10
Joining technologies for smart textiles

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Abstract: This chapter reviews important building blocks for the use of electronic systems on textiles. A major focus is on electrical and textile joining technologies and their properties. Furthermore, different means of electrical traces are described that are suitable for integration in textiles. Some challenges in technology and in the manufacturing processes for electronic systems on textiles are pointed out. Finally, the chapter provides an assessment of technological trends, as well as future applications.

Key words: electronic systems on textiles, joining technologies, connection technologies, e-fabrics.

10.1 Introduction

The first approaches to the integration of electronics into garments were made more than 14 years ago in 1998, with the wearable motherboard from GeorgiaTech. Whereas the first research demonstrators were rather bulky, using the garment as a supporting structure for large components and strands of wires (Post *et al.*, 2000; Jones *et al.*, 2002; Park *et al.*, 2002), recent approaches (Cherenack *et al.*, 2010) (BMBF TexoLED) (Bonderover and Wagner, 2004; Diaz, 2011) try to use the yarn itself as a functional element, making them more like conventional textiles. Some of the early approaches became redundant because electronics have shrunk so much that they can now be integrated into small devices such as today's mobile phones. The very first smart fabric products on the market, such as the MP3-Jacket, were from companies such as Infineon.

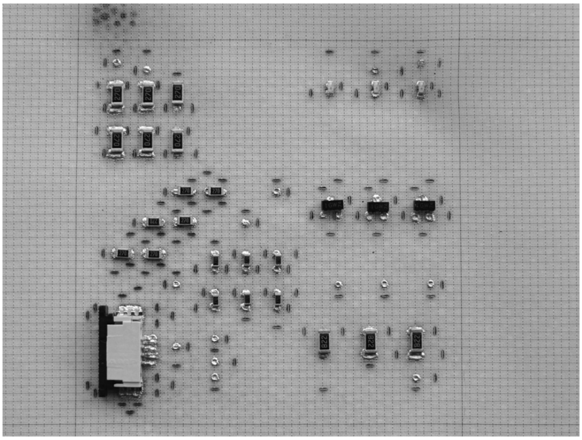
In 2012, industry and applied research institutes are utilizing various approaches in their products and demonstrators. For example, Interactive-Wear, Clothing+ and Ohmatex use textile ribbon cables as connection elements, while sealed conventional circuit technology provides the functional elements in their products. The garment itself is the carrier of the functional infrastructure. These products range from LED signal jackets to fire fighter uniforms with integrated temperature sensors. Companies such as Sefar AG, Future-Shape GmbH and NEL Ltd use the fabric itself as a circuit board to place and interconnect electronic components. Institutes, such as Fraunhofer IZM and TITV Greiz, also utilize these and other approaches in their research. When discussing smart fabrics, we might immediately think of apparel with smart functionality. However, it is interesting to see that apparel made up only about 40% of the global textile market in 2010. The rest was made up of technical and interior (home) textiles. For example, Sefar and Future-Shape supply these markets.

10.2 Components of electronic systems in textiles

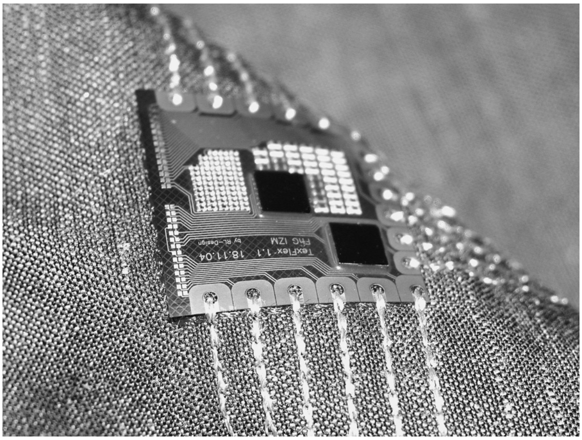
A principal goal in the smart-textile world is to combine the electronic and the textile world, while maintaining the functionality of electronics and the flexibility and the robustness of textiles. At present, this goal can only be achieved by making compromises in both areas. An example of an electronic system used in textiles is shown in Fig. 10.1. The textile substrate – a woven fabric – consists of PET monofilaments and insulated copper wires, used as a conductive element. It is formed as a mesh of cross running, electrically-floating copper wires. The copper wires are connected by the removal of the wire insulation and the addition of conductive paste. Some wires must also be cut, in order to avoid electrical shorts. Figure 10.1 shows an assembled electrical circuit using various component package generations, ranging from size 0402 to size 1206. They are assembled using standard processes in the electronics industry, such as laser drilling, stencil printing and pick-and-place techniques.

Another approach for the use of electronics in textiles is depicted in Fig. 10.2 (Linz *et al.*, 2005). The textile substrate does not embed any conductive elements. Instead, a flexible substrate film carrying the electronic circuit is mounted on the textile and conductive traces are sewn onto the textile substrate connecting the film pads. Here, the conductive traces are Ag-plated, multi-filament threads produced by Statex GmbH. Special attention must be given to the process of crossing the threads, as they are not insulated. Similar approaches are employed by TITV and Forster Rohner AG. The placement of the substrate film and sewing for connection of film pads with conductive traces are particularly important to these approaches.

The two examples given are very different approaches, but which achieve similar goals. However, in both processes, a reliable joining method is essential.



