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Evaluation and optimization of textile ultrasonic welds for textile temperature control elements using transient thermal numerical analysis

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ABSTRACT

Ultrasonic welding is an efficient method of joining thermoplastic fabrics or other textile semi-finished products in a watertight manner. It is applied in the making of functional clothing, such as chemical protective clothing, sportswear or smart clothing, or other technical products. Another special field of application developed at the Chair of Development and Assembly of Textile Products is the use of coated textiles as temperature control elements. For this type of product, it is necessary to design the ultrasonic welds in such a way that the media-tight coating is not damaged and the joint is continuous. This paper presents the option of evaluating and optimizing the ultrasonic welding process for the production of textile tempering systems using transient thermal analysis to improve the overall quality of the seam and ensure media tightness along the seam. In this article, the status of the welding process, in particular the ultrasonic process, the textile materials, the heating of the textile and the joining process of welding are presented. In addition, the transient heat flow through the textile is investigated with the aid of FEM methods, taking into account various seam structures.

Keywords
seam strength,
media density design,
ultrasonic welding technology,
thermal simulation,
seam stress investigation

1 Introduction

The thermal joining technology can be divided into different subject areas. This classification can be based on the type of energy input or whether it is a continuous or discontinuous process. This results in different classification possibilities to classify the thermal joining processes are shown in Fig. 1 as an example.

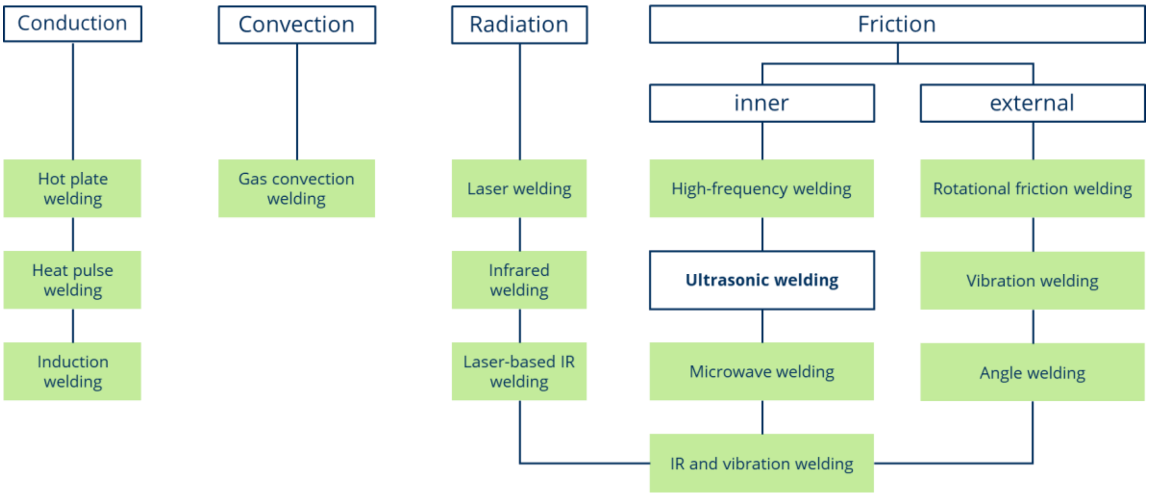

Fig. 1 Classification of welding processes according to ISO 4063 (classification based on type of heat input) [1].

For continuous ultrasonic welding, the feed and pressure of the anvil wheel and the energy input through the sonotrode can be adjusted to create the joining seam. In addition, different profiles for the anvil wheel (see Fig. 2) are available for continuous ultrasonic welding, which can change the mechanical or optical properties. The effects of these different settings during the ultrasonic joining process can then be determined and documented in textile-physical procedures (see Fig. 3). This entire procedure for determining the influencing parameters for the ultrasonic welding process is complex, time-consuming and expensive.

