Temperature measurement in laser transmission welding of plastics

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INTRODUCTION

Laser transmission welding of plastics inflicts high thermal stress in the joint zone. Improper parameters can destroy the joint structure or result in thermal degradation of the polymer. Up to now, individual and time-consuming welding tests had to be conducted for finding reasonable process parameters if joining problems occurred. Depending on the individual problem, iteration loops might be necessary for designing a suitable joint geometry. Numerical simulations allow the prediction of the heat affected zone and the resulting maximum temperature. Such a thermal analysis of laser transmission welding permits an initial optimisation of the joining process in advance and helps to shorten the process development time. This paper presents a numerical model for the thermal characterisation of laser transmission welding to predict the temperature distribution and the heat affected zone. The model uses commercially available FE software. The simulation results are compared to temperatures measured with thermal imaging sequences at the front of the joint. The comparison shows a good correspondence between the simulation and the temperatures measured, especially for the maximum temperature. The calculated heat affected zone as well as the calculated temperature gradients exhibit a good accordance with the actual values too, but the limits of the measurement method in relation to discriminating small differences in temperature become obvious.

An increasing integration of functions in plastics components together with higher component functionality create the need for ever greater complexity. Joining methods, which can be mechanical, thermal or chemical/physical, often play an important role in these components.

Laser transmission welding is a thermal joining method which has been an established technique for welding plastics for many years. It is characterised primarily by a targeted energy input which is spatially confined, and by low thermal loading of the base material [1]. The temperature distribution during welding is of particular importance for the resulting bond. Thermal degradation of the base material, which would result in lower bond strength, must be avoided. Knowledge of the temperature distribution is also advantageous in micro-joining. Laser powers that are too high, and the associated intense heat, would destroy the microstructures being joined.

The potential of a thermal process simulation will be demonstrated below and the simulation model used will be tested for its suitability.

STATE OF THE ART

Laser transmission welding

In laser transmission welding, a part to be joined which is transparent to laser radiation is placed over an absorbing mating part in the desired final position and adequate joining pressure is applied. Most engineering plastics are transparent to radiation in the near infrared range, which is why Nd:YAG or diode lasers are often used in laser transmission welding, since their wavelengths of...
1064 nm and 808-980 nm respectively are in the near infrared range. The absorption properties are created using absorbent pigments, usually carbon black. Concentrations of carbon black are generally between 0.1 and 1 wt%, the laser energy being absorbed in layers close to the surface with higher concentrations and in layers further from the surface with lower concentrations of carbon black.

The laser transmission welding process can be described in terms of the energy density (Eq. (1)):

$$w = \frac{PL}{dF\upsilon_L}$$

$P_L$ describes the laser power, $d_F$ the focus diameter and $\upsilon_L$ the scanning velocity of the laser. For welding partially crystalline thermoplastics, significantly higher energy densities are needed than for amorphous thermoplastics. This can be explained by the scattering of laser radiation on spherulitic structures, leading to beam expansion and an increase in reflection.

**Principles of numerical simulation**

Many commercially available FE programs operate in three steps. In the pre-processor, the user defines the physics of the model, creates a finite element grid and specifies fundamental mathematical properties of the elements or shape functions. In the solver, detailed information on the solution algorithm of the discretised FE model must be specified and a simulation period defined. The post-processor provides routines which are used to enable the results to be visualised in an appropriate form.

In the case of thermal conduction problems, a distinction can be made between stationary and time-dependent problems. For time-dependent problems, the partial differential equation to be solved is as follows:

$$\rho c_p \frac{\delta T}{\delta t} + \nabla \cdot [-\lambda \nabla T] = \Phi$$

with the density $\rho$, the specific heat capacity $c_p$, the temperature $T$, the time $t$, the thermal conductivity $\lambda$, and the volume-specific source term $\Phi$.

The thermal conduction equation is discretised by creating a finite element mesh, thereby making it accessible to numerical calculation.

**SIMULATION OF LASER TRANSMISSION WELDING**

Laser transmission welding is simulated by working through the steps mentioned in 2.2 using Comsol Multiphysics software. A way must be found to link the mathematical description of the three-dimensional transient heat transport (Eq. 2) with the heat introduced by absorption of energy from the laser. At the same time, the polymer-specific material behaviour also has to be implemented by taking account of temperature-dependent thermal material values.

