TEKSTİL VE KONFEKSİYON

VOL: 32, NO. 4
DOI: 10.32710/tekstilvekonfeksiyon.1065694

Numerical Calculation of Influencing Parameters on the Seam Allowances of Textile Materials During Ultrasonic Welding

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ABSTRACT

The ultrasonic welding process allows economically efficient and safe for the workers waterproof joining of textile materials and is applied in the production of various technical textiles, protective clothing, and other types of textile products. In this latest research work, a flexible, textile-based heating element is produced by the connection of waterproof laminated textiles using ultrasonic technique. This novel product allows completely new options for the design of flexible heating and cooling elements for rooms and various other applications but requires high quality seams. This work starts with the theoretical background about the heating of the textile until reaching the welding temperature within the welding zone. The heat flow through the volume of the welded textiles is investigated numerically using Finite Element Method software. The simulation is performed for different sizes and configurations of the seam allowances, so that options between overlapping only in the pressed area without side allowance (no free allowance), small allowance, and larger allowance are simulated. These simulations demonstrate different distributions of the temperature in the seam cross-section at the different configurations, because of the different amounts of textile material around the welding place.

ARTICLE HISTORY
Received: 30.01.2022
Accepted: 23.06.2022

KEYWORDS

Seam strength; ultrasonic welding technology; thermal simulation; seam stress investigations

1. INTRODUCTION

In the metal manufacturing and processing industry, software solutions for the simulation of thermal, form-fitting and material-fitting joining processes are in use [1]. In these thermal simulations, heat conduction is represented by means of partial differential equations. The diffusion equations for the homogeneous multidimensional case is:

$$\frac{\partial}{\partial t}u(\vec{x},t) - a\Delta u(\vec{x},t) = 0 \tag{1}$$

Dabei gilt: $u(\vec{x},t)$ Temperature u at time t at the point $\vec{x}$

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

The initial and boundary conditions for the use of this equation are that the material to be considered has homogeneous properties and distributions. This is usually fulfilled for metallic and armorphous plastics materials.

Such simulation-based tools have so far only been used to a limited extent in the textile and ready-made clothing industry. The reasons for this are the complex micro- and macroscopic structure of textiles and the wide-ranging property profiles of the plastics used [2]. In addition, textiles are generally considered heterogeneous materials, which have direction-dependent properties that require special and more complex calculation operations. Thus, the results already obtained from the metal manufacturing and processing industry cannot be easily transferred to the textile and ready-made clothing industry, which is why the use of these simulation-supported tools has been slow.

To cite this article: Reich A, Kyosev Y. 2022. Numerical calculation of influencing parameters on the seam allowances of textile materials during ultrasonic welding. *Tekstil ve Konfeksiyon* 32(4), 376-383.

1.1 The Ultrasonic Welding Process

By means of the ultrasonic welding process, different materials to be welded can be joined in a compressed and permanent manner with a frequency oscillating between the sonar line and the counterpart in the ultrasonic frequency range and with a suitable static pressure. Ultrasound physically belongs to the mechanical vibrations and is located between the audible sound and the hypersonic. Ultrasonic waves can have frequencies between 10,000 and 100,000,000 Hz with an intensity of 1W/m^2 to 1x10^{-12}W/m² (see Figure 1).

The oscillation effect of the frequency generator and the sound absorption of the materials convert the oscillation energy into heat. The following illustration shows the mechanical principle of ultrasonic welding. [3]

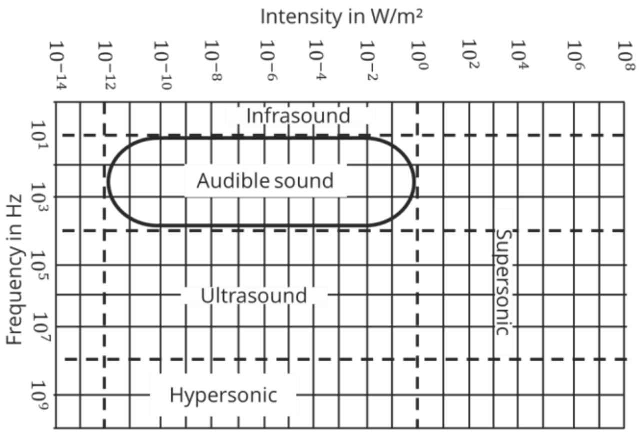

Figure 1. Classification of mechanical vibrations according to intensity and frequency range [3]