10.1 Electronic system on textile (Sefar AG).

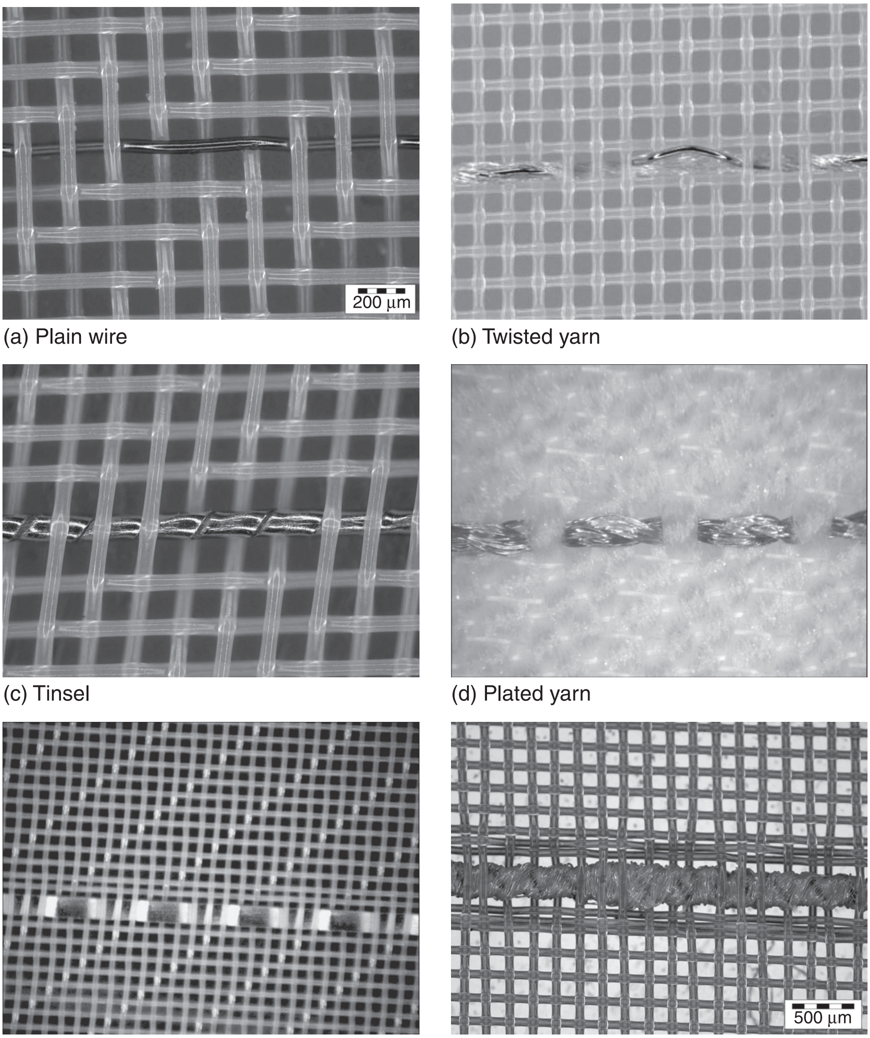


10.2 Electronic system on textile (Fraunhofer IZM).

Such electronic systems in textiles are considered to be an intermediate step towards the full integration of electronics into a yarn. The following section reviews the various joining methods that are utilized in the two worlds of electronics and textiles, and it presents a selection of different conductive threads as well. Each joining method and its properties are briefly explained and analyzed. Some of these methods can be used to construct electronic systems in textiles using the textile as an electrical substrate.

10.3 Conductive threads as electrical traces

An ideal electrical trace in a circuit will not distort or attenuate the carrying signal. However, in reality, no electrical trace is perfect, particularly not when it is integrated into a fabric. Trace configuration should thus be optimized according to the type of signal being carried. For instance, a power signal should be sent over a low-ohmic trace, in order to avoid ohmic losses and elevated temperatures in the trace. However, a radio frequency (RF) data signal (typically of a frequency above 1 GHz) should be transmitted through a trace configuration with constant line impedance, using a substrate (e.g. based on Teflon™ or ceramics) with low dielectric losses, or the signal will face severe distortion. Line impedance is defined by the dimensions of the traces and the substrate, as well as the material of which they are composed. Furthermore, the properties of the substrate will correspond to those of the signal trace; it can be a rigid board or a flexible film. However, experience shows that low ohmic traces are more important in fabrics than constant line impedance, since RF signal transport in fabrics rarely occurs in practical applications.



(a) Plain wire
(b) Twisted yarn
(c) Tinsel
(d) Plated yarn
(e) Plated strips
(f) Double twisted yarn

10.3 (a–f) Selection of conductive threads (Sefar AG).

The selection of conductive threads listed below, and in Fig. 10.3, is thus **not** among those that would induce constant line impedance:

- (a) *Plain wire*: Available in various metals and alloys, such as copper, copper alloys, stainless steel, nickel and tungsten. Wires possess the highest conductivity at a given thread diameter. They are sized at a minimum diameter of 10 microns and are connected using standard industrial methods. Companies such as Elektrisola offer wires with an additional, thin insulation. Wires have a well-defined position within a woven fabric, as can be seen in Fig. 10.3(a), but their mechanical strength and bending fatigue are weak in comparison to polymer threads.