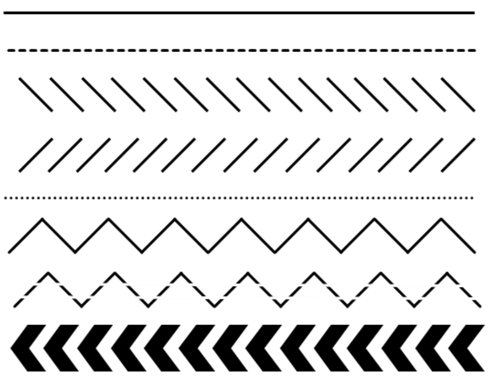

Fig. 2 Welds in different designs [2].

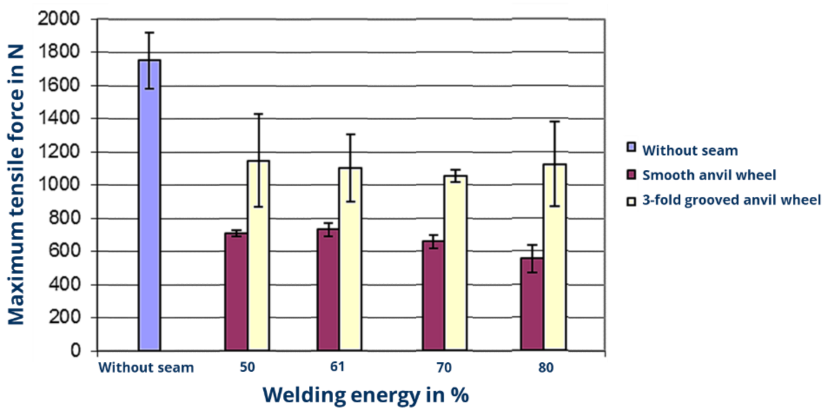

Fig. 3 Maximum tensile forces for different energy inputs and anvil profiles [3].

Figure 3 shows that the weld penetration and the anvil wheel profile are used to influence the maximum tensile strength and reproducibility of the ultrasonic weld. However, it is also evident that the methods of investigation used to date do not make it possible to estimate or establish correlations between the effects of the individual parameters on the ultrasonic weld.

In the metalworking industry, common methods are known to meet these challenges. The currently available simulation technology for metals and metallic semi-finished products is even linked to conventional CAD programmes so that the numerical calculations are linked to the developed CAD models [4]. This means that the development times for new products can be drastically reduced. For textiles, these links do not yet exist and the corresponding numerical calculations are still subject to severe limitations.

In the following, transient simulations are to be created that show the cooling process during the ultrasonic welding process when producing media-tight joining seams for textile tempering elements.

2 Method

2.1 Development, manufacture and construction of textile temperature control systems

For the development of textile temperature control systems, two fundamentally different options were available: temperature control using temperature-controlled media, or the use of active temperature control elements such as textile-based heating wires or cooling circuits. In turn, two possibilities were considered as basic constructions for media-carrying temperature control elements. Figure 4 shows variant 1, in which media-carrying hoses were integrated between two layers by sewing. This basic design represented an intermediate step and was further developed into variant 2, see Fig. 5. Here, ultrasonic welding is performed in such a way that the media-carrying channels are formed between the seams and join two layers.

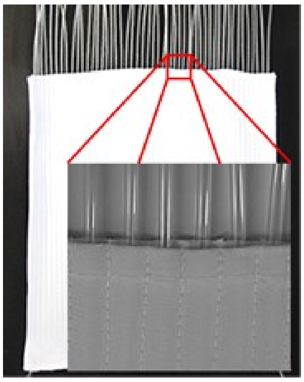

Fig. 4 Tube-based temperature control element.

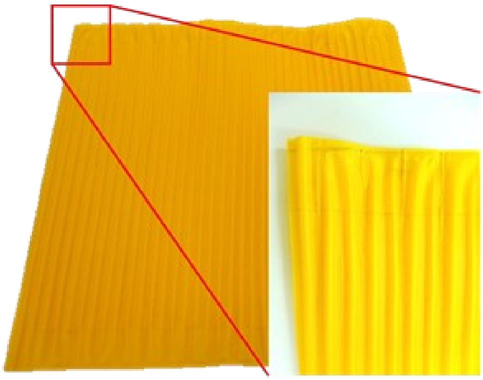

Fig. 5 Ultrasonic-welded temperature control element.

