallography was performed to observe the microstructure of the solder joint. Two manufactured samples were used in this experiment, which were produced with different laser powers. To obtain the micrograph, an optical microscope (OM) and a scanning electron microscope (SEM) were used. The acceleration voltage of the SEM was 15 kV. Figure 9 shows the areas of the two samples 1 (a, b) and 2 (c, d) around the strands. Sample 1 was soldered with 8 W, and sample 2 was soldered with 7 W. It is obvious that there is a blowhole at the solder joint, c) and d). Noticeable is that not only a large blowhole in the solder joint is formed, but also many bubbles and pores. The numerous soldering defects indicate a poor mechanical connection of the soldered joint as well as low electrical conductivity. Sample 1 shows a bad wetting of the conductors.

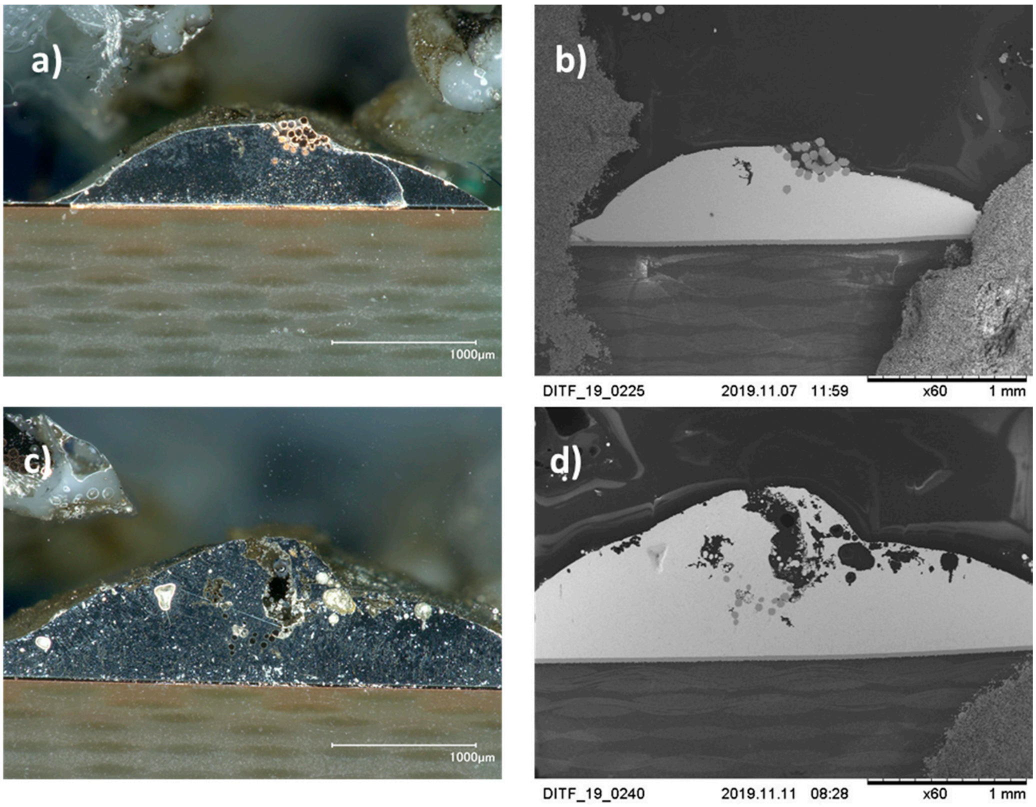


Figure 9. Pictures of the cross-sections of the soldered joints at 60× magnification; sample 1 (**a**,**b**) under OM (**a**) and SEM (**b**) with power 8W; sample 2 under OM (**c**) and SEM (**d**) with power 7 W. It can be seen that there is a blowhole at the solder joint of sample 2.

In the following Figure 10, the cross-section of the specimens are shown at 200× to 1000× magnification. Many soldering defects can already be determined here. Cracks between the strands and the solder can be seen in sections a) and b). This leads to a reduction in strength between the strands and the solder. Figure 10c,d shows the plate-shaped structures. They promote local crack growth.

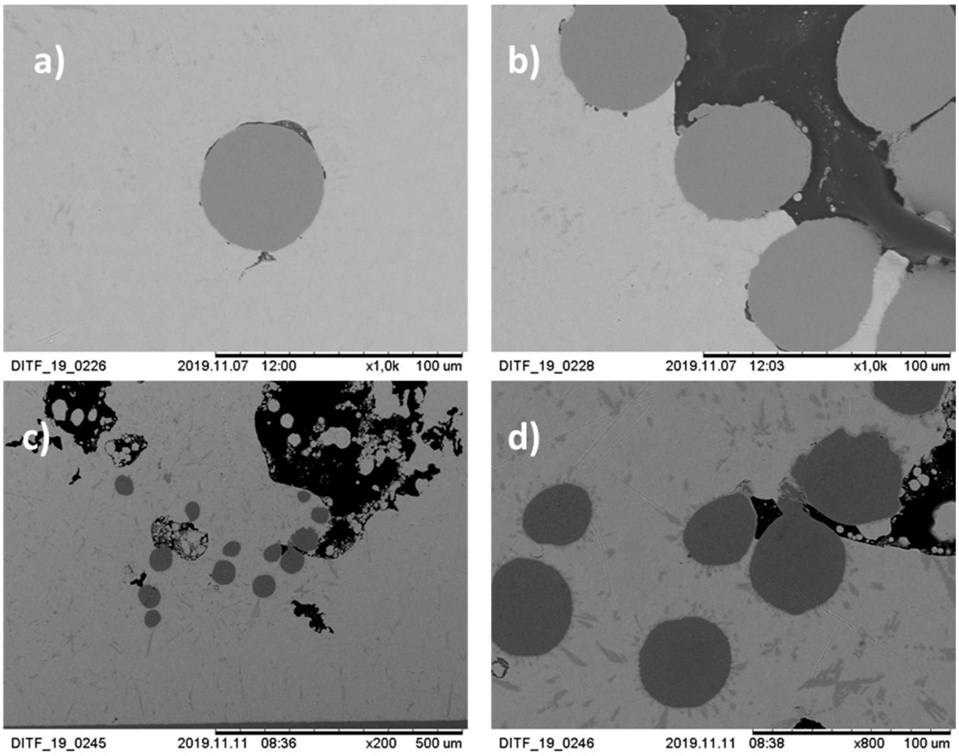


Figure 10. Picture of the cross-section of the solder joint at 200× to 1000× magnification: sample 1 under SEM at 1000× (**a**,**b**) magnification (power 8 W); sample 2 under SEM at 200× (**c**) and 800× (**d**) magnification (power 7 W).

In addition, the Cu/SAC interface of the solder joint was observed under the scanning electron microscope with 2000-fold magnification. The composition of the intermetallic layers cannot be determined because no EDS mapping (energy-dispersive X-ray spectroscopy) was performed. An intermetallic layer can be seen in Figure 11. During soldering, Cu diffuses into the liquid SAC solder and reacts with Sn to form Cu_6Sn_5 at the Cu/SAC interface. Ag can react with Sn to form Ag_3Sn. The structure of Cu_6Sn_5 is shell-shaped, while the structure of Ag_3Sn is plate-shaped [29]. No plate-like structure is found in Figure 11a. In Figure 11b, it is visible that some plate-like structures are present at the interface.

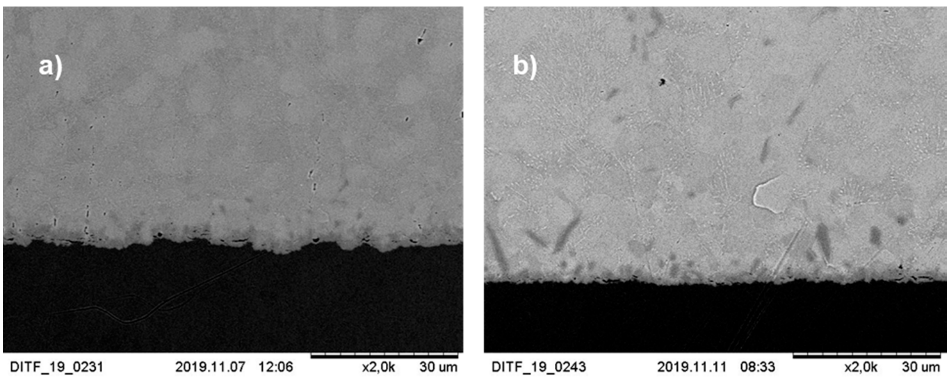


Figure 11. Pictures of the cross-section of the soldered joint with 2000× magnification: (**a**) power 8 W (**b**) power 7 W.

4. Conclusions

The automated integration of electronics in textiles is still a major challenge for the production of smart textiles. In this paper, the feasibility of contacting electronics on textile-integrated insulated conductors by laser soldering was investigated. A pulsed Nd:YAG laser with a wavelength of 1064 μm was used as a laser source. It was demonstrated that integration is possible. Especially with lacquer-insulated conductors, this is a very elegant way of contacting, because the conductors can be stripped with the laser in one process step, and the electronic components can be contacted directly afterward. This makes a positioning step in the production process unnecessary. This is one of the main advantages of laser soldering electronics to textiles. For parameter determination, a full factorial test plan was carried out for contacting, and suitable parameters were determined. Unfortunately, however, in some cases there are poorly-wetted conductors. As a result, the mechanical strength as well as the electrical conductivity of a few contact points drop from the usual values for soldering.

Author Contributions: Conceptualization, S.M.; Investigation, S.M.; Supervision, G.T.G.; Writing—original draft preparation S.M.; Writing—review & editing, M.H. All authors have read and agreed to the published version of the manuscript.