- (b) *Twisted yarn*: A metal wire is twisted together with a polymer yarn, with the wire twisted into the shape of a spring. The number of twists is an important parameter to enable a defined electrical resistance and a mechanical strength higher than that of a plain wire. However, the position of the wire within the fabric is difficult to know exactly due to the spring shape.
- (c) *Tinsel*: This consists of a non-conductive, multi-filament core with a wrap of metal film. Again, the metal contour resembles a spring, while the mechanical strength of tinsel is even higher than that of twisted yarn. Tinsel is only available uncoated.
- (d) *Plated yarn*: A polymer thread, of PA for example, is plated with a layer of silver or a similar metal. The layer thickness is usually in the range of 0.1 to 1 microns. It is recommended to use multi-filament threads, since there might be cracks in the metal layer of single fibrils. A thick thread or several threads in parallel are also necessary, in order to achieve similar resistance values as those achieved with metal wires. These types of threads are usually not solderable or weldable. However, in terms of mechanical strength, they are arguably the best option of this selection, although there might be an increase in resistance over time due to natural wear. Suppliers of these types of threads are Statex GmbH, imbut GmbH, Tersuisse and Amberstrand.
- (e) *Plated strips*: These are similar to plated yarn, and consist of a polymer film with plated film of a metal such as aluminum or silver. They are also known as Lurex™ yarn.
- (f) *Double twisted yarn*: This has the same core construction as twisted yarn, but has an additional protective layer wrapped around the twisted yarn (sold by W. Zimmermann GmbH).
- *Stranded wires*: Several pure wires are twisted together to form a tiny rope, with excellent conductivity and mechanical strength. However, a strand's handle is usually very different to a textile handle.
- *Coax*: There are tiny coax cables down at 0.2 mm diameter at 50 Ω line impedance available, e.g. from Mitsubishi. However, they are rather stiff.

10.4 Introduction to joining technologies for electronics

Hundreds of reliable soldering joints are necessary on a printed circuit board (PCB), in order to make a mobile phone work and a vast number of welding joints and a huge number of connectors are needed in order to make a car run. A single bad joint can cause your car to break down. Electrical connections are crucial ingredients for every electrical system. The study of connectors can almost be considered an individual scientific field in its own right. Connections interconnect various components to merge into an entire, functioning electrical system. They are intended not to distort the electrical signals running through them and to have a continuity and reliability over time. An ideal connection has no contact resistance, constant characteristic impedance equal to its feed lines, infinite bandwidth and no attenuation; it must also fulfill certain mechanical requirements.

In electronics, there are many individual electrical joining technologies that are designed to cater to specific connector requirements and applications (Mroczkowski, 1998) (Table 10.1). Joining technologies such as soldering and welding are appropriate for permanent connectors, while others such as jacks/receptacles (connectors) are more suited to temporary connections. Some are designed for only a few insertion cycles and some are designed for several hundred cycles; some are intended for high electrical currents or high voltages and some are designed for RF (i.e. frequency with defined characteristic impedance). Some are even made to be waterproof (see IP codes according to IEC 60529 for further information about watertight properties). Connections are usually sealed in a solid encapsulation, in order to satisfy the given requirements.

In textiles, connections mainly serve a mechanical purpose, for example holding a garment permanently together and closing a jacket temporarily, but they also need to be resilient, so as to survive natural wear and cleaning. Table 10.2 lists several textile joining technologies, along with their mechanical and electrical properties.

Combining all the desired properties of electrical and textile connections in a garment becomes tricky when some requirements are contradictory to others. For example, the electrical connection should have defined characteristic impedance and robustness to withstand cleaning, but it should also be flexible to maintain the textile handle.

10.5 Overview of existing jointing technologies in the electronics and in the textile world

10.5.1 Soldering

Soldering is a process whereby two metal conductors join together using a filler metal (solder) at temperatures below 450°C. The filler metal melts establishes an intermetallic alloy at the contact surface, in between the filler and the conductor. The soldering temperature is anything below the melting temperature of the conductors. Solder connections facilitate defined, permanent low-ohmic electrical connections, although these should not be subjected to too much mechanical stress ($3N/mm^2$ is about the maximum strain per solder connection).

The solder plays an important role. Usually, it works with the filler metal and the flux forming a paste (small filler metal balls embedded in liquid flux) or forming a wire (filler metal wire with flux core). The flux must become activated before the filler metal starts melting, since it has to clean the contact surface and to break the oxide layer that usually covers metal surfaces. The residues of the flux must also be removed, depending on type of flux. There are clean (aggressive) and non-clean (less aggressive) fluxes.

Table 10.1 Overview of electrical joining technologies

Joining technology	Permanent	Joining partners	Electrical properties	Mechanical properties	Corrosion behavior	Protection	Remarks
Soldering, brazing	Yes	Metal + metal, solder	Low resistance, constant	Weak, no load allowed	Good	E.g. in encapsulation	Thermal process, many different solders available, not every metal is solderable
Conductive adhesive bonding	Yes	Metal + metal, adhesive	Low resistance, constant	Weak, no load allowed	Okay, absorbs water	E.g. in encapsulation	Expensive, elevated temperature or UV for curing
Welding	Yes	Metal + metal	Low resistance, constant	Weak, no load allowed	Good	E.g. in encapsulation	Various processes (resistance, US, laser welding, etc.), high temperature exposure, not every metal combination is weldable
Cold-welding, Crimping	Yes	Metal + metal	Low resistance, constant	Good	Good	Not needed	E.g. press-fit on PCBs, for connector pins
Connector	No	Metal jack + metal receptacle	Low to medium resistance, might not stay constant	Very good	Good, when proper type	Connector case	Big variety of connectors available

Table 10.2 Overview of textile joining technologies

Joining technology	Permanent	Joining partners	Electrical properties	Mechanical properties	Corrosion behavior	Protection	Remarks
Welding	Yes	Fabric + fabric (+ joining tape)	No electrical conductivity	High strength	Good	Not needed	No electrical connection, e.g. with heat, RF, US, Laser
Press snap / Spring snap button / Eyelets	No	Metal cap/socket + metal stud/post	Medium resistance, might not be constant	Very good	Okay, depending on type	Not needed	It can be a compromise to serve the two worlds
Zipper	No	Interlocking metal teeth	No electrical connection among interlocking teeth	Very good	Okay	Not needed	Air gap in-between teeth
Velcro	No	Conductively coated hooks and loops	High resistance no constant resistance	Very good	Okay, but degrading	Not needed	Suitable for anti-static applications
Sewing	Yes	Conductive yarn + conductive fabric	Medium resistance, no constant resistance	Very good	Okay, degrading	Not needed	Conductive yarn can be electrical trace as well