The first production and use tests of the US welds showed a preferred solution, which should then be followed up. The material-locking connection of textiles coated with thermoplastic polyurethane shows the most suitable properties to ensure a combined solution for passive cooling as well as for active heating of rooms. In addition, this type of room temperature control represents an advantage, as only minor changes in the existing media supply of conventional building supply systems are necessary for its use. The possibilities for using textile temperature control systems are manifold. They can be used as partition wall systems (see Figure 6), window curtains (see Figure 7) or as wall textiles.

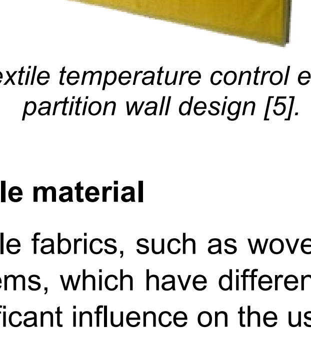

Fig. 6 Textile temperature control element in a partition wall design [5].

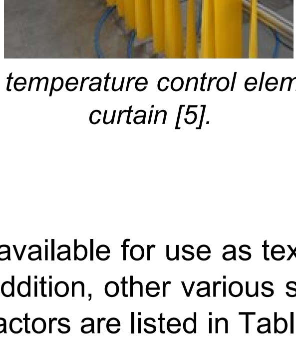

Fig. 7 Textile temperature control element as window curtain [5].

2.2 Textile material

Various textile fabrics, such as woven or non-woven fabrics, are available for use as textile temperature control systems, which have different mechanical properties. In addition, other various selection options have a significant influence on the use of textiles. These various factors are listed in Table 1.

Table 1. Selection options for the textile materials.

Parameter	Selection Option
Origin of the textile raw material	Natural/synthetic
Textile classification according to the type of plastic	Thermomers, elastomers, duromers
Filament cross-section geometry	Circular, rectangular, triangular, hollow filament
Textile sheet forming process	Weaving, knitting, braiding, winding, fleece laying
Classification of textile sheet formations (selection)	twill weave, single thread knitted fabric, felt nonwoven fabric
Use of additional coatings	coating on one or both sides
Additional finishing materials (selection)	Dyes, surface finishes, UV stabilisers
Textile running direction used	Warp direction, weft direction, diagonal direction

Furthermore, all textiles are characterised by multidirectional behaviour in their mechanical and thermal properties, which must be taken into account during use. All of the above factors have a considerable influence on the resulting applicability in the textile temperature control element as well as the use of the material-locking connection method. Therefore, the appropriate selection of the textile fabric is important. The final selection was made for a technical textile with sufficient strength and media tightness. The description of the material is given in Table 2.

Table 2. Description of the construction of the textile material used.

Properties	Description
Base material	Polyamide 6.6 (PA)
Coating material	Thermoplastic Polyurethane (TPU)
Thickness	0.2 mm (base material), 0.2 mm (coating material)
Fabric Construction	Woven fabric with plain weave construction

2.3 The Ultrasonic Welding Process

The ultrasonic welding process can be used to join different materials. The materials are permanently joined through oscillating frequencies in the ultrasonic range, static pressure and a dwell time. Ultrasound is a mechanical-physical oscillation that is positioned between humanly audible sound and hypersonic sound. Ultrasonic waves can assume frequencies between 10,000 and 100,000,000 Hz with an intensity of 1 W/m² to 1 x 10^{-12} W/m² (see Fig. 8).