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4.4 Integrating Electronics to Textiles by Ultrasonic Welding for Cable-Driven Applications for Smart Textiles

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The following article focuses on the formation of reliable connections between conductive textiles and conventional litz wires using ultrasonic welding. This paper offers a promising approach to solve this problem. The electrical and mechanical performance of the samples were investigated after 15 and 30 wash and dry cycles in a laundry machine. Here the contact resistances and their peeling strength were measured. Furthermore, their connection properties were analysed in microsections. The resistance of the joints increased by more than 300 %, because the silver-coated wires suffered under the laundry cycles. Meanwhile, the mechanical strength during the peeling test decreased by only about 20 % after 15 cycles and remained the same after 30 cycles. The results obtained in this study suggest that ultrasonic welding offers a useful approach for the connection of textile electronics to conductive wires and for the manufacture of smart textiles.

Summary of the individual contribution:
Sebastian Micus partly developed the concept of the investigation as well as the methodology. He performed all examinations. Afterwards he validated the results, prepared the original draft preparation and led the investigation himself. Moreover, Sebastian Micus evaluated the results and wrote paragraph 2, 3 and 4 of this publication.

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Article

Integrating Electronics to Textiles by Ultrasonic Welding for Cable-Driven Applications for Smart Textiles

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Abstract: The connection between flexible textiles and stiff electronic components has always been structurally weak and a limiting factor in the establishment of smart textiles in our everyday life. This paper focuses on the formation of reliable connections between conductive textiles and conventional litz wires using ultrasonic welding. The paper offers a promising approach to solving this problem. The electrical and mechanical performance of the samples were investigated after 15 and 30 wash-and-dry cycles in a laundry machine. Here the contact resistances and their peeling strength were measured. Furthermore, their connection properties were analysed in microsections. The resistance of the joints increased more than 300%, because the silver-coated wires suffered under the laundry cycles. Meanwhile, the mechanical strength during the peeling test decreased by only about 20% after 15 cycles and remained the same after 30 cycles. The good results obtained in this study suggest that ultrasonic welding offers a useful approach to the connection of textile electronics to conductive wires and to the manufacture of smart textiles.

Keywords: smart textiles; e-textiles; ultrasonic welding; electronics to textiles

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1. Introduction

1.1. Smart Textiles and Level of Integration

Smart textiles are technical textiles with additional intelligent properties [1]. These novel products have been developed by many researchers for more than 20 years [2]. Smart textiles may interact with the environment by sensing external stimuli, adapting in a programmed way, and reacting accordingly. These specific functionalities and features are gaining in importance in the development of wearables and e-textiles. Intelligent and wearable textiles functionalized with electronics and electrical features are called e-textiles [1].

There will be a high growth potential for the smart textile market in the next ten years [3]. Electronics will soon be used in smart textiles to create hybrid products, to add new smart functionalities and to follow emerging trends in communication, customization, health, longevity, protection, performance, well-being, and the internet of things (IoTs). According to a report from IDTechEx [2], in 2025, over US$25 billion will be spent on formulations and intermediate materials for wearable technology. On the basis of the information in this report, the e-textiles market is predicted to reach US$3 billion by 2026. Sports and healthcare will be the two largest sectors in this field [2].

Smart textiles usually comprise sensors, actuators, data processing, a power supply, and a communication interface. The integration of smart textiles can refer to the incorporation of any conductive or electrical feature into any type of textile substrate. The conductive or electrical components of smart textiles are conductive yarns, conductors, semi-conductors, wires, printed circuit boards (PCBs) and conductive ink, which can be incorporated into conventional textiles.

One of the main challenges for smart textiles is to maintain good performance once individual parts are integrated into the system [4,5]. Another important challenge is to increase their life cycle and reusability in order to overcome situations that create external exposure, such as the washing and drying processes [6,7]. Furthermore, combining dissimilar materials with different elasticities together to create a hybrid system with the desired functionality is another challenge in smart textiles development [8].

The attempts and efforts of many industries, professionals, and academic researchers to overcome integration challenges have helped to classify the integration techniques into three main categories [9,10].

The first-generation category of techniques is referred to as side-by-side or added-on technology, which includes any techniques that can incorporate, attach, or embed rigid electronic components, such as sewing, embroidery, and soldering, into the textile surface. Conventional sensors deliver much more precise data and provide a wide range of measurable values and opportunities. The main precaution when using wearables integrated with these techniques is to detach the electronics from the garment before washing or to protect the electronic components in a casing. Handwashing is also recommended for this type of product due to the fragility of its components, which do not have enough endurance in commercial or residential washing machines [9,11].

The extensive capabilities of textile machineries and manufacturing methods improved the level of integration that it was possible to achieve and helped to integrate electronics into fabric structures. This led to a more advanced form of integration, called built-in technology. By using various textile manufacturing methods, conductive components can be permanently integrated into textile structures to deliver a more hybrid system. These methods include printing and coating conductive ink on passive textiles, laminating printed electronics, knitting, weaving, and braiding the conductive yarn, fibre, and wire. Many industrial products on the market or under development may fit within this category. These products could be washed with commercial or industrial washing machines; however, their lifetime might be jeopardized after 25 wash cycles. Moreover, these types of electronics show a low level of conductivity, so they are not usable for many applications [9].

The development of conductive yarn manufacturing methods has led scholars to introduce the latest or third generation of integration level, which mainly aims to fully integrate and create smart materials with both textile and electrical functionality. Examples include creating an intrinsically conductive fibre with sensing and actuation capabilities, such as a transistor fibre, which is durable and washable. This is a challenging category and still requires a significant amount of research and development [9].

As of now, the smart textiles currently on the market are mainly a combination of conductive textile structures with rigid electronic parts [7]. Textile electrodes, strain and deformation sensors, capacitive sensors and heating applications are examples of the popular smart textile production chain [12]. Although conductive yarns can be used in fabric manufacturing processes and deliver a smart fabric, there is still a need for secured and light transmission lines, or a termination point, which cannot be always achieved with the conductive yarns. Conductive yarns can be metallic-based, such as carbon, or non-metallic based, such as metal fibre. These conductive yarns have been developed with conductivities ranging from five Ω/m to several kΩ/m [13]. Their low amount of conductivity makes conductive yarns fewer effective candidates for transmission lines in smart textile systems. Conductive yarns are generally not insulated, and they are not supposed to suffer from surface modification/oxidization either. However, it is hard to keep conductive yarns away from environmental exposures as they are embedded in substrates with tactile properties and in touch with water and moisture [13]. Therefore, insulation is crucial for conductive yarns if they are used as conductors for transferring signals. Besides, insulation increases the number of manufacturing steps for conductive yarns, which eventually affects their price. Therefore, the integration of available rigid conductors and semi-conductors into soft conductive textiles offers the most practical solution. Wires and PCBs are some of the main electrical components to be integrated into textiles [8,10]. There are cable-driven applications in smart textile products that use wires to make connections between sensors/electrodes/actuators to the terminal zone, such as the portable exoskeleton glove, which is used for object grasping and manipulation [14]. It is difficult to avoid exposing gloves to environmental features, such as water and moisture; therefore, the use of wire in multiple locations offers a safer option for transmission lines [14]. Other examples of cable-driven textile actuators are structured functional textiles in combination with a flexible actuation scheme that enables assistive torques to be applied to biological joints, such as soft exosuits for gait assistance [15] and shape memory alloy actuator-embedded smart clothes for ankle assistance [16]. In these devices, cables and wires are connected to textile-based components to provide mechanical linkage [9].

Advances in manufacturing have helped to develop the integration of flexible electronics into fabric structures. These have included fast-paced manufacturing methods, such as weaving narrow tapes with different gauges of insulated and non-insulated wires, the tailored wire placement (TWP) of wires on the fabric with e-embroidery and routing cables through garments during the knitting process on flat-bed machines. By embedding wires and conductors into textiles, the ease of attachment and aesthetics of a connection may be improved. However, physical strength, electrical reliability, durability, and low cost are yet to be achieved. There might be more than one location in smart textiles that requires a bond as a termination point between wires and other electronic devices.

Scholars have identified nine main factors to consider when choosing a connection method between rigid electronics and textiles: physical strength, electrical reliability, ease of attachment, repeatable re-attachment, aesthetics, size, comfort, cost and availability. The main methods involved are: soldering, different types of welding, the use of conductive adhesive and the use of pressure-based connectors. Solder is an option for metal-based yarns that offers physical strength and electrical reliability; however, its higher processing temperature may burn or damage textiles and affect the durability and aesthetic aspects of a garment [17].

Electrically conductive adhesives have been introduced to provide mechanical strength and electrical reliability for the bonding method. This method has been compared to t solder technology and some disadvantages have been reported, such as lower electrical conductivity, conductivity fatigue in exposure to humidity, high temperature and wear and tear [17].

Another method to connect wires or electrical components firmly to textiles is to use pressure-based connectors. These connectors could be staples or crimping. Each method has an impact on the fabric's properties. For example, staples can clamp the wires into place and offer a conductive pathway. The staples are considered non-reversible. Crimping uses some metal holders to penetrate the textile, in order to create an electrical connection between the connector and the conductive part. This method is non-reversible, and the connector must endure the wear and tear [17].

A quick bonding process that ensures physical strength and electrical reliability is required. As has already been stated, the existing method mainly involves several manual tasks and, in many cases, it requires commodity materials, such as conductive epoxy, solder paste, clips, and snaps. Furthermore, an extra encapsulation technique is required to secure the termination point from environmental exposure, including mechanical tensions and wash cycles [17].

1.2. Ultrasonic Welding as an Integration Technique for Smart Textiles

Ultrasonic welding is one of the most popular welding methods for joining and it has been used in numerous industrial fields, including the automotive, aerospace, medical, electronics and textiles industries [18]. This welding method uses mechanical vibrations to generate heat at the joint to soften and melt the materials in order to bond them. It is fast, economical, easily automated, and well-suited to mass production. As it does not introduce contaminants or sources of degradation to the weld that could possibly affect the biocompatibility of the medical device, it is a favorable joining method for medical applications [19]. It produces consistent, high-strength joints for seam sealing applications in the textile industry. Its quick weld time and elimination of the need for an extra ventilation system are other advantages of this welding method that make it suitable for mass production in the textile industry. Its other applications include strapping, belt loops, filters, and vertical blinds.