**Sample geometry**

The sample geometry to be investigated can be seen in Figure 1. The task lies in welding together a bar and a T profile to form an I profile. The bar represents the transmitting part and the T profile the absorbing part. The mating parts are fixed in a sample holder which also applies the joining pressure (Figure 2). Since the geometry has a plane of symmetry (Figure 1), this can be used to reduce the calculation time for the simulation.

During the welding process, very high temperature gradients occur in the area around the weld seam. This area is therefore regarded in the geometry as a separate zone with a thickness of 1 mm, which means that it will subsequently be easy to discretise this section particularly finely.

**Figure 1. Geometry of test pieces used for simulation**

**Figure 2. Laser transmission welding test setup**
Thermal material properties

Both of the mating parts are made of polycarbonate (Makrolon 2405 from Bayer MaterialScience). The thermal conduction equation requires a description of the thermal conductivity $\lambda$, heat capacity $c_p$ and density $\rho$. These parameters are defined as a function of temperature. Elementary mathematical functions can be used for this purpose, or discrete data (e.g. measured values) for which an interpolating function of the desired order is created. In the present case, the measured values were taken from the literature [4]. They were linked with piecewise linear polynomials.

Optical material properties

For the absorbing part to be joined, samples with varying carbon black contents were available. According to [5], the following simplifications can be used for implementation of the absorption properties in the simulation model:

- The absorption coefficient of amorphous plastics does not generally have a significant dependence on temperature, so it is sufficient to state it at ambient temperature.

- For the approximate determination of the shape and position of the melt zone geometry, the absorption behaviour of the transmitting part can be ignored. This results in a significant reduction of the calculating time.

- For carbon black concentrations greater than 0.02 wt% in the absorbing part, the absorption capacity of the polymer is negligible compared with that of the carbon black. Based on this assumption, the absorption coefficient behaves proportionally to the carbon black content and can be described approximately for any base polymers by a linear relationship.

Under these conditions, the absorption coefficient $\alpha$ can be determined for the absorbing part. It is needed for the subsequent description of the absorption of laser energy in the plastic (Eq. (3)).

For pure polycarbonate, as is present in the transmitting part, an almost constant curve can be observed for the transmittance as a function of material thickness [5, 6]. Since no data could be found in the literature on the interfacial reflection of electromagnetic radiation in the transition from the transmitting part to the absorbing part, the values for air/polymer and polymer/air were used. This resulted in a transmittance of 0.9 [5] for the transmitting part.

Process parameters, initial conditions and boundary conditions

The process parameters used for modelling are compiled in Table 1.

An initial temperature of 23°C (ambient temperature) is assigned to the mating parts. Heat transport takes place at the edges via radiation and convection. However, it may be assumed that this has no great influence on the result because of the rapid input of energy by the laser.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_z$</td>
<td>40</td>
<td>mm/s</td>
<td>Scanning velocity of laser</td>
</tr>
<tr>
<td>$P_{tot}$</td>
<td>10</td>
<td>W</td>
<td>Total laser power</td>
</tr>
<tr>
<td>$r_0$</td>
<td>0.75</td>
<td>mm</td>
<td>Radius of laser focus</td>
</tr>
</tbody>
</table>

Field conditions

The influence of heat generation in the transmitting part can be ignored in a first approximation because of the low coefficient of absorption [5]. Thus, the radiant power that is introduced is converted to heat only in the lower part, through absorption. Because of the axial movement of the laser, this can be interpreted as a heat source which “migrates” along the welding zone. Modelling the heat source requires the radiation distribution of the laser to be described as realistically as possible. The laser used for welding has a top-hat distribution and a focus diameter of 1.5 mm. This fact is taken into account in modelling and therefore a constant intensity distribution is assigned to the heat source over its cross section.