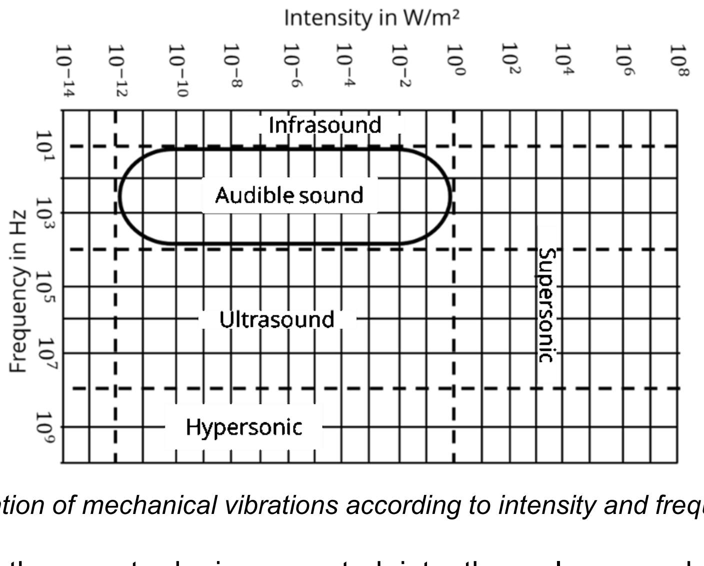

Fig. 8 Classification of mechanical vibrations according to intensity and frequency range [2].

The vibration energy of the sonotrode is converted into thermal energy by the sound absorption properties of the textile material. Fig. 9 shows the mechanical principle of ultrasonic welding [2].

Fig. 9 Mechanical representation of the ultrasonic welding process [6].

The abbreviations in the figure indicate:

M1 - The first textile material,

M2 - The second textile material,

K - Damping constant between the involved partners and

P - Pressure of the welding machine.

The surface pressure P of the ultrasonic welding system changes the damping constants K (*Sono/M1, M1/M2* and *M2/Anvil*) of the textile material. The damping behavior of plastics is linearly dependent at small and medium stress amplitudes [7], but they show a frequency-dependent behavior [8]. Furthermore, the damping constant K (*Sono/M1, M1/M2* and *M2/Anvil*) is modified by the surface properties of the respective materials. From practical work, it has proven useful to roughen the corresponding surfaces for the welds in a preparatory step to partially increase the static friction between the material partners. In this mechanical system, the horn delivers a constant vibration energy to the system, which is defined as follows (see Eq. 1):

$$W = \frac{1}{2} m (2\pi f A)^2 \quad (1)$$

The abbreviations in the figure indicate:

W - vibration energy of the sonotrode (J)

m - mass of the sonotrode (kg)

f - frequency of the sonotrode (Hz) and

A - amplitude of the vibration (m).

There are different designs for welding patterns and thus for the resulting contact surface between the anvil and the welding material, which are suitable for decorative seams, high-strength seams or, as for the textile tempering elements, for media-tight seams. Furthermore, the arrangement of the textile fabrics and the welding arrangement influence the resulting properties of the resulting seam. With the same process parameters, the resulting contact area influences the heat transfer as well as the maximum local joining temperature in the welding materials [3]. Furthermore, Ref. 3 shows that the resulting heat transfers in the weld metal have positive and negative influences due to the variation of the resulting contact area, which is directly dependent on the process parameters used. Ultrasonic welding can be carried out discontinuously as well as continuously. The continuous process is cost-effective and productive and has wide applicability for technical textiles. Regardless of the process used, a phase transformation and cross-linking take place in the joining partners to be cross-linked during ultrasonic joining. Three parameters are of particular importance for the real manufacturing process. The welding energy is applied by the sonotrode (in the form of frequency and amplitude), the applied welding pressure and the dwell time at the joint by the anvil wheel. These three parameters are different for each textile used.

3 Model development and simulation

In these thermic simulations, heat transfer is presented with the use of partial differential equations. For the homogeneous multidimensional case, the diffusion equations is:

$$\frac{\partial}{\partial t} u(\vec{x}, t) - a \Delta u(\vec{x}, t) = 0 \quad (2)$$

In this context: $u(\vec{x}, t)$ Temperature *u* at time *t* at the point $\vec{x}$

$a, a > 0$ Thermal conductivity of the material

For the use of this thermal formula, the initial and boundary conditions are that the materials under consideration have homogeneous properties and distributions. In general, this applies to metals and amorphic plastics.