The main applications of ultrasonic welding in the textile industry include cutting and seaming, slitting, trimming, embossing and quilting. These methods consume little energy, eliminate the need for commodity materials, such as glue, clips or needles and can be manufactured very quickly [20]. Ultrasonic vibrations and pressure cause heat-activated materials to melt and penetrate the inter-fibre spaces of fabrics. Many studies have been performed on different ultrasonic welding modes and their processing parameters, namely, weld time, weld pressure and hold time. Their results show that the ultrasonic welding of textile materials depends on their thermoplastic content, fabricating types (woven, knitted, non-woven) and desired end use [17]. The ultrasonic welding of thermoplastic substrates is divided into two categories, based on the position of the horn. In near-field welding, the distance between the joint interface and the horn is 6.35 mm or less, whereas in far-field welding, the distance is greater than 6.35 mm [21].

W. Shi [22] investigated the potential for building smart seams by incorporating optic fibres through ultrasonic welding machines. The morphologies of the optic fibres embedded were examined under varying welding conditions and the power loss in the signal transition of the incorporated optic fibres was tested to determine the degree of attenuation of their signal transition properties. The analysis of the power loss of the embedded optic fibres indicated that the signal transmission properties of the optic fibres were not significantly changed under certain welding conditions. Therefore, optic fibres can be integrated into fabrics ultrasonically [22].

O. Atalay [19] used ultrasonic welding to analyse its suitability for e-textile transmission line manufacturing. Two groups of silver-plated and stainless-steel yarn with different linear densities were used. The yarns were placed between two layers of polyester fabric and welded with ultrasonic seam-sealing machines. Based on the experimental results, the conductivity of the stainless-steel yarns barely changed; however, increasing the contact force resulted in the rupture of strands. Filament rupture was also observed in silver-plated nylon yarns after the contact point was increasing. The electrical resistance values showed significant fluctuations for the silver-plated nylon yarn, even at low contact force values. Therefore, stainless steel yarn can be considered a suitable candidate for textile transmission lines integrated with ultrasonic welding; however, the use of silver-plated nylon is not recommended. Welding the conductive yarns between layers of hydrophobic polyester fabric adds an encapsulation property to the transmission lines, which increases their durability by protecting them from water contact and probable short circuits [19].

J. Lesnikowski [18] studied the properties of textile signal lines (TSLs) made using ultrasonic a welding machine, model PFAFF 8310. Three plain-woven nickel metalized polyester fabrics with a length of 150 mm and a width of 35 mm were placed between two non-conductive layers of fabrics with different weaving constructions, including plain, satin and panama. In both constructions, two of the signal paths were used as ground paths. The linear resistances characterizing the properties of the TSLs working as direct current (DC) lines were measured. To check the signal integrity of the TSLs transmitting high-frequency signals, characteristic impedance and scattering parameters were described and measured. The bonding strength between the electroconductive path and passive fabric was measured using a tensile testing machine. The results of this research showed that despite the ability to produce TSLs capable of transmitting DC and alternating current (AC) signals offered by ultrasonic welding technology, the direct welding of electroconductive paths on fabric affected the TSLs' functionality. Based on these observations, ultrasonic bonding has a destructive effect on electroconductive paths, and these effects cause partial or complete loss of electrical conductivity. The precise positioning of paths and the manual production process were described as difficulties involved in this integration technique. The increased stiffness properties of constructed TSLs compared with samples made with other technologies was described as another disadvantage of the ultrasonic welding method [18].

In this study, we went one step further. Textile conductive sensory surfaces have advantages over conventional electronics in terms of drapability and haptics. Textile sensors are already very well developed and researched and can already be manufactured. The conductivity of the yarns used in textile sensors cannot compete with that of metallic strands. However, the connection of textile sensor technology with conductive cables has been rather difficult up to now. Over longer distances, energy sources as well as electronic control units should be equipped with highly conductive cables. Since the connection of textile electronics and cables has not yet been investigated in detail, the use of this sensor technology is limited. Therefore, this article presents a method for bonding wires to the functional textiles with ultrasonic welding for cable-driven applications.

2. Materials and Methods

In this study, we investigated a method for bonding wires to functional textiles with the ultrasonic welding method for cable-driven applications (Figure 1). This production method for smart textiles opens up totally new opportunities. The products of this combination of conventional electronics and textile sensors the products increase value for customers.

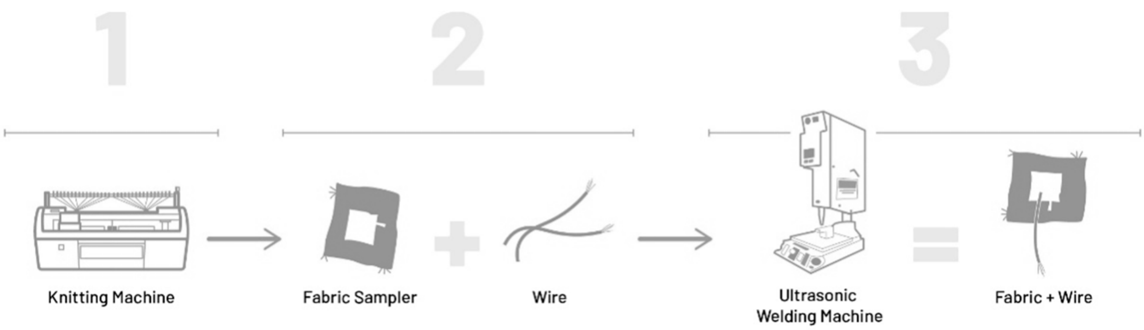


Figure 1. Schemes follow the same formatting.

During the assembly process, conductive knitted fabric was joined with a copper litz wire. In order to make the proper contact point between the silver yarns and the copper conductor, the conductor was stripped manually to about 10 mm and then inserted between the active textile and a waterproof tape to provide proper encapsulation. The samples were integrated using an ultrasonic welding machine (Emerson Electric Co.—Branson 2000; Saint Louis, MO, USA), as shown in Figure 2. The method involved a longer optimization process with an experimental design. During this process, there were several parameters involved that ensured the optimization of each joint between the two materials. In order to optimize the welding parameters for a bond, some visual characteristics were taken into consideration. As the method applies to to wearable technologies and its base materials are flexible textiles, one of the main factors involved in its visual characteristics is the avoidance of damage to the conductive fabric during the bonding process and of the possibility of burning and tearing due to overheating and thermal energy discharge from the horn during bonding.

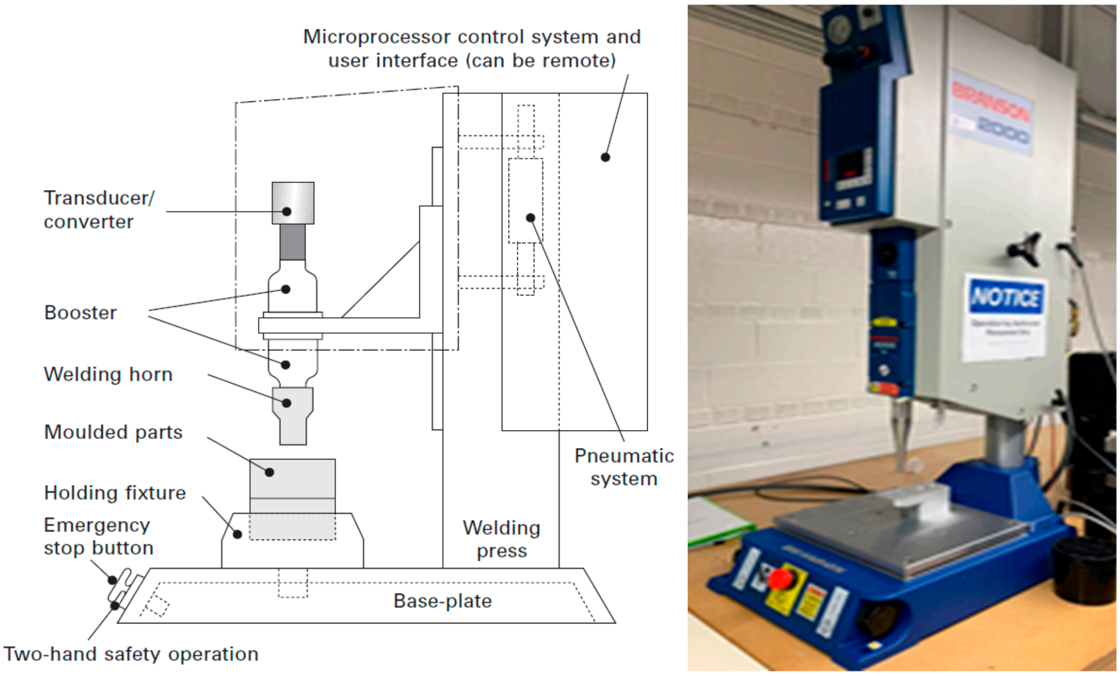


Figure 2. Schematic of the ultrasonic welding machine, displaying its key features [9] (**left**); Photograph of the ultrasonic welding machine (**right**).

Over-melting wires and breaking the conductors are the other important factors to take into consideration. Over-melting the fabric around the wire might leave some residual chemicals on the fabric, which lead to imperfections on smart textiles and e-textiles. Besides, it is very important not to break the conductor strands under the anvil pressure as this might result in an unreliable joint for electrical applications, such as conductivity. For this reason, American Wire Gauge (AWG) 24 copper conductors were chosen, as they are soft and flexible.