The damping constants K (Sono/M1, M1/M2, M2/Anvil) of the material are changed by the contact pressure P of the welding system. According to [4], the damping behavior of polymers is linearly dependent in small and medium stress amplitudes. However, they exhibit a frequency-dependent behavior in this respect [5]. Furthermore, the damping constants K (Sono/M1, M1/M2, M2/Anvil) are additionally modified by the surface properties of the respective materials. In practice, it has proven useful to roughen the corresponding welds during preparation in order to increase the static friction between the material partners. In this mechanical system, the sonotrode delivers constant vibration energy to the system, which is defined as follows (see Eq. (2)):

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

Where W the vibration energy of the sonotrode is, m is the mass of the sonotrode, f is the frequenz of the sonotrode and A is the contact area of the sonotrode. Figure 3 shows several possible designs for weld patterns that affect the resulting contact area between the anvil and the weld material. In addition, the arrangement of the textile sheet structures and the welding arrangement used have an influence on the resulting properties of the joining seam (see Figure 4). The resulting contact area, while maintaining identical process parameters, influences the heat transfer as well as the maximum local joining temperature in the welding materials [6]. It was clearly shown [6] that the resulting heat transfers in the weld material show positive and negative influences due to the variation of the resulting contact area, which are directly dependent on the used process parameters.

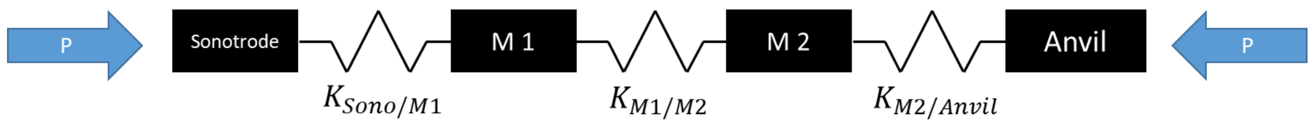

Figure 2. Mechanical representation of the ultrasonic welding process

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.

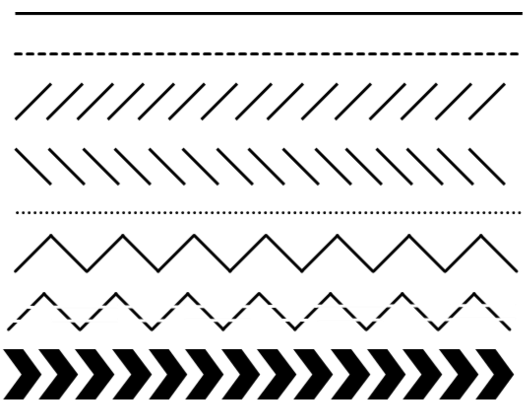

Figure 3. Ultrasonic welds in different designs [3]

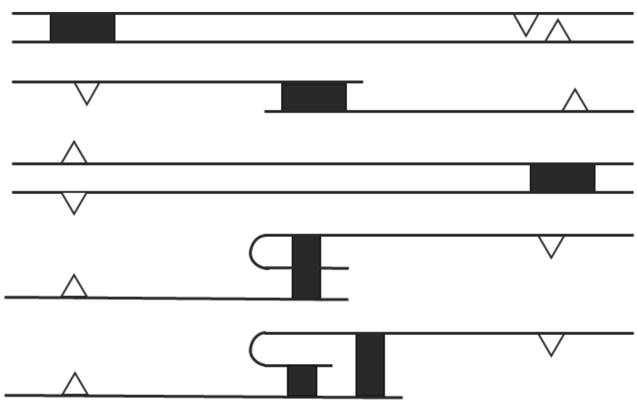

Figure 4. Arrangement of textile fabrics [3]

Ultrasonic welding can be performed both intermittently and continuously. Especially the continuous process is cost efficient and productive and has a wide applicability for technical textiles. Regardless of the process used, a phase change and cross-linking takes place in the joining partners to be cross-linked during ultrasonic joining. These processes are shown schematically in Figure 4.