In the first step for the numerical calculation of heat propagation in the SolidWorks software, a corresponding model is created. The model is arranged to resemble an overlap seam. For the simulations, the initial models are created with four different seam widths to show the thermal influence of the overlap seam widths on the heat propagation during the ultrasonic welding process. The initial model "overlap seam" for the numerical calculation is shown below.

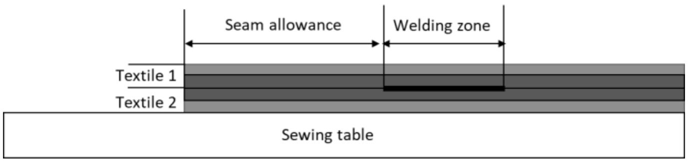

Fig. 10 Model arrangement "Lap seam" for the numerical calculation

In the model for the numerical calculation, the welding zone has a width of 3 mm and is arranged centrally between textiles 1 and 2. Furthermore, a total height of 0.4 mm is defined for the model. Besides, for the analysis the weld width is set to 0 mm, 1 mm, 2 mm and 5 mm to represent the propagation of the thermal energy to the textile edge. Finally, various material parameters are assigned to the model. These are listed in Table 3.

Table 3. Thermal properties of the used materials [9].

	Thermal conductivity in W/(mK)	**Specific thermal capacity in J/(kgK)**
Table material (Epoxy resin)	0.188	1100
Textil 1/2: base material (PA)	0.233	1601
Textil 1/2: Coating material (TPU)	0.2618	1900

The thermal parameters shown in Table 3 refer to conventional plastics and not to textile fibre materials. Due to the way the textiles are manufactured, their thermal and mechanical properties may differ from conventional plastics, which is why this must be taken into account. For the numerical calculations, it is assumed that the plastic-based textile fibre materials are homogeneous materials with identical properties in the x, y and z directions. This must be assumed because the production and geometry-related deviations cannot yet be represented.

After developing the model, the associated mesh and the material parameters, the corresponding thermal states are implemented in the model. The position of the thermal energy is assumed to be in the joining zone, which is located between the two textiles and has a constant temperature of 150 °C (423.15 K) with a width of 3 mm. This is a simplified assumption for the numerical calculation, as the conversion of mechanical energy (vibration energy of the horn) into thermal energy depends on the textile material and the vibrations used. Figures 9 show the initial temperatures for the plastic layers (substrate and coating material) and the heat source in the middle of the joining zone.

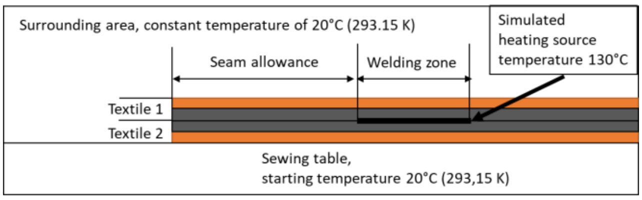

Fig. 11 Thermal sources for numerical calculation in the model "lap seam".

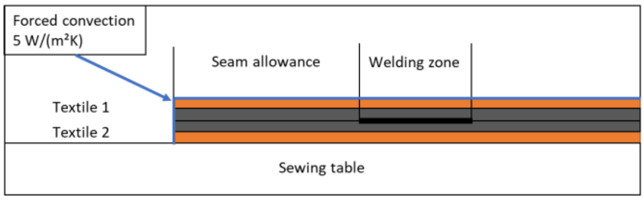

Fig. 12 Thermal sources for numerical calculation around the model "lap seam".

In addition, forced convection is built into the model to represent heat transfer to the environment (see Figure 10). With these initial and boundary conditions, the numerical calculations are carried out and the temperature distribution is determined.

4 Results

Numerical calculations have been carried out with the defined models. These are:

- Variation of the seam width on the heat propagation behaviour for lap seams.
- Execution of the numerical calculation for 5 seconds with a time interval of 0.1 seconds.

The results of the numerical calculations are shown below.