The source term $\Phi$, according to Equation (3), corresponds to the total differential of the intensity. The intensity $I_0$ is obtained from the laser power passing through the transparent part, based on the focus area (Eq. (4)). Now, to define the points in the laser focus on the one hand and to image the scanning velocity of the laser on the other hand, the circular laser focus moving with the scanning velocity $u_z$ is defined in Equation (5). By inserting Equation (4) into Equation (3) and multiplicative linking of Equation (3) with Equation (5), the laser absorption can be described as a variable heat source in the material with the source term $\Phi$ represented in Equation (6). This simplifies the treatment of laser absorption considerably.

$$\Phi = -\frac{dI}{dy} = \alpha(y) = \alpha l_0 e^{-\alpha y} \tag{3}$$

$$I_0 = \frac{P_{tot}}{\pi r^2} \tag{4}$$

$$x^2 + (z - u_z t)^2 \leq r^2 \tag{5}$$
This relationship clearly defines the points in the joining plane which are located within the laser focus for each point in time.

\[ \Phi = \alpha \frac{P_{\text{tot}} \tau}{\pi r^2} e^{\alpha (x^2 + |z - \nu z t|^2) \leq r^2} \]  

(6)

**Choice of element type and mesh generation**

The fineness of the finite element mesh greatly influences the calculation time and quality of the calculated solution. In the area around the weld seam, qualitatively speaking, very fine structuring of the grid is required in order to guarantee a good approximation of the temperature field owing to high temperature gradients. In regions not immediately adjacent to the weld seam, only very small temperature gradients can be expected because of the low thermal conductivity of polycarbonate, so that a coarse mesh is permissible there. To make it easy to achieve this structuring of the grid, tetrahedral elements are a good choice. By inputting the maximum element lengths for the area of the weld seam, these elements enable a suitable grid to be produced more or less automatically in the FE software, which is finely structured in the relevant area of the weld seam and coarse in less relevant areas.

As well as the grid structure, the choice of shape functions for the elements is also crucial. Linear tetrahedral elements generally have four degrees of freedom for temperature, while quadratic ones have ten. The higher accuracy of the quadratic approach is associated with longer calculation times. Nevertheless, because of the improved accuracy together with the high temperature gradients that can be expected, it makes more sense to choose the quadratic approach.

The number of elements actually needed for a good approximation cannot be predicted in advance, since no analytical solution to the problem exists. For this reason, a convergence study is conducted before producing the simulation results. This firstly requires the creation of a coarse finite element grid, the calculation of the associated solution and the evaluation of the temperature at one point at a fixed time. The grid is then refined and the procedure repeated. This is continued until no significant change in temperature at the point can be observed with further refinement of the grid. This grid then acts as the starting point for further simulations.

For the simulations presented here, a grid with 931,930 elements was used. The maximum element edge length in the area of the weld seam is 0.08 mm for this mesh.

**TEMPERATURE MEASUREMENTS IN LASER TRANSMISSION WELDING**

To verify the results obtained in the simulation, a suitable temperature measurement setup must be found.

In principle, temperatures can be determined by contact methods or contactless methods. The contact methods have the advantage of being in thermal contact with the object to be measured, and therefore after an equalisation time they display the temperature in thermal equilibrium. However, in the case of highly dynamic temperature curves, the contact methods of temperature measurement have a disadvantage, since they always experience a delayed reaction owing to their mass. Contactless methods of temperature measurement, particularly using radiation, do not have this disadvantage, but precise knowledge is needed of the emission coefficient of the object being measured in the wavelength range of the radiation thermometer.

The above disadvantages in terms of the dynamics of contact methods mean that they are of practically no use in laser transmission welding. Thermographic temperature measurement was therefore employed. Temperature recording took place on the front of the sample geometry using a thermal imaging camera (Figure 3). This measures in the wavelength range of 7.5 - 13 µm. Only those temperatures occurring at the edge of the sample geometry when the laser passes through were of interest. The thermographic temperature measurement required the determination of the emission coefficients of the plastics used for the wavelength range of the thermal imaging camera. A simple method of determining these is already contained in the software of the camera used, in which the emission coefficient for an object of known temperature is output directly by comparison with the measuring signal from the camera. The emission coefficients for polycarbonate are approx. 0.9 over large sections of the temperature range. Accordingly, a coefficient of 0.9 was used for all the measurements. This corresponds to the known behaviour of plastics of absorbing strongly in the mid-infrared range.

![Figure 3. Thermographic temperature measurement](image-url)
The sampling rate of the measuring sequences was 200 Hz and the object distance was 0.3 m. For the combination of the number of pixels of the detector matrix and the lens used, a minimum diameter of 0.2 mm was obtained for the test object. Thus, for the sample geometry under investigation, the test sector was divided into just ten zones. For high temperature gradients, therefore, interpolation errors may occur towards the edge zone.