Based on these thermal-physical interlinking processes, a schematic representation of the welding process can be derived (see the energy-time diagram in figure 5). For comparison, the temperature-distance pairs for continuous ultrasonic welding processes with different energy input (50% to 80%) are shown (see figure 6 with a feed rate of 150 mm/min). It can be clearly seen that the temperature profile is similar.

For the actual manufacturing process, three parameters are of particular importance. These are the applied welding energy (in the form of frequency and amplitude) from the sonotrode, the applied welding pressure, and the dwell time at the joint from the anvil. These three parameters differ for each used textile. Thus, before the actual production of the textile products, extensive, cost-intensive and time-consuming investigations must be undertaken in order to create optimal parameter windows.

1.2 Description of the Mechanical and Thermal Properties

Various textile semi-finished products are available for the use of textiles in technical applications. These can differ in terms of their material, their make-up and their finish. The following table lists the possible options for various selection aspects that can be considered for use in technical applications.

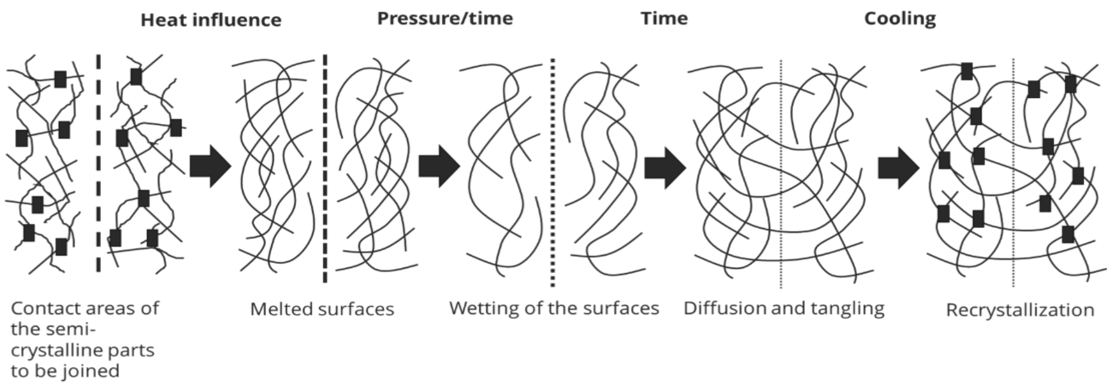

Figure 4. Melting and cross-linking process in the ultrasonic welding process [7]

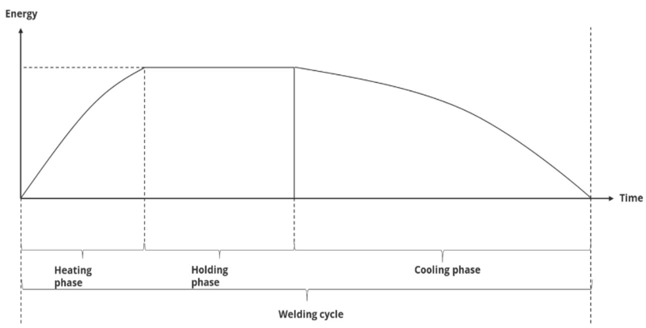

Figure 5. Energy/time curve of the ultrasonic welding process [7]

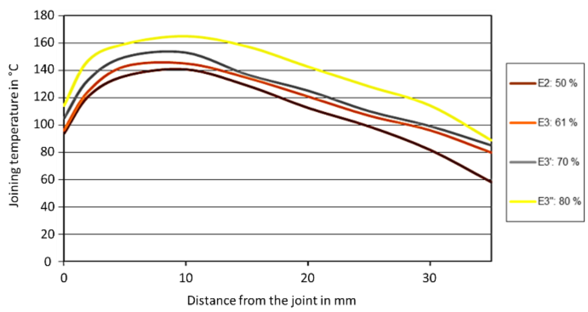

Figure 6. Temperature profile at the seam outlet as a function of the welding energy [6]

Table 1. Selection options for the textile materials [8]

Origin of the textile raw material	Of natural or synthetic origin
Textile classification according to type of plastic	Thermomers, elastomers, duromers
Filament cross-section geometry (selection)	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

These different options have a noticeable influence on the usage properties of the textiles and can even give them additional properties such as electrical conductivity or temperature-dependent colour properties. In particular, the used material or combination of materials and the geometric structure of the fibres, filaments and yarns significantly influences the thermal properties of the textiles used later. Figure 1 shows a comparison of different filament cross-sections for the material viscose.