Not every metal is easy to solder; titanium, metal and solder must fit together and inertial gas atmosphere improves solder results. Nowadays, lead-free solders according to RoHS (Restriction of Hazardous Substances Directive, Directive 2002/95/EC) are commonly applied in the PCB industry. There are only a few exceptions where lead-based soldering is still allowed, such as in aerospace. A common RoHS-compatible, low-cost solder is the SAC (Sn-Ag-Cu), which has a eutectic melting point of 217°C. It is widely used for assembly of PCBs in the electronics industry.

Solder as a paste is usually employed in automated assembly processes in industry. The paste is screen or stencil printed, or dispensed on the surface of the PCB; the dispensing paste having a lower viscosity than the printing paste. The electronic components are then placed on the PCB in such a way as to ensure that the components' pads are imbedded in the paste. Finally, heat needs to be applied, according to the temperature profile given in the datasheet, in order to melt and establish the solder joint. Solder quality cannot be monitored during the process. Its quality is checked by visual inspection (using random samples) or by destruction (using cross sections). There are many different paste soldering processes (reflow, wave, laser, induction, flame, vapor phase, hot bar, laser, ultrasonic, to name a few).

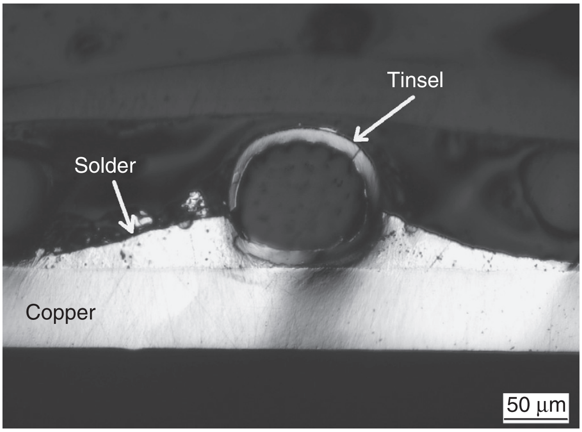
The textile industry needs solders that melt at much lower temperatures than SAC, so that the fabric is not destroyed by the effect of high temperatures. Hwang (1996) gives an overview of the many different solder alloys: indium-based alloys are usually brittle, expensive and incompatible to SAC solders, while lead-based alloys no longer comply with RoHS guidelines. Indeed, Bi-Sn and Bi-Sn-Ag pastes seem to be the only feasible solders for the textile world, melting at 138 and 140°C, respectively. These solders are somewhat brittle, but they are compatible to SAC. Figure 10.4 shows a cross section of a woven fabric, whose imbedded tinsel thread is soldered to the copper surface of a PCB.

10.5.2 Brazing

Brazing is a similar process to soldering, but works at temperatures above 450°C, and uses specific brazing solders and fluxes. Brazing is most notably used for joining of copper pipes. Since this technology works at high temperatures though, it has little use in the textile world.

10.5.3 Thermocompression bonding (TCB)

Resistance welding is the method used to join two plain metal work pieces together by running an electrical current through them. The necessary welding heat is generated by the electrical resistance of the metals, by the contact resistance in between them and by the electrical current. No filler metal and no flux are needed. TCB is a special type of resistance welding that can be used to join



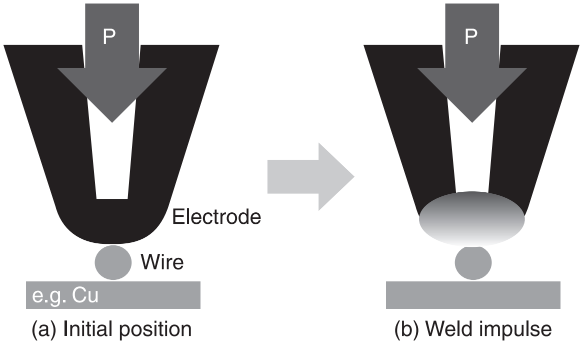
10.4 Woven tinsel thread soldered to a PCB (cross section, Sefar AG).

insulated metal surfaces. The TCB electrode consists of two legs that are connected together at the tip. The electrical current thus runs only through the electrode and generates the welding heat directly at the tip. The generated heat destroys any insulation layers of the metals instantly.

In contrast to resistance welding – where the electrical current generates heat exactly at the welding location – the heat generated from a TCB must flow from the electrode tip to the welding location at the interface of the two metals. As a result, more heat is transferred to the top than to the bottom of the two metals. This, along with the necessary melting point, limits the choice of the joining metals. The process window for TCB is therefore smaller than for resistance welding. An overview to some metal combinations is given in AVIO (2011).