Finally, leaving a visible trace of the anvil shape behind the welded area would not be acceptable given the possibility that there might be more than one wire required for a garment. To avoid this effect, a rounded 10 mm-diameter threaded horn was chosen to weld the copper conductors to conductive fabric. Besides, the materials for the fabric were chosen based on their ultrasonic weldability. For instance, it was previously established that wool and cotton are not very suitable for ultrasonic welding due to their lack of thermoplastic content. The following parameters were used to bond the copper conductors to the conductive textiles with the ultrasonic welding machine (Table 1).

Table 1. Ultrasonic welding parameter.

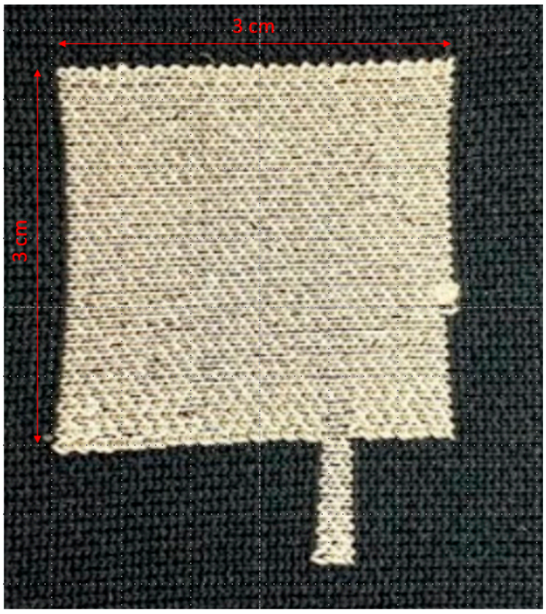
Type of Horn (Head)	Weld Time (s)	Hold Time (s)	Pressure (Psi/Bar)	Trigger Force (N)	Amplitude (µm)	Near Field or Far Field
Threaded Horn with 8 mm diameter	0.070	1.5	20/1.37	15	50	Near Field

2.1. Sample Preparation in Knitting

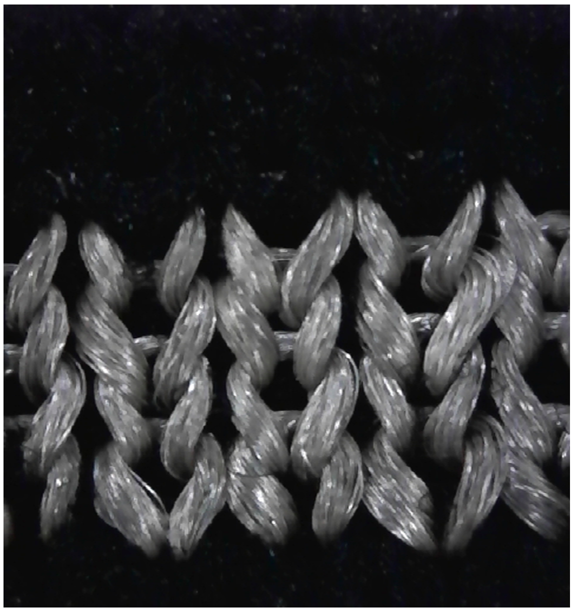
The type of knit structure used is an important factor in ultrasonic bonding. The thickness of the fabric, whether there is elasticity in both directions and whether there is a tight or a loose textile structure all influence the bonding strength. For instance, an increase in fabric thickness would require an increase in weld time and amount of pressure, which may affect the bonding strength adversely. As our purpose is to use the bonding technique in smart textiles, the machine gauge was chosen based on the reproducibility of smart textiles on the knitting machines with finer gauges (Table 2). The active textile samples were knitted on an 18-gauge Stoll flat knitting machine. The silver-plated polyamide yarns were knitted on the surface of a double-knit structure in 3 cm by 3 cm (9 cm^2) area. A small 2 mm by 8 mm tail was added to the square structure to make a junction for a further integration contact point. Polyester yarns were chosen for the passive parts of the knitted sample because of their suitability for ultrasonic welding. In order to provide the fabric's structure with elasticity, one end of elastane was used as an interlocking connection between the two layers of knitted fabric (Figure 3) [17,21].

Table 2. Knitting parameter.

Conductive Yarn	Knitting Structure	Thickness (mm)	Stitch Density (Course × Wale)
Silver Plated Polyamide/Nylon 220 Denier	Double Jersey with Elastane interlock	1.8	4 courses × 10 wales = 40



(**a**)



(**b**)

Figure 3. Picture of the knitted sensor (**a**) and knitting pattern (**b**).

2.2. Test Scenarios

The electrical and mechanical properties of the joints in different test scenarios were investigated. The measurement of contact resistance is well suited to the characterisation of the electrical properties of connections. The contact resistance was measured within a four-wire resistance measurement setup. The mechanical properties of the contacts were examined in a peeling test. The test made it possible to determine whether the connection was robust enough for further production steps and as a product during wash and wear cycles. Furthermore, several microsections of the joints were taken from multiple replicates before and after washing.

2.2.1. Electrical Properties: Contact Resistance Test

Contact resistance is one of the decisive variables in the analysis of electrical contacts. The four-wire resistance test is particularly suitable for determining contact resistance because it makes it possible to measure only the contact resistance, excluding the line resistance of the measurement wires. When the contact resistance is not of a high value, the resistance of the cables becomes significant [23]. The contact resistance measurement can indicate the quality of the contact itself. A four-wire measuring instrument, in this case a micro-ohmmeter (Chauvin Arnoux Group—C.A 6255, Paris, France), was used to eliminate connection and line resistances in the test setup (Figure 4).

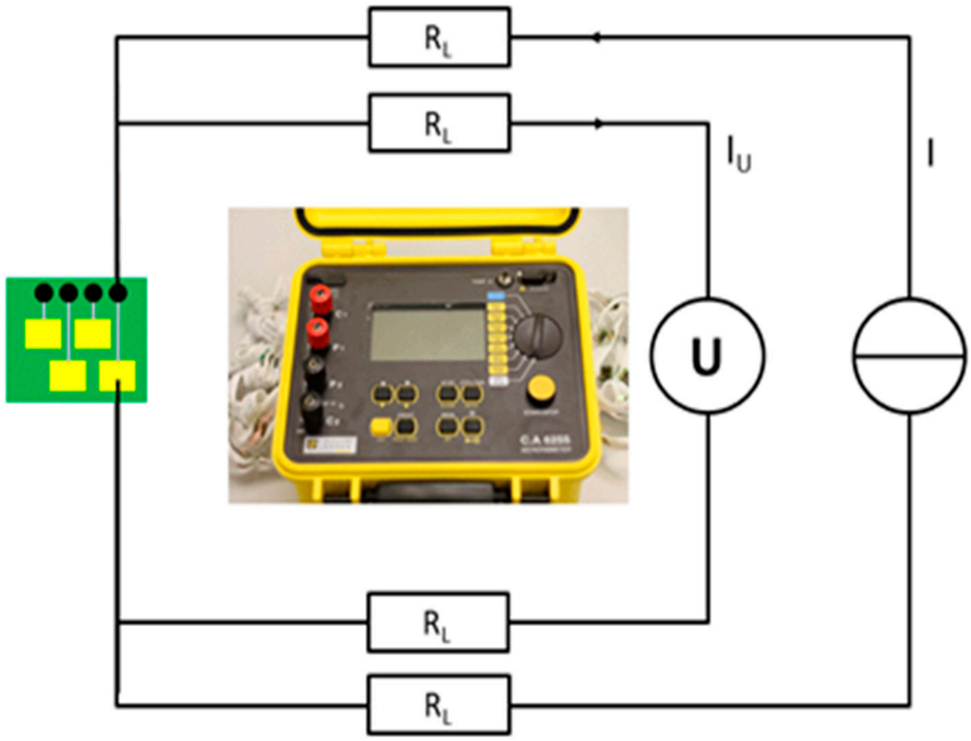


Figure 4. Measuring setup to determine the contact resistances using four-wire measuring technology.

In order to generate a measurable voltage, high currents of up to 10 A were required. The current was provided by two of the four contacts. The falling voltage at the resistor was measured by a voltmeter over the two remaining conductors. Based on Ohm's law, it was possible to calculate the resistance of the contact. The contact resistances were in the range of only a few milliohms [24].

2.2.2. Mechanical Properties: Peeling Test

A peeling test was carried out to determine the mechanical strength of the joint for further processing. It is a simple and fast method to analyse the adhesion of electronic interconnectors on ribbons [25]. Therefore, the self-developed peeling test is ideal for inspecting joints between PCBs and conductive textiles.

The textiles were clamped on a table, which was fixed on the bottom section of the Zwick tensile testing machine (Z020, measuring head: 50 N). The conductors were peeled off the textile at a 90° angle. The force was applied perpendicularly to the textile (Figure 5). A load cell with a maximum force of 50 N was used at a travel speed of 100 mm/min [26–28].