Figure 13 shows that within the first few seconds after heating the joining zone, a heat build-up forms at the interface of the textile materials. In addition, this area cools down more slowly than the remaining areas of the joining zones, resulting in a thermally induced stress gradient that is difficult to describe and thus represents a weak point. Applied to the textile tempering systems, this welding arrangement cannot be recommended as the seam quality suffers due to the heat accumulation and, above all, the media-tight design of the textile semi-finished products can no longer be guaranteed.

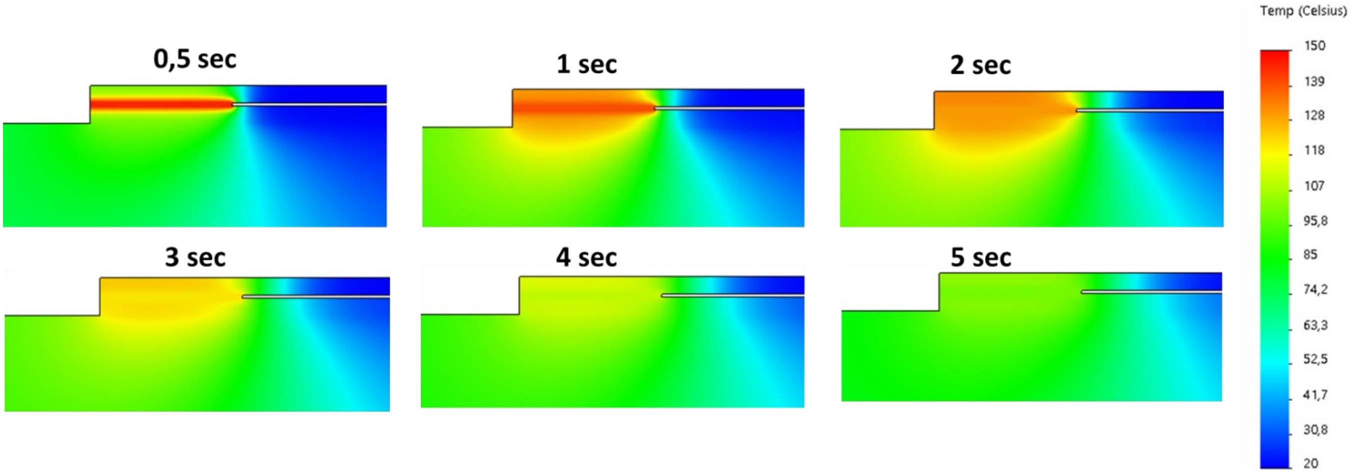

Fig. 13 Transient thermal calculation for a seam spacing of 0 mm.

In Figure 14, the seam distance to the joining zone was increased by 1 mm. As a result, thermal energy from the joining zone is distributed more evenly in the first 3 seconds. Afterwards, however, the effect of heat accumulation at the border of the textile semi-finished products can be observed again. This heat accumulation remains at this point for the calculated time period. Geometrically, the temperature at this heat accumulation is about 10 K above the opposite point of the weld seam. This temperature gradient is thus lower than the heat accumulation at a seam distance of 0 mm. However, this also leads to thermal stresses which can negatively affect the weld seam.