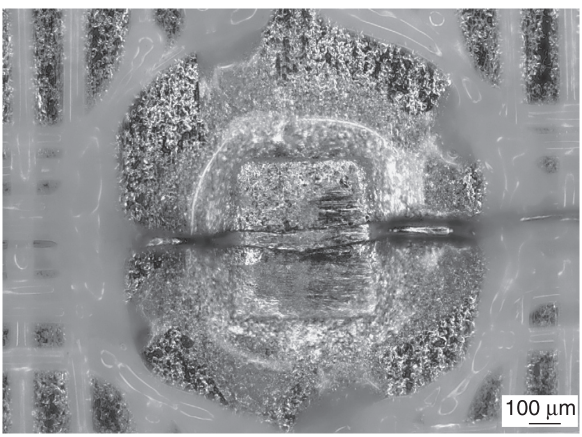
TCB has three main process parameters: welding power (P), welding time (T) and pressure of the tip (P). These parameters are usually kept within a given window, to ensure quality. The off-the-shelf welding equipment controls the process by an adjustable pulse in the current (I), voltage (V) or power (P). The control mode depends on the material configuration, and it is important to differentiate between diffusion bonding and fusion welding. Diffusion bonding (solid-state bonding) occurs at 70 to 80% of the melting points of the work piece metals. Such bonds possess very good shear strength and tenacity, but less desirable peel strength. Fusion welding occurs above the melting points of the work pieces. These bonds have very good shear strength, tenacity and peel strength (Zhou, 2008).

Figure 10.5 illustrates the TCB process schematically. The electrode is placed with defined pressure on top of the work pieces; in this example, a wire is pressed onto a copper pad. The weld is then released with carefully controlled impulse shape, defined energy and time. A solid work surface is crucial for a high-quality



10.5 (a, b) TCB weld process.

weld. The strength of the weld can only be tested with certainty by destruction of the weld, for example by using a peel test. A weld is generated within a few milliseconds to several seconds, depending on the dimensions and materials of the two work pieces. Resistance and thermo-compression welding are typically employed for electrical coils, electric motors and light bulbs. An entire welding cycle takes about 3 to 10 seconds in an automated process set-up. Major companies, currently producing welding control units, welding heads and electrodes, include Miyachi, Avio, Kombitec, Lingl and Resistronic. Figure 10.6 shows the welding spot of a wire on a PCB surface. The shape of the welding electrode can clearly be identified. The wire itself is directly woven into the PET fabric and the PET fabric and the wire insulation around it melt and evaporate during the welding process, thereby welding the wire to the PCB.



10.6 Weld of a woven wire onto a PCB (Sefar AG).

10.5.4 Ultrasonic welding

The ultrasonic welding process utilizes ultrasonic acoustic vibrations to generate heat and pressure to weld two work pieces together. Frequencies between 20 and 70 kHz are commonly used to join plastics, whereas frequencies of 20 or 40 kHz are employed for metals. Plastics, moreover, are joined using fusion welding, whereas metal joints are formed with solid-state welds. The weld process for plastics delivers the weld energy via longitudinal vibrations, perpendicular to the weld surface. The metal weld process delivers the weld energy via transverse vibrations, parallel to the weld surface. US welding is the most widely used industrial welding process (Ensminger and Bond, 2012); it is, for example, used to connect cables to surfaces and to compact copper cable strands. Its most prevalent producers include Rinco Ultrasonics, Schunk Sonosystems and Telsonic.

10.5.5 Radiofrequency (RF) welding

Fabrics can be welded using RF energy and an RF absorbing polymer tape. The tape, placed in between the two fabric pieces, is activated by RF. It then melts and bonds the two fabric pieces together. This process is usually employed when the fabric materials themselves are not weldable.

10.5.6 Bonding (using adhesives)

There are various types of electrically conductive adhesives currently in use. They can be categorized into isotropic conductive adhesives (ICA), anisotropic conductive adhesives (ACA) and non-conductive adhesives (NCA). ACAs are conductive in only one axis and NCAs are not conductive at all. They are typically used in applications with even and well-defined surfaces, such as flip chips. Usually, heat and pressure must be applied for curing. Li (2010) gives a good introduction to the aforementioned three categories.

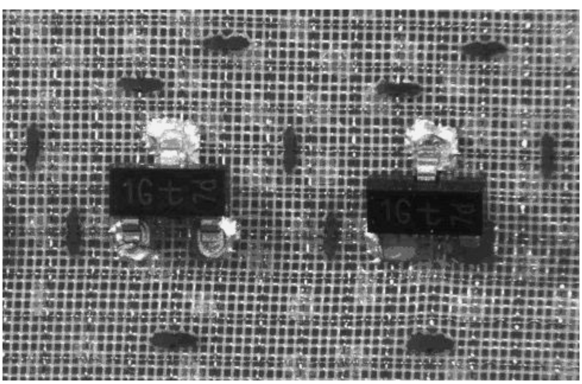
The project 'MST4IT' funded by Germans BMBF (#16SV3425), 2008–2011, has led to some notable investigations into electrically conductive hot melts. There are also various conductive adhesives available for shielding applications, such as copper tapes with conductive acrylic adhesive (e.g. supplied by 3M) or conductive silicone paste by Chomerics. Their resistance is high in comparison to ICAs and they are designed for low currents, meaning they are prevalent in shielding and anti-static applications.

ICAs are typically two-component epoxy resins, and are employed in solar cells, LEDs and RF circuits on ceramic substrates. They are filled with silver flakes at a filling grade of 80 to 90%, making them somewhat expensive. However, they can be ordered frozen and mixed to the appropriate ratio. Usual curing parameters for epoxies is at 150°C for durations of a few minutes to several hours. The higher the temperature and the longer the time, the better the eventual conductivity of the bond (its conductivity is usually similar to solder) and the cross-linking of the polymer. However, it will also be more brittle than adhesives cured at a lower temperature and for a shorter time. The bond strength is almost as high as that of solder (Gilleo, 2004). Pot life can vary from a few minutes to several days. There are also some epoxies that can be cured using UV exposure.