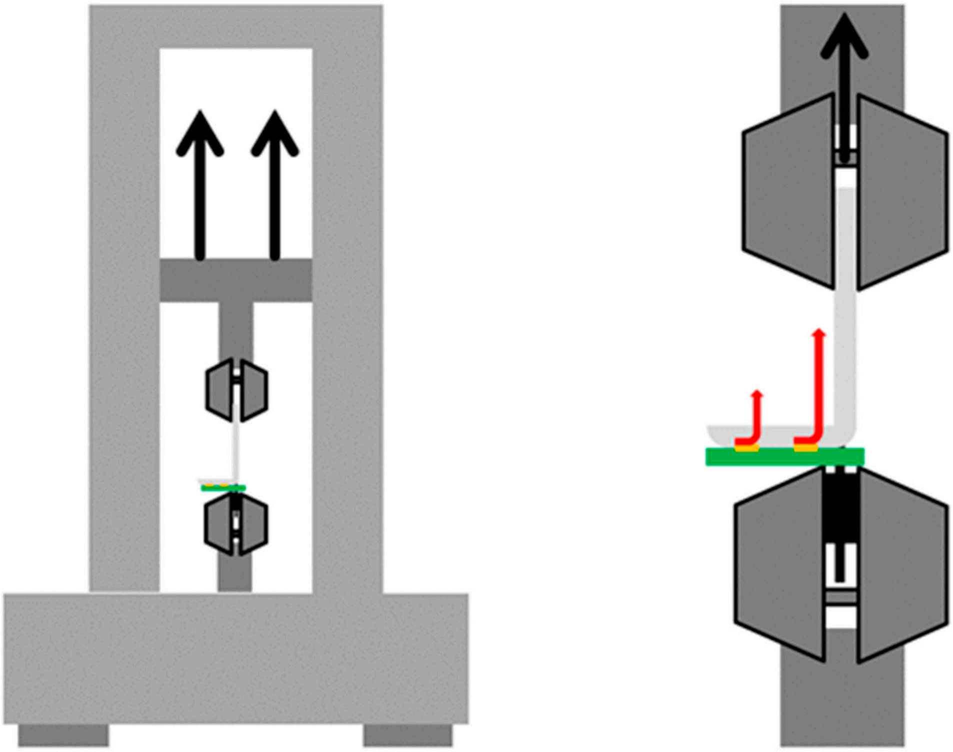
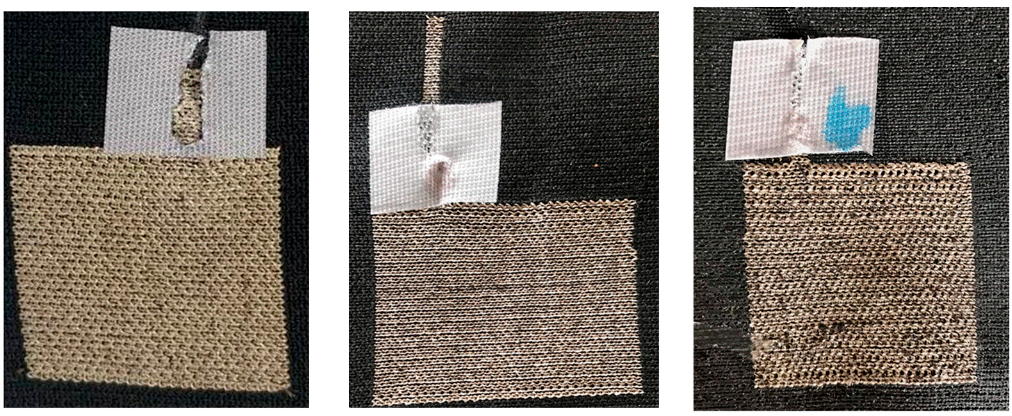


Figure 5. Peeling test setup, in which the samples were clamped to the blank and pulled on the attached wires with a speed of 100 mm/min.

3. Results and Discussion

3.1. Optical Properties: Microsection

Figure 6 shows pictures of the different samples: unwashed, 15× washed and 30× washed. The samples featured the same kitting parameters and the same tail structure, but the size of the textile electrodes differed. The size of the conductive electrode did not influence the connection process of the wire and the tail. The pictures showed structural alterations in the knitted fabric. The white waterproofed tape secured the connection and supported the connection area.



(**a**) (**b**) (**c**)

Figure 6. Photos from the samples: Unwashed (**a**), 15 timeswashed (**b**), 30 times washed (**c**).

In order to investigate the integrity of the bond between the copper conductors and the conductive fibers, SEM pictures were taken of the cross-section of the joint. Due to the pressure applied by the ultrasonic welding anvil during the bonding process, the copper conductors were completely adhered to the conductive fibers.

Figure 7 demonstrates microsections of the unwashed, 15 times washed and 30 times washed samples. The microsections were examined under an incident light microscope

(KEYENCE—VHX-2000 Digitale Mikroskop, Osaka, Japan, upper row: a, c, e) and a scanning electron microscope (SEM: Hitachi—Tabletop Microscope TM-100, Chiyoda, Japan bottom row: b, d, f). The pictures illustrate the connection between the textile conductive yarns from the tail structure of the electrode and the metallic wire. Pictures (a) and (d) in particular show several contact points, which is a good sign for a low-resistance joint.

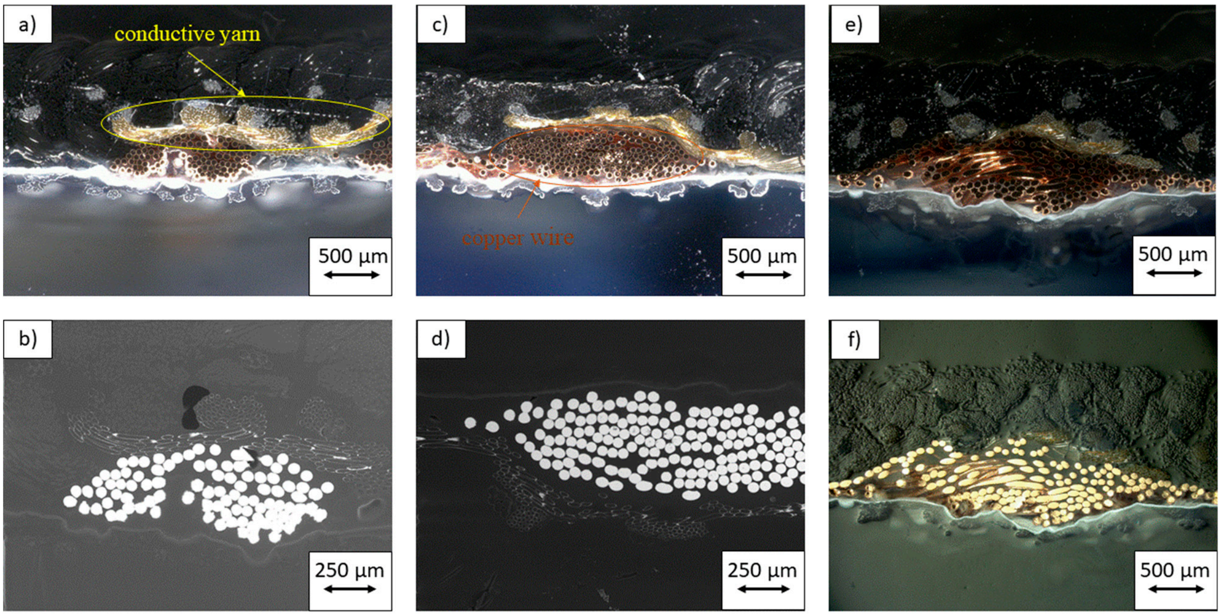


Figure 7. Microsections unwashed (**a**,**b**); 15× washed (**c**,**d**); 30× washed (**e**,**f**). Incident light microscope (upper row: **a**,**c**,**e**) and scanning electron microscope (SEM) (bottom row: **b**,**d**,**f**).

3.2. Electrical Properties: Contact Resistance Test

In order to investigate the electrical properties and the quality of the connection, a four-wire resistance test was performed. As expected, the electrical resistance increased with the number of washing cycles. While the unwashed samples demonstrated a resistance of just 1.95 Ω, after 15 washing cycles the resistance reached 2.55 Ω and after 30 cycles the samples demonstrated a contact resistance of 7.15 Ω. Moreover, the standard deviation of the values rose with the number of washing cycles (Figure 8). The strands were connected by ultrasonic welding to silver-coated conductive yarns. The coating suffered heavily due to the mechanical and chemical stress during the washing process. In the beginning, there was enough coating on the yarn, so the first cycles did not have a high influence on the resistance of the connection. After repetitive wash and dry cycles, the coating was reduced in thickness and the resistance increased. In summary, it can be said that the number of washing cycles must be regulated to ensure the perfect functioning of smart textiles.

3.3. Mechanical Properties: Peeling Test

To analyse the mechanical properties of the connection, a peeling test was performed at aa 90° angle. The unwashed samples reached a strength of almost 29 N in the peeling test. After 15 times and 30 times cycles of washing, this value dropped to just under 23 N (Figure 9). When comparing the results with those of soldered joints [26], ultrasonic welding shows comparable values of 23 N. It can also be seen that the strength does not decrease further with the number of washing cycles, which indicates that the designed joints were very durable. The number of washing cycles did not have to be regulated due to the strength of the joints. Evidently, the connection was not influenced by mechanical stress during the washing cycle.

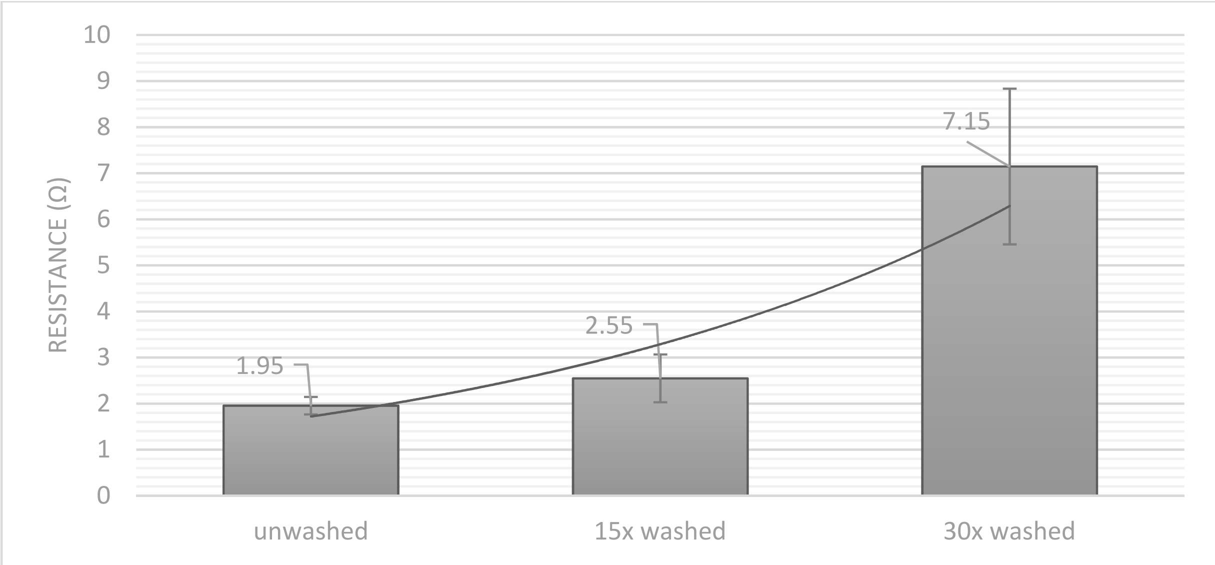


Figure 8. Contact resistance from the four-wire resistance test after different washing cycles (black exponential trend line).