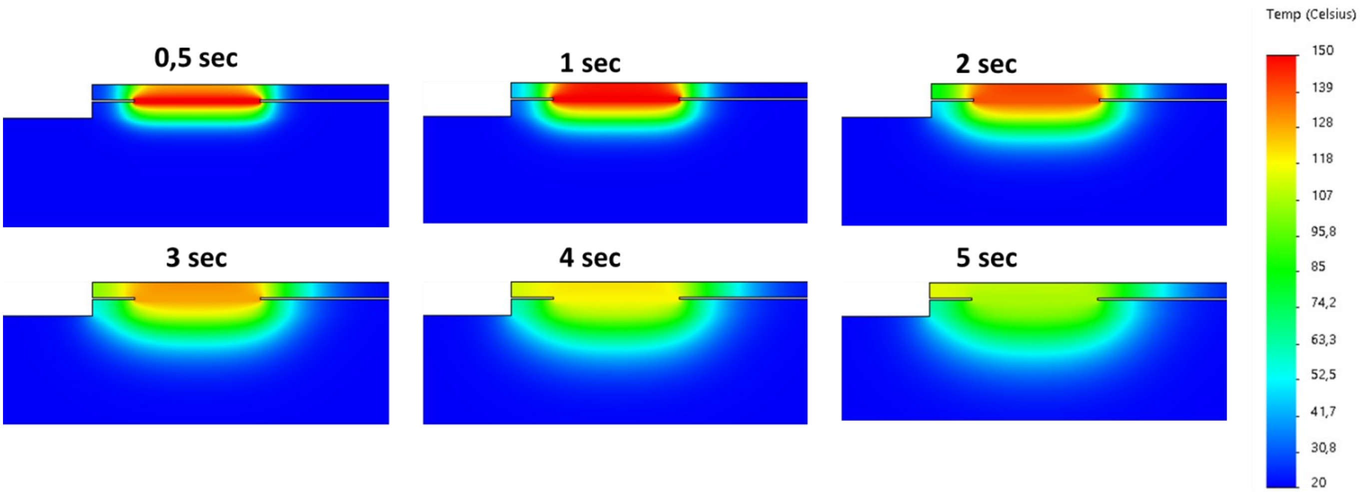

Fig. 14 Transient thermal calculation for a seam spacing of 1 mm.

In the third numerical calculation, the distance to the joining zone was increased to 2 mm. The results of this calculation are shown in Figure 15. It can be seen that the thermal energy of the joining zone is distributed very evenly over the textile semi-finished products. However, slight temperature differences are still visible in the seam geometry.

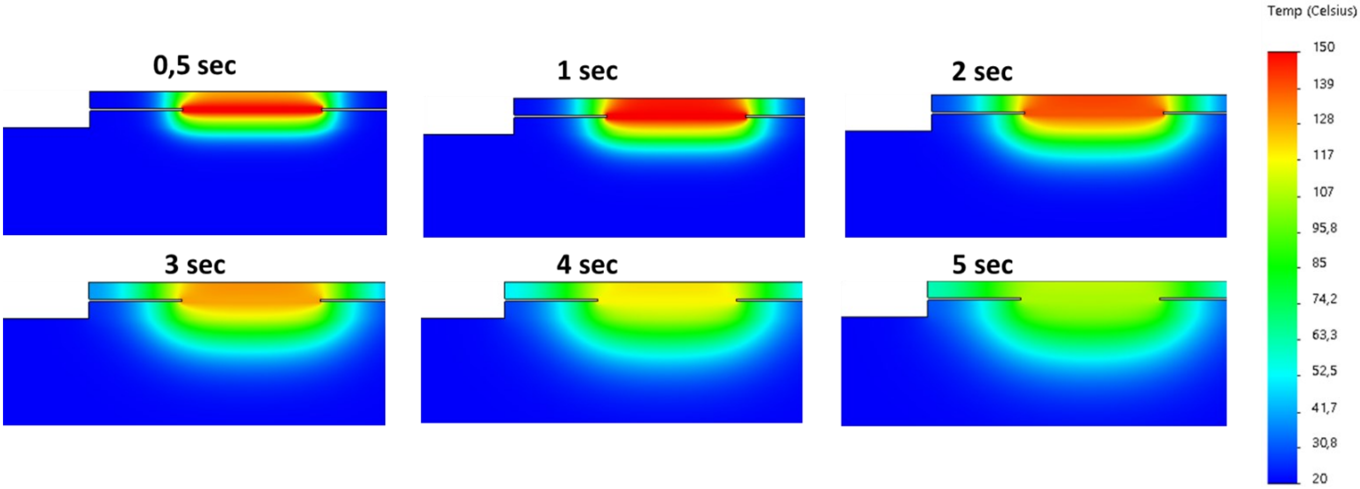

Fig. 15 Transient thermal calculation for a seam spacing of 2 mm.