COMPARISON BETWEEN MEASURED AND SIMULATED TEMPERATURES

With the above inputs, the calculations for polycarbonate were performed for various test parameters. An example of a temperature curve is shown in Figure 4. For comparison purposes, the measured temperatures are plotted on the diagram together with the simulated temperature curves. The calculation of the temperature curves for the maximum refers here to the front face in the plane of symmetry at different distances from the joining plane. The different distances from the joining plane are obtained from the shift in the maximum temperatures in deeper regions for lower carbon black contents. Although most of the laser energy is converted to heat at the surface of the absorbing part, the converted heat is largely dissipated into the transparent part by thermal conduction (greater temperature gradient towards the transparent part than to deeper regions which are also heated by the laser), resulting in the shift. The diagram also contains the temperature curve for a point shifted by 0.5 mm from the laser’s centre, which serves as a comparison with the temperatures measured to the left and right of the maximum temperature (Figure 5). Overall, Figure 5 compares the simulated with the measured temperature distribution.

The temperature curves for the simulated and measured maxima largely coincide. This is true of both the position of the maximum and the heating and cooling phase (Figure 4). It applies particularly to combinations of parameters in which no material damage is to be expected, i.e. to maximum temperatures below 600°C. In this case, the position of the maximum temperature can be calculated very precisely for energy densities of up to 0.25 J/mm². For energy densities of 0.375 J/mm² and above, the calculated position of the maximum temperature deviates significantly from the maximum that was actually determined, as the calculated temperatures for high energy densities are in some cases several hundred °C higher than the measured temperatures. There are two possible explanations for the large deviations with higher energy densities. On the one hand, there may be an error in the measured temperature curves for temperatures higher than 660°C, since only temperatures of up to 660°C can be represented in the temperature range used by the thermal imaging camera, although the actual temperatures may be higher. For actual temperatures higher than 660°C, therefore, only T>660°C is output. On the other hand, material damage with degradation and gas emissions is not taken into account in the simulation model. Thus, for temperatures over 600°C the simulation still solves the thermal conduction equation for a homogeneous material, which may explain the large discrepancies.

The temperature curves for the points outside the plane of symmetry only coincide with the measured curves to a limited degree. This can be put down to the limited spatial resolution of thermographic temperature measurements. Although the points for evaluating the temperature curve were not changed for the individual measurements, the temperature cannot be measured accurately because of the high temperature gradients in the joining plane. Another reason for the marked differences may be the flowing of melt in the joining plane. This results in hot melt moving out of the centre into edge zones, which leads to higher temperatures for these zones.

![Figure 4. Laser transmission welding – simulated and measured temperature curves*](image)

![Figure 5. Thermographically measured and simulated temperature distribution in the welding zone immediately after passage of the laser](image)
The formation of the heat affected zone is reflected well by the simulation model in terms of position (Figure 5). The lateral expansion, on the other hand, only coincides with the measured dimensions to a limited degree. This is also based on the melt flowing in the welding zone, since the observed heat affected zone is larger than the calculated one.

CONCLUSIONS

To make laser transmission welding accessible to thermal simulation, both the thermal and the optical properties of the thermoplastics used must be determined. In addition, temperature-dependent material values enable the simulation to be adapted to the thermal behaviour of thermoplastics, allowing greater accuracy to be achieved in the results.

Simulation of laser transmission welding is simplified considerably by the assumption that the heat input is regarded as a moving heat source in the material. In this way, only the thermal conduction equation needs to be solved in the simulation.

To validate the model developed here, joining tests were performed in which the temperatures occurring were measured using a thermal imaging camera positioned in front of the joining assembly. This showed that the accuracy is very good for the joining parameters selected in the lower energy density range. For higher energy densities and in the edge zones of the model, there is still room for improvement. The three-dimensional view enables the maximum temperatures to be predicted as well as providing information on the size of the welding lens.

Future work is planned on implementation of beam scattering in partially crystalline plastics and the simulated coupling of thermal and mechanical behaviour. This will lead to a significant increase in the model accuracy, which will enable the user to design components which are more suitable for laser welding.

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