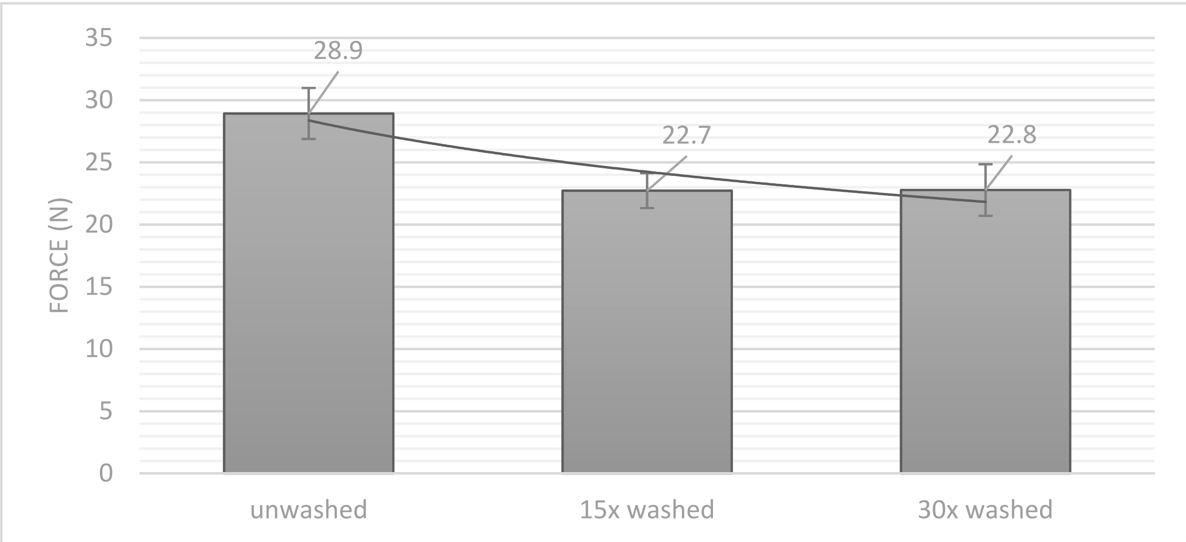


Figure 9. Peeling strength force after different washing cycles (black exponential trend line).

Figure 10 illustrates the course of force during the peeling test for each sample. The graphs show an approximately uniform development. The washed samples demonstrated an irreducibly lower maximum force than the unwashed samples, but the course and the pitch angle were nearly the same. The results show the excellent mechanical properties of the joint. Both the unwashed and the washed samples demonstrated very high peel strengths. It can be concluded that the joints were hardly affected mechanically by the washing process. Figure 10 also shows that the maximum ductility of the joint decreased with the number of washing cycles. The entire structure thus became more brittle.

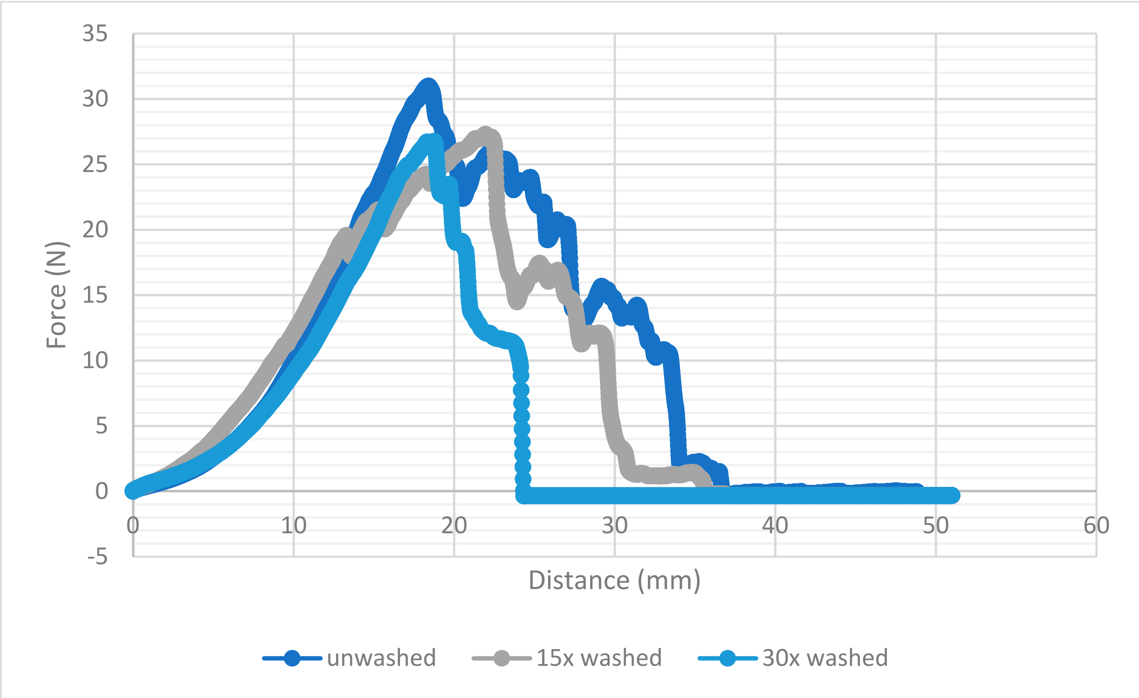


Figure 10. Peeling strength force after different washing cycles: course of force during the peeling.

4. Conclusions

This paper dealt with the development of direct connections between conductive textile sensors and copper strands via ultrasonic welding. The application relevance and the advantages of wash-stable compounds was the reason for the investigation. The joining of conductive textile surfaces and wires helps to develop new smart textiles with the advantages of the usage of pure textile sensors and the high conductivity of metallic strands in clothes, for example. Textile sensors offer great opportunities for several smart textile applications in everyday life because the drapability and haptic quality of textiles make them suitable for wearing on the skin. The method replaces much larger snap fastener connections and enables the production of totally new smart textiles. For this purpose, we adapted the well-known ultrasonic welding technique to connect these joining partners. Therefore, we optimized the parameter-sets and produced the setup presented here. During the connection process, fabric and wire damage were considered. An increasing weld time and pressure would affect the bonding process adversely. The ultrasonic parameters were carefully examined and chosen in order to maintain proper bonding between the conductive fabric component and the wires. Afterwards, we examined the joining section of the samples, as a combination of wire and fabric damage. To ensure the usability of the resultant smart textile, we performed several washing tests. Some of the samples were washed 15 times and others 30 times. The samples were optically analysed under an incident light microscope and an SEM. Thus, microsections of the joints were made. The microsections clearly showed connections between the textile conductive yarns and the metallic strands. The electrical properties, especially the contact resistance, were investigated using a four-wire measurement setup to minimize the influence of the wire resistance. The resistance increased during the washing cycles because the silver coating of the conductive yarns suffered under the mechanical and chemical stress during the washing process. The coating washed away and rubbed off, so the conductivity decreased and the resistance increased exponentially. The mechanical properties of the connection were analysed during a peeling test, where the wire was peeled off at a 90° angle from the textile. At the time of writing, there is no equivalent method through which to measure the bonding strength of electrical components to textiles. As a result, the connections were hardly subject to any mechanical stress. The results of the washing cycles also proved that machine washing has no effect on bond strength. The presented method enables the secure and reliable connection of metallic wires to knitted textile sensors, as shown by the results of the washing tests and the peeling test.

In summary, ultrasonic welding technology is an effective method for the connection of metallic wires to conductive textile sensors. The technology will significantly broaden the commercial applications of smart textiles.

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5 Discussion of all Results and Embedding in the Overall Scientific Context

The aim of this work was to solve one of the most pressing problems in designing and the construction of e-textiles: The automated integration and connection of conventional electronic hardware components to textiles. Ensuring the textile properties: Drapability, flexibility, handling and feeling are one of the main objectives. Therefore, the present work investigates connections between textile-integrated, insulated, metallic strands and PCB sensors in chapter 4.1, chapter 4.2 and chapter 4.3. Chapter 4.4 focuses on connections between textile-integrated, insulated, metallic strands and textile sensors. To achieve this initial goal, various integration methods from electrical engineering have been adapted for the usage of smart textiles. The focus of this thesis lies on the usage of litz wires, due to the superior electrical and mechanical properties of insulated metallic conductors compared to silver-coated polyamide yarns. Fig 5.1 gives an overview of the covered methods in this thesis.