For the numerical consideration of these fibres, the cross-sectional area and the fibre length can be considered constant for the comparability of the thermal properties. Thus, only the fibre geometry would have an influence on the thermal properties. The following table (see table 2) shows the geometry-related shifts of the thermal values for kidney-shaped, star-shaped and hollow fibres in comparison to a round fibre. In addition, the corresponding heat flows and temperature intervals are constant for the calculations.

It is clear from Table 2 that the thermal properties can be greatly changed by specifically varying the fibre and filament geometry. In particular, the use of star-shaped cross-sections leads to a high heat transfer coefficient compared to round cross-sections. In addition, the thermal properties, similar to the mechanical properties, of the textile fibres would have to be split into their x, y and z coordinates, as different internal structures are present due to the manufacturing process of the fibres/filaments. With regard to this influence of the cross-section, the manufacturing parameters in the thermal joining of textiles in particular must be adapted.

2. MATERIAL AND METHOD

2.1 Description of the Material

Various textile semi-finished products are available for the use of textiles in technical applications. These can differ in terms of their material, their make-up and their finish. These different options have a noticeable influence on the usage properties of the textiles and can even give them additional properties such as electrical conductivity or temperature-dependent colour properties. For the numerical calculation of the seam allowance during the ultrasonic welding process, the selection was narrowed down to the following textile (see Table 1). In order to guarantee the media-tight design of the weld seam, a one-sided coating of the backing material is provided.

2.2 Model Development and Mesh Creation

For the numerical calculation of the heat propagation in the SolidWorks software, two corresponding model are generated for the investigation. The models are arranged in such a way that they resemble a lap seam or a flat seam. For the actual simulations, the initial models are created with four different seam widths to show the thermal influence of the transfer seam widths on the heat propagation during the ultrasonic welding process. The initial models "lap seam" and "flat seam" for the numerical calculation are shown in figure 8 and 9.

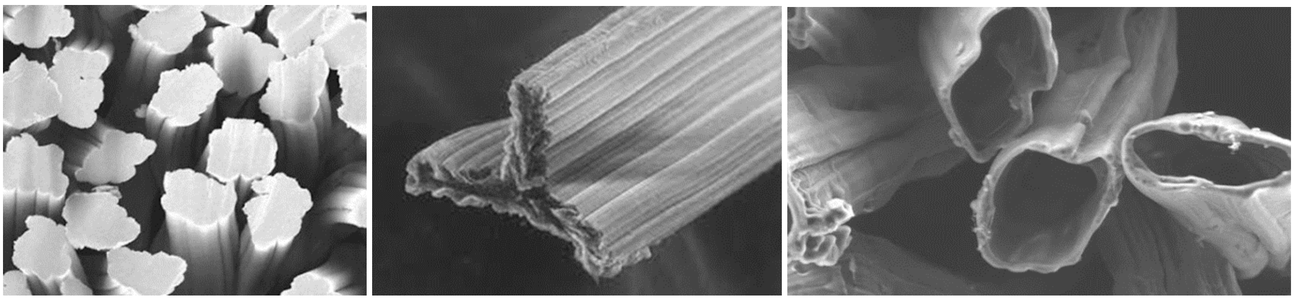

Figure 7. Viscose in kidney-shaped form (left) [9]; in star-shaped form (centre) [10] and as void fibre (right) [11]

Table 2. Comparative thermal quantities for different fibre geometries

	Sheath area in mm²	Heat capacity in %	Heat transfer coefficient in %
Round-shaped	6.33	100	100
Kidney-shaped	6.77	100	107
Star-shaped	65.32	100	1032
Hollow fibre	27.04	77	427

Table 3. Description of the construction of the textile material used

	Description
Base material	Polyamide 6.6 (PA)
Coating material	Thermoplastic Polyurethane (TPU)
Thickness	0.2 mm (base material), 0.2 mm (coating material)