By further increasing the seam width in the model from 3 mm to 5 mm, the most uniform temperature profile is obtained. Over the entire calculated period, the thermal energy can spread symmetrically across the cross-section from the joining zone (see Fig. 16). Heat accumulation can be detected. Just as the spread of thermal energy is uniform, the textile semi-finished products also cool geometrically uniformly. Differences in the temperature profile between the upper and lower textile semi-finished products can still be detected, but these differences are caused by contact with the substrate. Overall, it can be determined that a seam width of 5 mm is the most suitable for creating a uniform temperature profile and thus also for ensuring media tightness for the textile temperature control systems.

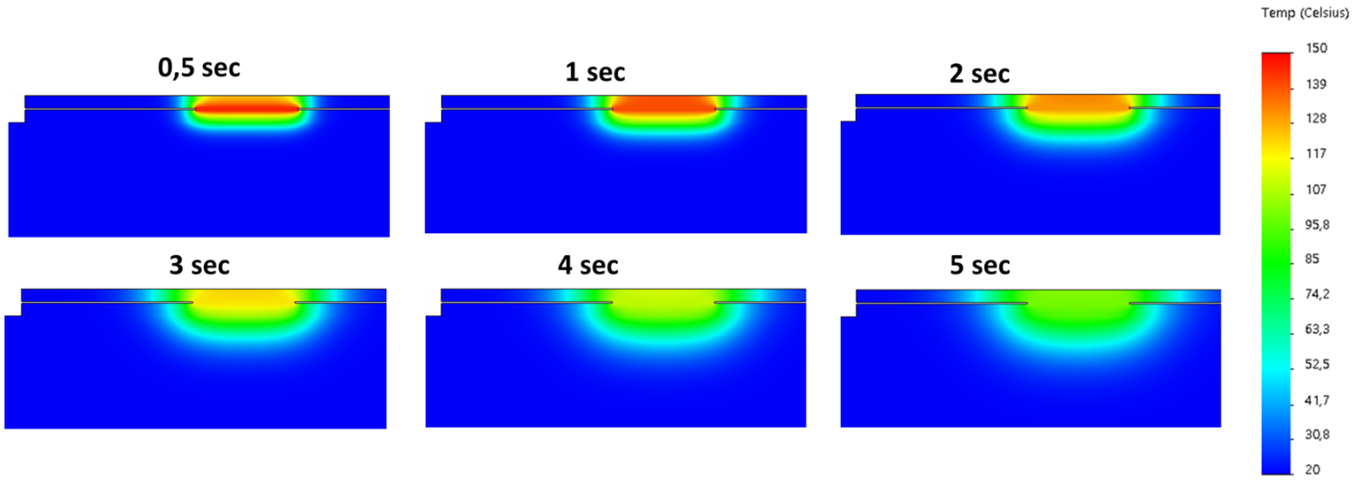

Fig. 16 Transient thermal calculation for a seam spacing of 5 mm.

5 Conclusion

By using numerical calculations, information can be collected and processes can be displayed during ultrasonic welding to better analyses the thermal processes in the joining zone. This can be used to increase process reliability and the reproducibility of welds. The numerical calculation of textile welds is challenging because textile materials are multidimensional, heterogeneous materials that can be strongly changed by environmental influences. Another topic in this context is the conversion of mechanical vibration energy into thermal energy.

The numerical calculations showed that for the material combination of polyamide 6.6 and thermoplastic polyurethane a seam allowance of 5 mm is advantageous. Employing this minimum distance during the ultrasonic welding process, it is possible to maintain the interface of the welded textile materials and to achieve a uniform thermal design of the welding surface. A smaller seam distance, on the other hand, leads to the formation of thermal hotspots, which are a sign of overheating. In practice, this can mean that in such arrangements of textile materials, it can lead to melting of the interface and leakage of the material from the weld, which significantly reduces the strength of the weld. Especially for the textile tempering elements, this also means that the media-tight design of the welded ultrasonic seams is at risk. The actual welding process cannot yet be mapped, which is why further research is needed. In particular, the replication of the textile materials utilizing substitute models is necessary.

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Author Contributions

A. Reich: concept, experiments, simulation and text; Y. Kyosev: supervision, theoretical guidance; H. Saeed: text editing, support in experimentation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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