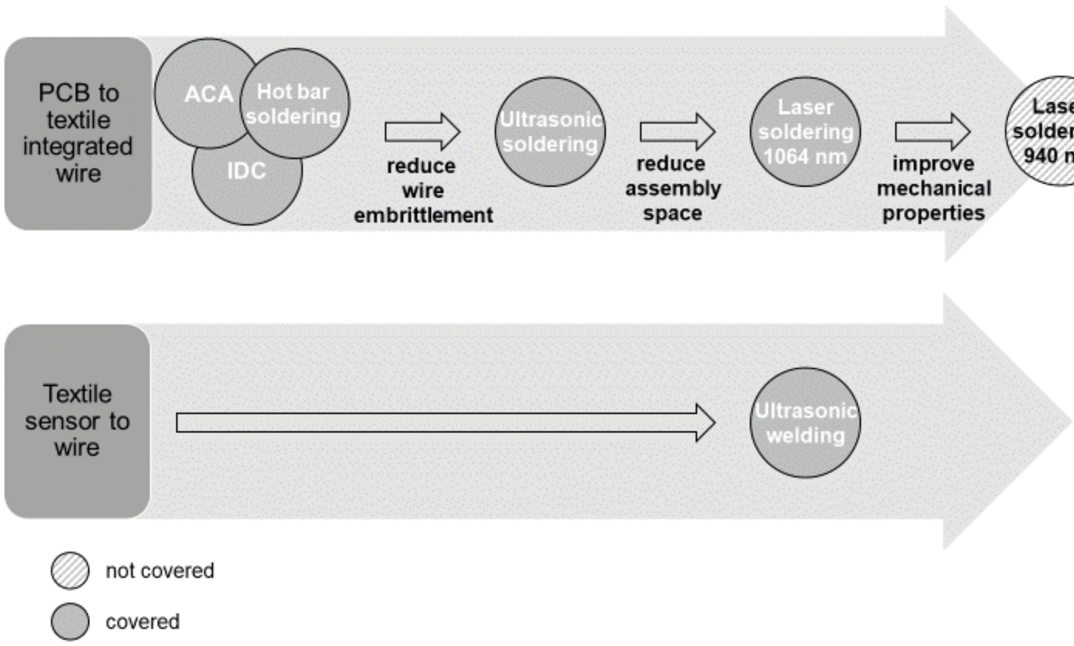

Fig. 5.1 Overview of the covered methods in this thesis to connect conventional and textile sensors to litz wires.

The first paper (chapter 4.1) focuses on hot bar soldering, anisotropic conductive adhesives and insulation wire displacers. During a pre-evaluation, the three different contacting methods proofed to be suitable for the automated production of smart textiles while being a cost-effective solution. Anisotropic conductive adhesives are appropriate for very small and nearby contacts, but there are still disadvantages in contacting electronics to textiles.

In some cases, the textile between the curing unit and the PCB could not be compressed sufficiently and, therefore, the necessary pressure for contacting could not be applied. This means that not all contact points are reliably connected. It should be noted that this process was primarily developed for joining flex PCBs with very closely spaced contact points. The process simplifies their application and handling immensely, because the low quantity of conductive fillers makes shortcuts between adjacent contacts statistically impossible. Whereas, pressure was applied to the contact point via the flex film in the original application. After adapting the technique to smart textiles, the curing unit directly touches the conductive adhesive. On the one hand, this can lead to a weakening of the joint when the curing unit is removed. On the other hand, this also leads to residues on the curing unit. Another disadvantage is that the visual inspection of the contact points allows only limited conclusions about their quality and durability. Due to the low proportion of conductive particles within the adhesive, the ACA bonded joints have a relatively high contact resistance. Moreover, the measurement results show a high standard deviation. The peeling test provides sufficiently good results. However, the bonded joints cannot compete with the results of the soldered joints and without further protection of the contact points, the bonded joints cannot withstand a washing cycle in a laundry machine.

Insulation wire displacers stand out as a particularly simple method for contacting: There is no need for prior stripping of the conductors and only a suitable insertion tool is required. However, during our investigation, ICA connectors were not available for our common AWG 32 strands or thinner wires. The dimensions of the connectors make their use for miniaturized electronics almost impossible. This makes them unsuitable for smart textiles. Nevertheless, good results could be achieved in terms of electrical and mechanical properties when samples with conductors with a larger cross-section were produced. Due to the gas-tight connections between the conductor and the connector, very low contact resistances were achieved. The washing cycle also had comparatively little influence on this. The results from the peel test cannot be compared with the values of soldered connections, but exceed the pre-defined force of 5 N for further processing.

In the first paper, hot bar soldering proved to be particularly suitable for integrating electronics into e-textiles, but it should be noted that dispensing solder paste requires a further production step. In addition, the holes in the textile must be relatively large to avoid contact between the thermode and the textile. The textile melts immediately after touching the hot thermode. This causes residues on the tool and has a negative influence on subsequent contact points. In addition, the residues have to be removed manually – causing extra effort. During the contact resistance measurement soldered connections showed low contact resistances. In the peeling test soldered connections have a more than three times higher peeling force than IDC connections. However, when soldering with flux, the liquid solder is drawn between the individual strands via the capillary effect within the stranded wire. After solidification of the solder in the stranded wire, the solder-impregnated stranded wire has far less ductile properties than areas without solder. As a result, the less ductile area is a weak point in the overall composite. Wire breakage can occur, particularly in the case of mechanical loads from different directions and bending stresses.

This hazard can be reduced by using solder materials without flux and the associated ultrasonic soldering process. For this purpose, the ultrasonic soldering process was adapted and automated for the connection process of PCBs into textiles. Furthermore, a number of different materials and parameters were investigated. The investigation examined the properties of three different solder alloys (Sn95.5Ag3.8Cu0.7, Sn97Ag3 and Sn99.7Cu0.3), the amount of solder, the processing temperature, the soldering time, the ultrasonic energy, and a pre-treatment of the surface with acetone. The samples were evaluated using the same test methods from the first paper. Moreover, microsections of the connection points were made and analysed. The samples made of Sn99.7Cu0.3 showed the best results in the peeling test, thus this solder alloy was used for the further tests. However, it turns out that the amount of solder had only a very small influence on the results, so that a barely wetting amount is recommended. Soldering temperature, ultrasonic energy and process time appeared to be highly influential parameters, as they have a great impact on the microstructure of the joint. A lower soldering temperature causes less imperfections in the solder alloy which reduce the mechanical strength of the connections. A shorter ultrasonic treatment showed better results, as the metal structure was formed much more homogeneous and showed fewer defects. For the integration of electronics in textiles using ultrasonic soldering, the following parameter set was determined: Sn99.7Cu0.3 at a temperature of 350° C and an ultrasonic processing time of 0.5 s with a power of 10 W.

Comparing the ultrasonically soldered samples and the hot bar soldered samples, it can be observed that less solder was drawn into the strands during ultrasonic soldering. This may reduce the embrittlement of the strand around the contact points. However, cyclic bending tests or cross sections were not performed to quantify the difference. Apart from that, hot bar soldering and ultrasonic soldering require relatively large processing areas within the textile to connect the textile-integrated conductors on the PCB underneath. These larger joining areas weaken the textile in the area of the sensor, which can reduce the mechanical properties of the overall system. Contactless laser soldering was used to reduce the size of these areas.

Laser soldering at a wavelength of 1064 nm was investigated for the automated integration of sensors in textiles. This connection technique offers different advantages. The stripping and contacting process can be carried out in one workstation by the same laser machine and no further positioning step is necessary. In addition, it is also a non-contact joining technique, which means that significantly smaller contact and processing points can be realized in the textile base material.

A full factorial test plan was performed for the parameter determination. However, the expectations could not be meet to full extent. Some conductors were very poorly wetted, because of an inhomogeneous heating of the joining zone through a very thin laser beam. Moreover, too many residuals of the insulation were left on the laser stripped wires. The results were evaluated according to the developed test methods. Microsections of the samples were optically examined. The contact resistance was measured to evaluate the electrical properties of the sample and a peeling test was performed to analyse the mechanical properties of the connection. Thus, they had insufficient electrical and mechanical properties.

Tab. 5.1 summarises the results of the investigated connection methods for the integration of PCBs to smart textiles and evaluates the processes according to their contact resistance, peel strength, assembly space and assembly effort. The table shows the superior properties of laser soldering with the exception of the peeling strength. Therefore, following this investigation, significantly better results were achieved using a diode laser with a wavelength of 940 nm and a less focused laser beam specifically developed for soldering. This technology improved the mechanical strength of the connections and got it on the same level than hot bar soldering or ultrasonic soldering.

Tab. 5.1 Comparison of the investigated connection methods for the integration of PCBs to smart textiles.

	Anisotropic conductive adhesives	Insulation displacement connections	Hot bar soldering	Ultrasonic soldering,	Laser soldering
Contact resistance	-	+	+	+	+
Peeling strength	o	-	+	+	-
Assembly space	o	-	o	o	+
Assembly effort	-	+	o	o	+

Ultrasonic welding of copper strands to textile electrodes greatly expands the field of the application and it differs from those of the previous chapters. A fast connection process to conventional electronics to the textile sensor technology was developed. Both, conventional and textile sensors can be connected through insulated wires. The textile sensor technology opens up numerous possibilities of application. At the same time, the haptic of the sensors does not differ from the rest of the textile. In addition, it also offers the advantage of an unrestricted drapability of textiles on different surfaces. Neither the melting point of one of the materials is reached nor a hot melting joining aid is required. In the present study, copper strands were bonded to flexible knitted electrodes using the ultrasonic welding process. In order to stress the connections, the samples were washed both 15 and 30 times in a household washing machine. Subsequently, cross-sections of the joints were visually inspected and the quality of the electrical connection was analysed by a four-wire resistance measurement. The cross-sections showed a direct contact between the copper wires and the conductive yarns of the textile without high deformation of the textile or the strands. When analysing the contact resistance, the silver content on the conductive fibres was reduced due to the strong chemical and mechanical stresses during the washing process. Consequently, the contact resistance increased by more than 300 % at the joints. However, the reduction of the silver content and the conductivity are not unusual as a result of the washing processes, and yet the sensory properties of the surface were still functional.

In order to evaluate the mechanical properties of the ultrasonically welded joints, the samples were also tested with the well-known peeling test. But the test required an adaptation of the test apparatus to the changed base material. In contrast to the previously used PCBs, the textile base material is ductile in the tensile direction. Due to the low elongations, the results can be compared with each other. However, the constantly high mechanical load of the connection during the laundry process shows low signs of mechanical damage. The unwashed samples reached equal values as the soldered connections on the PCB. The peeling strength after 15 washing cycles was reduced by about 20 % and stayed the same after 30 cycles. Therefore, this joining method is very suitable for connections between textile sensors and copper strands.