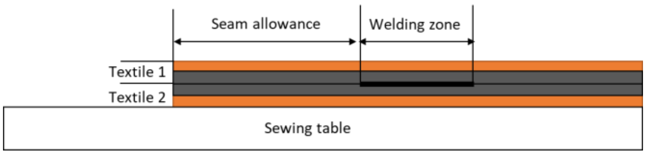

Figure 8. Model arrangement "Lap seam" for the numerical calculation

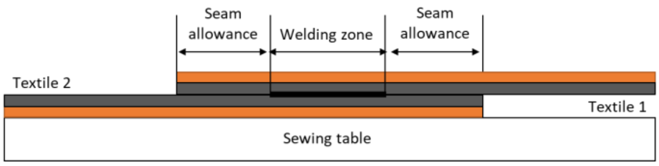

Figure 9. Model arrangement "Flat seam" for the numerical calculation

The welding zone has a width of 3 mm in the numerical calculation, which is positioned centrally between textile 1 and textile 2. The total height of textile 1 and 2 is 0.4 mm. The weld width is set to 0 mm, 1 mm, 2 mm and 5 mm in the numerical calculation to investigate the heat propagation to the textile edge. Furthermore, the various components have been given thermal material parameters for the numerical calculation. These are presented in Table 4.

It should be mentioned that the thermal parameters shown in Table 4 refer to conventional plastics and not to partially stretched textile fibre materials. Due to the different production methods, the thermal and mechanical parameters of the textiles may differ, which is why this must be taken into account in the final considerations. Furthermore, it is assumed for the numerical calculations that the various plastic-based textile fibre materials are homogeneous materials with identical characteristics in the x, y and z directions. This assumption must be made at the moment, as the differences due to production and geometry cannot yet be completely transferred into the simulation.

For the generation of the numerical mesh, as a basic requirement for the thermal calculations, the SolidWorks software provides various solvers. These solvers use various mathematical algorithms to transfer the created components into a suitable mesh. The three solvers provided by the software are shown below in Table 5 with their areas of application.

For a suitable selection of the necessary solver, it must first be examined how detailed the necessary simulation network for the thermal calculations must be for the representation. The resulting meshes for different element sizes (from 0.1 mm to 0.05 mm) are given below in Figure 10. It can be seen that as the element size decreases, the number of nodes in the mesh increases dramatically, which increases the accuracy of the simulation as well as the calculation time.

Table 4. Thermal properties of the used materials [12]

	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: base material (PE)	0,461	1796
Textil 1/2: Coating material (TPU)	0,2618	1900
Textil 1/2: Coating material (PVC)	0,147	1355

Table 5. Properties of the different SolidWorks solvers [12]

Direct Sparse Solver	**FFEPlus**	**Intel Direct Sparse**
Suited for multi-area contact problems Suited for multi-material problems Needs the most RAM of the computer	Suited for solving problems with more 100.000 dots	Suited for solving problems with less than 25.000 dots

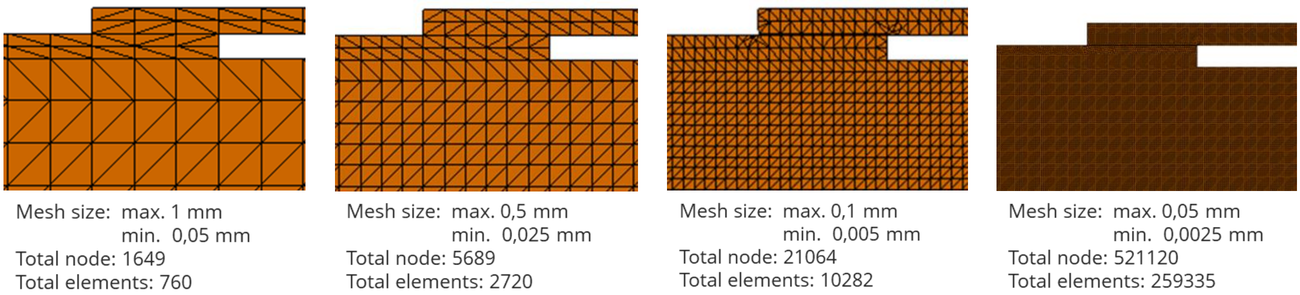

Figure 10. Diffrent mesh sizes for the thermal calculation

For the final selection of the element sizes for the mesh, the individual CAD elements must be considered more closely. In particular, the joint seam, which serves as the heat source in the calculation, as well as the transitions between the carrier and coating materials were examined more closely. It was found that up to an element size of 0.1 mm, the zones under consideration can only be insufficiently represented. Therefore, an element size of maximum 0.05 mm was chosen for the mesh generation. Figure 11 shows the generated mesh around the joining zone for the element size.