Typical suppliers of ICA epoxies include EpoTek, Emerson and Cummings, and Henkel. Some epoxies, such as the EpoTek H20E, have already been used in the electronics industry for more than 30 years. Other epoxies are more suitable for laboratory experiments, such as the EpoTek E4110. There are a vast number of epoxies, and in order to obtain the optimum results in an application, it is advisable to consult the supplier. Some epoxy pastes are more suitable for dispensing processes and some are preferred for stencil and screen-printing processes. The uncured epoxy usually has a thixotropic consistency (shear stress to a thixotropic paste lowers the paste's viscosity). Unlike solder, ICAs are not able to break oxide layers, since they do not contain any flux. The component pads and circuit pads should thus be treated accordingly in advance to achieve best results. Figure 10.7 shows electronic components connected to a fabric with copper wires in warp and weft using conductive epoxy. The cuts in the copper wire avoiding shorts can be clearly seen.

10.5.7 Crimping

This technology is generally used to connect stranded wires of a cable to their connector pin terminals. The copper strand is positioned in a cavity at the back of the crimp terminal. Pressure is then applied in such a way that the back becomes wrapped in strands, establishing a cold-weld connection. Crimps have a high mechanical strength, and in contrast to soldering and adhesive bonding, crimping quality can be monitored (semi-)automatically by logging the crimping force curve. Notable crimp suppliers include Tyco, Nicomatic, Harting and Molex.



10.7 Electronic components bonded to a woven fabric substrate (Sefar AG).

10.8 Crimping of conductive yarn (Fraunhofer IZM).

A similar, but less robust cold-welding connection is utilized for ribbon cable connections. Here, the copper strands are pressed in between adjacent tiny blades of the connector at the back of the terminal. Figure 10.8 shows crimping technology for conductive twisted yarn developed by Fraunhofer IZM.

10.5.8 Sewing and embroidery

This technology is used to join two pieces of fabric together using two threads. Sewing principle and stitch formation are described in Wulfhorst (1998). There are many types of stitches, such as lockstitch, overlock, and overlock safety. Electrical conductivity can be introduced using a conductive yarn, such as conductively plated yarn and twisted polymer/wire yarn. In contrast to soldering, welding and other techniques, a sewed connection does not establish a well-defined electrical connection. The contact is created simply by surface contact and yarn tension. As a result, electrical contact resistance is undefined and varies over time. Furthermore, moisture and liquid can settle in between, forming a galvanic element if different surface materials are present, leaving it exposed to contact corrosion and oxidation. However, it is a low-cost connection with high mechanical strength, durability and, to a large extent, a capacity to be washed. Programmable sewing machines, which in principle allow the creation of an electrical circuit layout, are available from Laesser, Oerlikon, Saurer and Tajima.

10.5.9 Velcro™

Electrical connections are possible with plated, conductive Velcro™. However, the electrical contact resistance shows high variation in each open/close cycle. This is primarily due to the fact that an undefined number of hooks, or loops, are active in each cycle, but also that the conductive plating generally starts peeling off after a couple of cycles, leading to a decaying contact quality over time. Therefore, a large area must be utilized to achieve a sufficiently low contact resistance. Companies, such as LessEMF and BlockEMF, supply conductive Velcro™. Since the technology has originally been developed for shielding applications, it is again not suitable for high currents. The question of how to connect the Velcro™ itself remains unanswered.

10.5.10 Zippers

We might think that metallic zippers would be a good approach to obtain low-ohmic connections. However, a closer look at the zipper mechanism exposes the fact that most zipper teeth do not touch each other. Instead, there is an air gap in between the teeth. However, even without this problem, the question of how to connect the zipper itself would still be problematical.

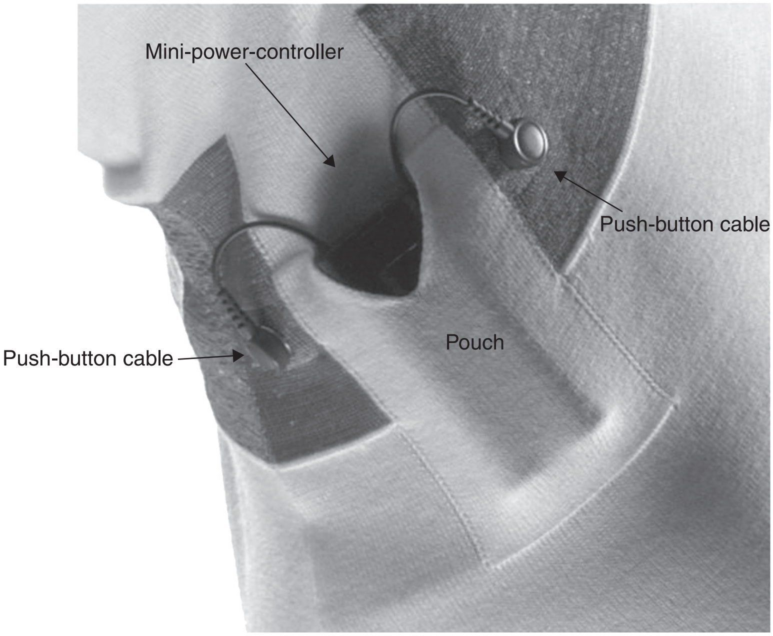
10.5.11 Press snap, spring snap buttons and eyelets

Metallic buttons/eyelets consist of corrosion resistant alloys, and enable a medium ohmic and a largely consistent electrical connection. The button itself can be electrically connected using standard welding processes (US, resistance), sewing or simply by clamping a conductive yarn in between the cap and socket of the button. The buttons are generally washable and are manufactured by companies such as YKK STOCKO Fasteners GmbH.