This thesis presents various joining processes for the automated production of smart textiles. Based on the four described hypotheses (chapter 3.1) the following results can be concluded.

1. Adaption of joining processes from the electronic industry: Hot bar soldering, ultrasonic soldering, laser soldering, IDCs and ACA to join PCBs to textile-integrated metallic conductors.

   ⇨ The joining processes from the electronic industry: Hot bar soldering, ultrasonic soldering, laser soldering, IDCs and ACA can be successfully adapted to join PCBs to textile-integrated metallic conductors.

2. The adapted joining methods enable secure connections between the textile integrated litz wires and PCBs.

⇨ Textile-integrated, insulated, metallic conductors can be robustly and reliably connected to conventional electronics.

3. The developed and adapted joining processes enable an automated integration of PCB sensors to textile-integrated metallic conductors.

   ⇨ Ultrasonic soldering and laser soldering were the most promising processes and have been successfully automated to integrate PCBs to textile-integrated metallic conductors.

4. Ultrasonic welding is suitable to connect full textile sensors to insulated metallic litz wires.

   ⇨ Ultrasonic welding showed highly promising results for the connection of full textile sensors to insulated metallic litz wires.

In summary, all working hypotheses can be confirmed (Fig. 5.2).

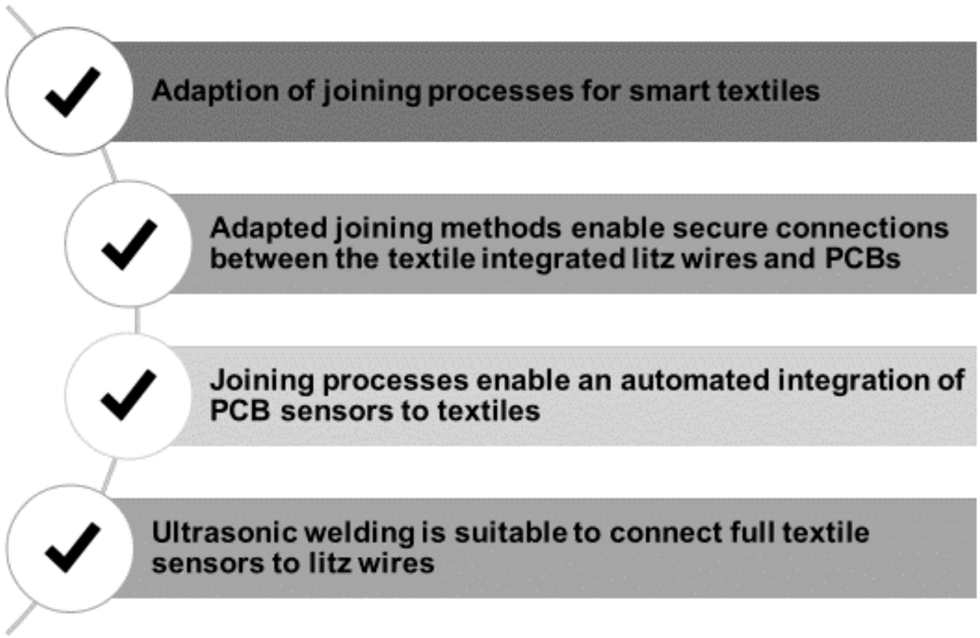

Fig. 5.2 Overview the postulated hypotheses.

6 Conclusion and Outlook

This thesis shows efforts to integrate electronics to textile-integrated, insulated, metallic strands. To achieve this goal, various integration methods from electrical engineering were adapted for the usage of smart textiles. The focus of this thesis was on the usage of litz wire, due to the superior electrical and mechanical properties of insulated metallic conductors compared to silver-coated polyamide yarns. Based on the low market penetration of smart textiles and the insufficiently investigated integration processes of electronics in textiles, the research question was raised how this process can be automated in the future. The results of the investigations are summarized on the following pages.

In chapter 4.1, thermode or hot bar soldering was adapted to join textiles and electronics. The same thing was done for the usage of anisotropic conductive adhesives and insulation wire displacers. The three different contacting methods have turned out to be suitable for the automated production of smart textiles. Insulation wire displacers are characterised as an especially simple method of contacting. There is no need for prior stripping of the conductors, and only a suitable insertion tool is required. The dimensions of the connectors do not allow them to be used for miniaturised electronics. Anisotropic conductive adhesives are suitable for very small and nearby contacts. For using UV-curing adhesives, a special apparatus was created. During contacting, some disadvantages appeared, as the textile between the curing device and the PCB could not be adequately compressed in some cases and thus the necessary pressure for contacting could not be applied. Hot soldering proved to be an appropriate method for contacting. It should be noted that the application of the solder paste needs a further production step.

To avoid contact between the thermode and the textile, the holes in the textile must also be relatively large. Furthermore, the liquid solder is drawn between the individual strands by capillary action within the stranded wire when soldering with flux. The solder impregnated litz wire has far less ductile attributes than areas without solder. Wire breaks may occur. During the contact resistance measurement ICA and soldered connections showed nearly equal low resistances. While the bonded ACA connections had a much higher resistance. In the peeling test IDC connections showed the lowest peeling force. The average peeling force of ACA connections was more than twice than with IDC connections, and the soldered connections more than three times the peeling force of IDC connections.

Chapter 4.2, an approach was made to eliminate the influence of flux in the solder filler material. For this purpose, the ultrasonic soldering process was adapted and automated for the contacting process of PCBs into textiles. In addition, a number of different materials and parameters were investigated. These involve the usage of three different solder alloys (Sn95.5Ag3.8Cu0.7, Sn97Ag3 and Sn99.7Cu0.3), the amount of solder, the processing temperature, the soldering time, the ultrasonic energy, and a pre-treatment of the surface with acetone. The samples were analysed with the different test methods and a suitable set of parameters was recommended. The samples made of Sn99.7Cu0.3 showed the best results in the peeling test, so this solder alloy was used for further experiments. However, it was found that the amount of solder had very little impact on the results, so a closely sufficient wetting amount is advised. Solder temperature, ultrasonic energy and process time proved to be very influential parameters, as they have a great impact on the structure of the joint. A shorter ultrasonic treatment showed better results, as the metal structure was formed much more homogeneously and showed fewer defects. The electrical and mechanical properties did not really differ from the hot bar solder connections from chapter 4.1. The following parameter set was determined for the integration of electronics in textiles by ultrasonic soldering: Sn99.7Cu0.3 at a temperature of 350° C and an ultrasonic processing time of 0.5 s with a power of 10 W.

In chapter 4.3, laser soldering at a wavelength of 1064 nm was investigated for the automated integration of sensors in textiles. This connection technique offers different advantages. The stripping and contacting process can be performed in one workstation and no additional positioning step is required. Furthermore, it is a contactless joining technique, which means that smaller contact and processing points can be realised in the textile base material. A full factorial test plan was performed for the parameter assessment. The results were evaluated according to the developed test methods. The expectations could not be entirely fulfilled. Some conductors were only very slightly wetted due to inhomogeneous heating and residues of the insulation. Thus, they had insufficient mechanical properties. They reached less than 30 % of the maximum peeling force of the soldered connection from chapter 4.1 and chapter 4.2. Due to the metallic soldered connection between wire and PCB, the electrical properties were comparable with the contact resistances from the soldered connections of hot bar and ultrasonic soldering. Following this investigation, significantly better results were achieved using a diode laser with a wavelength of 940 nm and a less focused laser beam specifically developed for soldering.

In chapter 4.4, the ultrasonic welding of copper strands on textile electrodes is examined. There are differences in the application compared to the previous chapters. The fast connection to conventional electronics to textile sensors was examined. The textile sensor technology offers a wide range of possible applications. The haptics of the sensors do not differ from the rest of the textile. In addition, it offers the advantage of unrestricted drapability of textiles. There is a lack of suitable methods for the connection between textile sensor technology and conventional electronics. Ultrasonic welding provides the ideal solution, because it allows a wide variety of materials to be joined together. Moreover, neither the melting point of one of the materials is reached nor is a welding aid required. In the current study, copper strands were connected to flexible knitted electrodes by ultrasonic welding. Therefore, the ultrasonic welding process was modified to meet the requirements. The samples were washed 15 and 30 times in a household washing machine in order to stress the probes. Subsequently, cross-sections of the joints were visually inspected and the quality of the electrical connection was analysed by a four-wire resistance measurement. In order to guarantee sufficient mechanical strength, samples were destroyed in a peeling test. The samples proved to be very durable in these tests. The chemical and mechanical stress during the washing process increase the contact resistance. This diminution is caused by a reduction of the silver content on the conductive yarns during washing. The resistance of the joints increased by more than 300 %. However, the constantly high mechanical load of the washing process shows only little signs of mechanical damage. The mechanical strength dropped by only approximately 20 % after 15 cycles and remained the same after 30 cycles. Therefore, this connection method is very well suited for connections between textile sensors and copper strands.

Finally, the results of the investigation were implemented in a fully automated, camera-supported production line. This is intended to demonstrate their automatability for the production of smart textiles. In the production line, the PCBs were contacted by laser soldering (940 nm). The results and the setup of the plant will promote the market penetration of smart textiles in the upcoming years. Thanks to the presented results, sensors can be integrated automatically into textile, minimizing manual work steps and optimizing the quality of the products. This can reduce the price of these hybrid products in the long term and increase the number of available units.

The final encapsulation of the sensor technology in an injection melding machine with two-component silicone was developed and published in a separate publication. However, the final step of automating has not yet been completed and offers room for further investigation and improvement. Moreover, the adaption of the wire bonding process would be the next big step for the smart textiles industry. Wire bonding is used in the production of SMD parts. The adaption of the wire bonding process to the smart textiles industry would allow to integrate much smaller electronic devices to textiles.

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