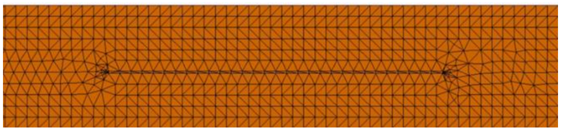

Figure 11. Detailed view of the meshed welding zone

Furthermore, in the numerical model, thermal propagation takes place over different geometries along the cross-section. In addition, for the investigation of coated textiles it is necessary to use different material parameters for the calculation. Therefore, the choice of the solver was made for the "Direct Sparse Solver" to represent the thermal propagation.

After creating the numerical mesh, the corresponding heat sources and transitions must be implemented in the model. For the positioning of the thermal energy source, it is assumed that it is located between the two textiles and has a constant temperature of 130 °C (403.15 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. This complex, non-linear process cannot be calculated numerically at this time. Figures 11 and 12 show the initial temperatures for the plastic layers (substrate and coating material) and the heat source in the centre of the joining zone.

Furthermore, forced convections have been implemented in the models to represent the heat transfer to the environment. These additional heat transfers are shown in figures 13 and 14 for the models.

With these conditions and configurations, this numerical analysis is performed and the static equilibrium of the temperature distribution is determined. For the current numerical calculation, only the middle plane of the weld is calculated. The 3D effects of the rounding are not yet considered.

2.3 Simulation

Using the previously defined mesh models and the corresponding initial conditions, various numerical calculations can be carried out. These are presented in this publication:

- Variation of the seam width on the heat propagation behaviour for cut-off and flat seams.
- Variation of material pairings using the example of polyester with a PVC coating as a cut seam and flat seam (seam width 0 mm and 5 mm for lap and flat seam)
- Variation of the joining temperature between 100°C, 120°C, 140°C and 160°C as a cut seam with the material combination nylon with a TPU coating (seam width 2 mm for lap seam)

The results of the first numerical calculations are shown in the figures below.

The two different simulations in Figures 14 and 15 show that for seam distances less than 5 mm, the heated and melted area is too close to the ultrasonic joining seam. If the distance to the ultrasonic joining seam is greater than 5 mm, the plastic layers remain in their solid phase and do not melt as a result of the joining process.

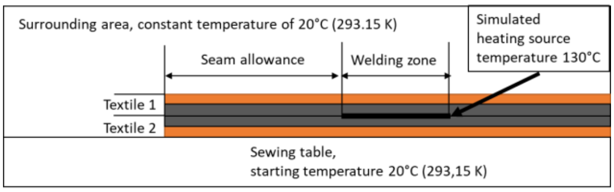

Figure 11. Thermal sources for numerical calculation in the model "lap seam"

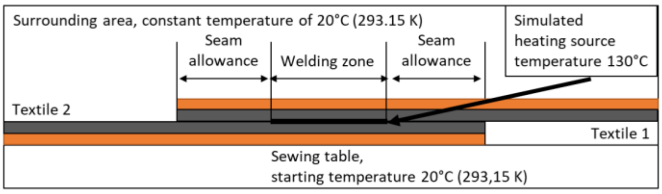

Figure 12. Thermal sources for numerical calculation in the model "flat seam"

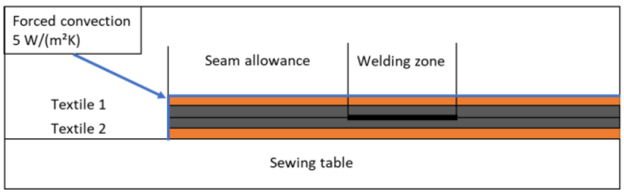

Figure 13. Thermal sources for numerical calculation around the model "lap seam"

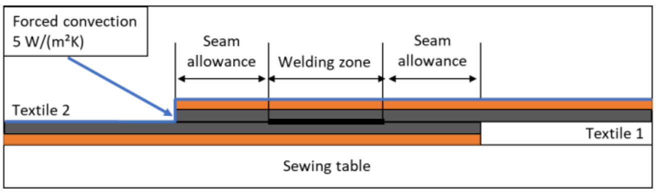

Figure 14. Thermal sources for numerical calculation around the model "flat seam"