10.6 Summary to the joining technology overview

It has already been established that no joining technology satisfies the requirements of both worlds (namely by having good electrical properties while being robust and flexible). The industry therefore largely employs two, straightforward approaches. The company WarmX uses metallic buttons to connect their battery to their heating garment (Fig. 10.9). Mechanically, it is a very robust connection. If the buttons' resistance slightly increases over time, heating power will slightly decrease; however, this will be largely unnoticeable. Interactive-Wear, however, borrows connection technologies of the electronic world (e.g. soldering) and seals them completely in epoxy resin or in low-pressure injection hot melts to increase robustness. As can be seen in Fig. 10.10, the two white textile cable strips are connected to the black heating pad, before the connections are completely sealed in black hot melt.

In summary, the following recommendations should be acknowledged. If permanent connections are desired, soldering and welding are recommended, along with strong sealing. They possess low and constant resistances over time and processes are well understood. Furthermore, solder and welding joints can be made by hand and in a controlled industrial process. Crimping is an alternative, if only few connections are necessary or process temperature must be kept at room temperature. Buttons and electrical connectors are suggested for removable connections. Buttons



10.9 Metallic buttons to connect electrical power (WarmX GmbH).

10.10 Electrical connection sealed with hotmelts (Interactive-Wear AG).

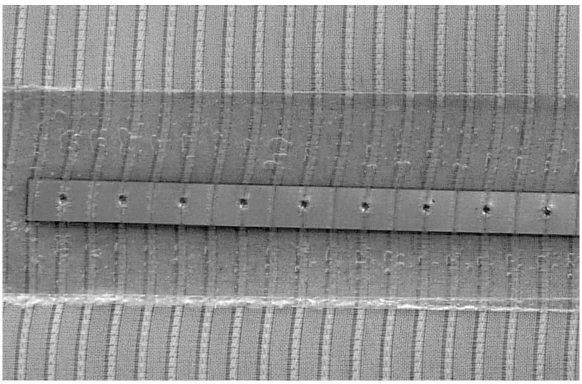
are preferred if user acceptance in the garment field is important and electrical requirements are low. Electrical connectors are recommended if the number of electrical contacts and electrical requirements are high.

10.7 Protection of electrical connections

Most electrical connections must be protected from mechanical stresses and from moisture, since they cannot withstand any mechanical impacts. In the electronics world, PCBs and their solder connections are hidden – for instance, in housings – and cable connections are consolidated with strain reliefs and sealing. Small PCBs can be entirely sealed in epoxy resin (as with solid-state relays) or in low-pressure injection hot melts (connectors) as well. A bare die on a PCB is usually sealed with a special UV curable resin, creating a so-called globtop. Furthermore, flexible circuits (using films as a substrate) are physically partitioned into two areas, a flexible area with electrical traces only and a rigid area with electronic components and connections, meaning movements apply to the flexible area alone.

The sealing of electrical connections is more challenging for electronic systems on textile, since protection should not affect textile handle and flexibility, and electrical connections should, in principle, also stay flexible. There is no generic solution to this problem, since the application determines the manner of protection. If a system is tiny enough to fit into a button, it most probably will not affect wearing comfort when solid and placed in the right location. Sometimes, an additional PVA cover or the like is wrapped around the sealed block to soften it.

Gemperle *et al.* (1998) have studied the impact of solid objects worn on the body. In larger areas, sealing materials such as silicones and polyurethanes (PU) can be used for mechanical protection. The company Stretchable Circuits (http://www.stretchable-circuits.com) has utilized PU films in their 'Klight' project, in order to seal their LEDs. Sefar laminates PU film tapes for protection of welding spots, as can be seen in Fig. 10.11.



10.11 Welding spots between woven wires and FPC are protected by PU film (Sefar AG).

No matter what sealing method has been chosen, special attention must be paid to the transition area from hard to soft, that is, from seal to fabric. This area is prone to breaking of conductive traces, since the laws of physics dictate that the highest stresses and smallest bending radii will occur at this location.

10.8 Challenges for electronic systems on textiles

So far, all known approaches borrow technologies from both the electronics and the textiles industries, for the implementation of electronic systems on textiles. From the textile perspective, this is a necessary compromise, as electronic components and local encapsulations limit the flexibility and washability of fabric products, and add significant weight, especially batteries and large chips. Furthermore, the definition of robustness differs between the two industries. A slightly damaged shirt, for example one with a broken button, can still be worn. In contrast, an electronic device with a broken button may no longer function and it must be replaced. Redundancy in the imbedded circuits might improve reliability, but it also increases cost.

From the perspective of electronics, fabrics are undefined substrates with uneven surfaces and skew. They do not have a defined shape because of their low slippage resistance. After a fabric substrate has been moved, it always has a slightly different shape. This fact affects the use of automated process equipment. Fabrics are also a poor base material for electromagnetic compatibility (EMC). They can carry high static charges, especially in dry air, and damage imbedded electronics when moved (i.e. by electrostatic discharge (ESD)). Such discharges can even occur at the manufacturing stage. Moisture can reduce these discharges, but it could induce delayed corrosion.

Fabrics usually do not provide ground planes for shielding and for defining line impedances. Noise and other disturbances can easily affect the circuitry, making it unreliable. Special design rules are needed in fabrics as well. In general, electrical traces in fabrics have higher resistances than traces on PCBs given by dimensions and conductive materials. Current load capacity and the corresponding voltage thus drop along trace lengths, which must be considered in a design, or traces will heat up and digital components will no longer work due to illegal voltage levels. In addition, the circuit could start to fail due to high-ohmic, disturbance-conducting ground lines. Using several traces in parallel can lower electrical resistance, but these occupy more space. Electrical insulation is generally difficult to achieve in fabrics. Therefore, voltages should be kept below 42V, since this low level is not harmful to humans, and since ISO standards (e.g. IEC 60335) have no requirements for insulation below 42 V.