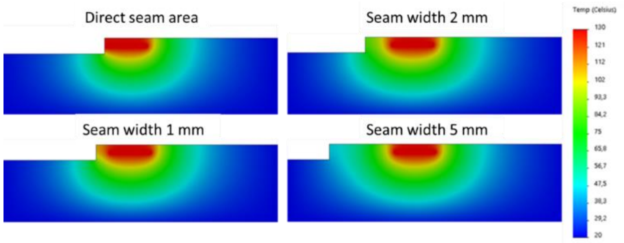

Figure 14. Thermal influence of the transfer width on the cooling behaviour of the textile plastic (stationary heat propagation; ambient temperature 20°, material combination TPU/PA-textile with solid substrate) for the model “lap seam”.

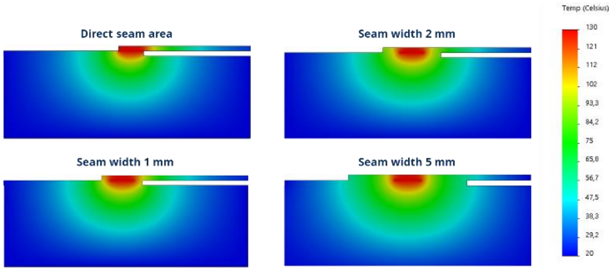

Figure 15. Thermal influence of the transfer width on the cooling behaviour of the textile plastic (stationary heat propagation; ambient temperature 20°, material combination TPU/PA-textile with solid substrate) for the model “flat seam”.

Practical experience has shown that with shorter seam allowances, the immediate boundary area to the joint melts in an uncontrolled manner and shrinks or is deformed by the additional mechanical loads, thus impairing the seam strength and quality. Figure 16 shows an infrared image of a continuous ultrasonic welding process with a seam spacing of 1 mm. In it, clear temperature differences are visible in the joining zone, which are caused by different cooling zones.

Figure 17 shows the thickness-temperature diagram for a continuous ultrasonic welding process. The different temperature curves are given for different energy intesities. It shows that there is a temperature maximum in the middle range (at 0.4 mm, which represents the joining range of the joining partners involved), which cools down accordingly towards the top and bottom of the joining partners. With a few exceptions, in particular the thickness of the assumed joining zone in the simulation, the tendens show similarities to reality with the initial numerical calculations.

Figure 18 below shows the numerical calculations for an alternative material combination for the "lap seam" and "flat seam" simulation models. The base fabric was replaced by polyester and the coating material by polyvinyl chloride. The polyester used has a higher thermal conductivity and thermal capacity than the polyamide, whereas the polyvinyl chloride used has a lower thermal conductivity and thermal capacity than the thermoplastic polyurethane (see Table 4). For the temperature propagation in and around the joining zone, this means that the thermal energy is passed on more strongly through the polyester. In practice, there would be a presumption that the joined sheet structures cool down faster than the joined sheet structures made of PA/TPU, which requires a change in the manufacturing parameters.

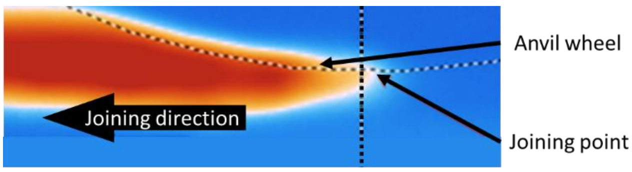

Figure 16. Infrared image of a continuous ultrasonic welding process with a seam spacing of 1 mm [6]

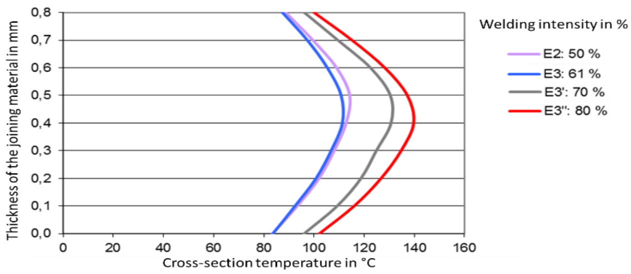

Figure 17. Temperature-thickness diagram for different single-energy intensities in the ultrasonic joining process [6]

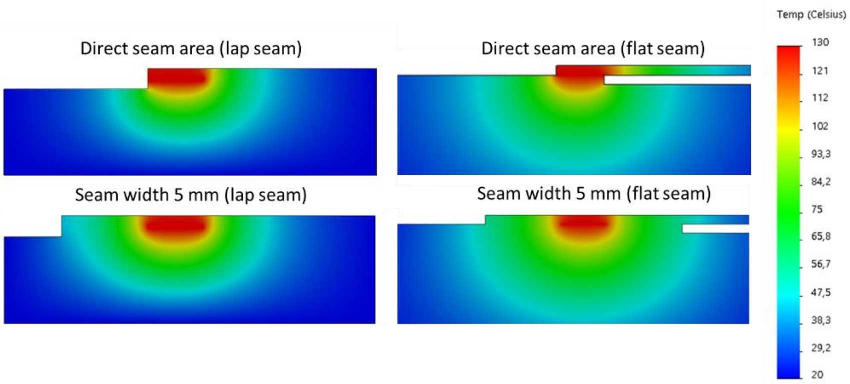

Figure 18. Different numerical calculations for the thermal influence of the material parameters thermal conductivity and heat capacity for the model "Lap seam" and "flat seam" for a seam allowance of 0 mm and 5 mm

The final numerical calculation serves to determine the influence of the joining temperature in the melting zone. For this purpose, the "lap seam" model with a seam spacing of 2 mm was selected and considered with different temperatures. The results of these numerical calculations are shown in Figure 19.

Figure 19 clearly shows that the increase in temperature significantly increases the cooling down area. In practice, this would mean that the seam allowance must also be increased to prevent damage to the joint. It also shows that at high joining temperatures, additional methods must be used to prevent the substrate from heating up.

4. CONCLUSION

By means of numerical calculation of the heat propagation during ultrasonic welding, information can be collected and processes can be represented in order to better understand the processes in the joining zone. This creates new options that can be used to increase process reliability and weld seam reproducibility for industry. However, the numerical calculation of textile ultrasonic welds is very challenging. In contrast to metals and other homogeneous materials, the textile material is a multidimensional hetrogenic material which can be strongly changed by environmental influences. Furthermore, the energy transformation processes between mechanical vibration energy and thermal energy are still not fully understood by science.

The numerical calculations carried out showed that a seam allowance of at least 5 mm is required for the selected material combination. By maintaining this minimum distance during ultrasonic welding, it is possible to keep the interface of the welded materials at room temperature and thus achieve a uniform design of the weld area. A smaller seam allowance will cause the interface to melt and the material to escape from the weld, which will significantly reduce the seam strength. This process cannot be reproduced with the current numerical calculation. For the representation of such processes, the existing numerical models must be executed as transient calculations.

The investigations in this article are a first step in the simulation-based investigation of ultrasonic textile welding. For further work and for a better understanding of the ultrasonic process, the existing model will be converted into a transient model.

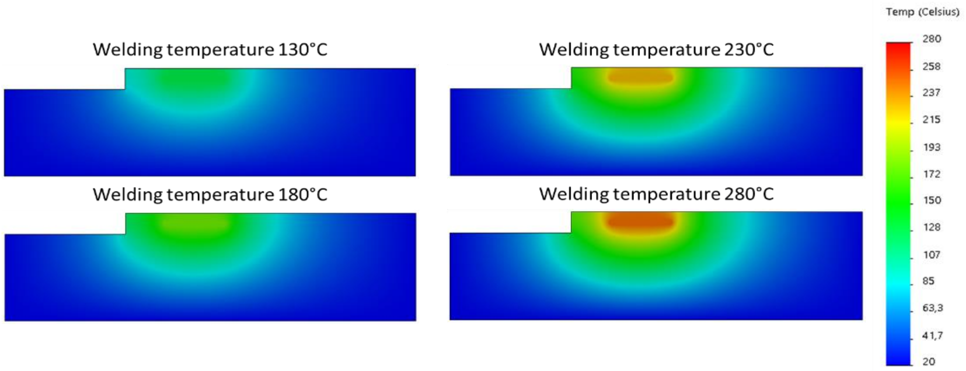

Figure 19. Numerical calculations on the influence of the joining temperature thermal conductivity and heat capacity for the "lap seam" models for a seam allowance of 2 mm and the initial temperatures of 130°C, 180°C, 230°C and 280°C

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