Stricter thermal limitations must also be considered in textile designs as opposed to PCB designs. Textile substrates conduct heat less effectively than copper loaded PCBs (e.g. FR4 and PI boards), while fabrics made of polyamide and polyester cannot withstand temperatures as high as PI boards. Furthermore, rigid PCB circuits can easily be cooled by fans. Large electronic components such as microprocessors with large number of pins are unsuitable from both perspectives. They limit flexibility of fabrics and are difficult to connect through fabrics.

To summarize, a good way of maintaining textile handling while integrating functionality is to mount dedicated components, such as LEDs and sensors, sparsely around the fabric. Dense circuits on textiles known from PCB technology will be impractical and unreliable. The structure of fabrics and its threads introduce certain granularity in dimension that reduces the realizable precision of circuit routings.

10.9 Challenges for automated processes in electronic systems on textiles

There are several approaches to the mass production of electronic systems on textiles. Following the business models of the mainstream apparel industry, production mainly takes place in low-income countries. The smart fabrics companies Clothing+ and Texsys have adopted this model. Another approach is to design the manufacturing process with proprietary equipment towards a specific product. The processes can be efficiently adapted to the product in question. However, a new product requires new process engineering and development. Textrace provides equipment for fabrication of textile RFID tags (RF identification), for instance. A third approach tries to adapt equipment of PCB industry and thereby establish a universal fabrication process for various products. However, this flexibility leads to inevitably high costs for equipment development. Sefar, TITV and IZM have started investigations into this approach.

In technical terms, there are numerous approaches around and myriad possible combinations of processes and materials. For example, electrical traces can be sewn, woven, printed, plated, etc. on fabrics. No single technology currently stands out as superior to the others. Depending on the product, one technology might be more suitable than another.

Several tendencies can be identified in future manufacturing chains for electronic systems on textiles. PCB industry relies on the precision of their substrates; after having etched the PCB, the stencil for solder paste printing must exactly match the etched circuit layout. Other processes, such as the component pick-and-place, use alignment marks (so-called fiducials) as optical orientation, in order to compensate for dimensional tolerances. In this manner, a process chain for systems on textiles will begin to rely more heavily on optical recognition and processes such as stencil printing will be less applicable. Instead, dispensing processes are applied that allow position adjustments by optical orientation.

Process temperatures must also be reduced compared to PCB industry. This means that low-temperature solders or conductive adhesives must be applied, since fabric substrates usually shrink or melt at elevated temperatures. One issue that remains unsolved is the testing of systems on textiles during manufacturing. The use of flying probes and needle adapters is most probably not feasible, because of the textile nature of the substrates. Nowadays, moreover, tin whiskers (Tu, 2007) can grow over time in electrical circuits, eventually leading to shorts and failure of the circuits. Similar effects might occur in textile circuits by fraying and fibril breaks. The processing of fabric substrates will certainly become more expensive than the processing of PCB substrates, since additional and slower processes will be involved, as mentioned above. However, fabric as substrate is about ten times cheaper than FPCs based on polyimide. Eventually, electronic systems on textiles might be in a similar price range as standard circuit boards.

10.10 Future trends

In the early stages of smart textiles, many so-called 'Smart Shirts' were proudly displayed, most of them handmade. The impression was given that every function can be integrated in fabrics. However, technology and manufacturing processes are still yet to reach that stage. At least some specific process steps must yet be implemented to bridge the gap between the textile and the electronics world. Happily, the smart-textile community has matured over the past few years and certain universities and companies are about to establish some of these specialized manufacturing steps.

Apart from specific processes, there are still various unsolved issues regarding materials. Many companies are currently trying to improve conductivity of polymers and coatings, for example, by using carbon nanotubes (CNTs). The goal is to combine the robustness and flexibility of polymers and the conductivity of metals. Of the various polymers, only a few can be spun to threads that eventually compose a fabric. The emerging molded injection device (MID) technology is a promising portfolio of methods to apply robust and highly conductive structures on polymers. Improvements in conductive elastic adhesives based on silicones or PUs would, furthermore, help to make connections mechanically more robust, although these adhesives are still expensive. The implementation of functionality at the fibre level of a fabric is, in short, still seen as the most elegant development possible, but also as one of the most futuristic.

Future miniaturization of electronics, as well as research in plastic electronics, will also help to further integrate the two worlds of electronics and textiles. Nevertheless, even in this harmoniously integrated world, standardization will be necessary to a certain degree, in order to enable modularization and to establish basic system components. That, again, is crucial for an accelerated progress in innovation in the world of smart textiles.

There are already smart fabric products in the fitness and outdoor business on the market. The most notable include the Polar belt and the sports bra by adidas for monitoring heart rate. Furthermore, the first smart fabric products in the field of healthcare are about to emerge, which will fulfill such functions as the monitoring and managing of vital parameters. Philips is very active in this field. The automotive industry is also interested in smart fabrics, since they allow new freedom of design and they imply potential to save weight. Some combinations of electrical systems and fabrics, such as heated seats, have already been around for a while, but have never been truly acknowledged as smart fabrics. However, the ideal application is still yet to be identified. We are convinced that a small, very simple application with limited functionality will eventually facilitate the successful launch of smart fabrics as new industrial branch.

10.11 References

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