POTENTIALS OF THE ALE-METHOD FOR MODELING PLASTICS WELDING PROCESSES, IN PARTICULAR FOR THE QUASI-SIMULTANEOUS LASER TRANSMISSION WELDING

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ABSTRACT

The Arbitrary-Lagrangian-Eulerian-Method (ALE-Method) offers the possibility to model the quasi-simultaneous laser transmission welding of plastics, in which a squeeze-flow of molten plastic occurs. It is of great interest to get a deeper understanding of the fluid-structure-interactions in the welding zone, since the occurring squeeze-flow transports heated material out of the joining zone, causing a temperature decrease inside. In addition, the numerical modelling offers the possibility to investigate the flow conditions in the joining zone. The aim of this article is to show the potentials of the ALE-Method to simulate the quasi-simultaneous laser transmission welding with the commercially available software LS-DYNA. The central challenge is to realize a bi-directional thermo-mechanically coupled simulation, which considers the comparatively high thermal expansion and calculates the interactions of solid and melted plastic correctly. Finally, the potentials of the ALE element formulations for the mathematical description of welding processes are shown, especially for those with a squeeze-flow.

Keywords: Arbitrary-Lagrangian-Eulerian, squeeze-flow, plastics welding, laser transmission welding, friction welding, stud welding

INTRODUCTION

Laser transmission welding is an established joining technique for thermoplastics and used in many industrial sectors, such as automotive or electronics industry. The two joining partners are clamped in an overlap and irradiated along the weld trajectory with a high feed rate (v > 0.5 m/s) for several scan repetitions (see Fig. 1 top left).

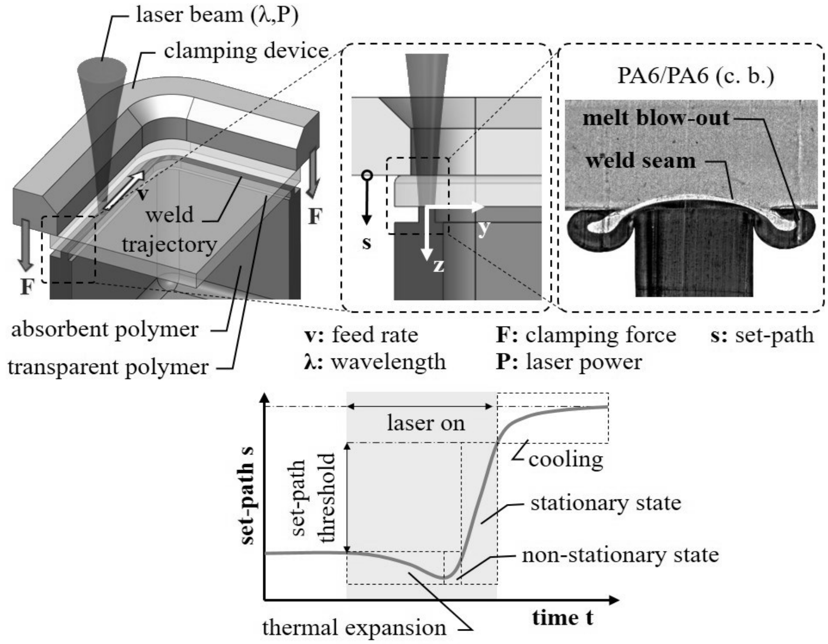

Fig. 1 Principle of quasi-simultaneous laser transmission welding: a typical geometry with a clamping device (top left), a thin-cut of a typical weld (top right) as well as a sketch of the measured set-path with the process states (bottom).

The laser radiation is mainly transmitted through the upper and absorbed by the below placed joining partner close to the interface, since this one is filled with carbon black (c.b.). As far as the joining partners are in contact, heat is transferred via heat conduction, which also causes the melting of the upper joining partner. Typically, the movement of the clamping device is measured during welding and named as set-path (s). Immediately in the beginning, thermal expansion occurs, which leads to negative data of the set-path (see Fig. 1, bottom). By performing further scan repetitions, the material is more and more softened, which leads to a squeeze-flow of the material, as soon as the stiffness of the material falls below a critical softening level. Later on, a continuous squeeze-flow is seen, and the set-path shows a linear course (see Fig. 1, bottom). The laser is switched off, until a predefined set-path threshold is reached, leading to cooling of the weld, which is seen in a digressive progression of the set-path. A typical joining zone of a PA6/PA6-weld with the weld seam and the melt blow-out is seen in a thin-cut in Fig. 1 (top right).

It is expected that the joint strength depends on the squeeze-flow conditions in the interface, as also seen in hot plate welding [1]. By measuring the velocity of the squeeze-flow, using tracer particles and x-ray radiation, it is found out by FARGAS RIBAS [2], that high joint strengths are achieved, if the squeeze-flow velocity in the centre of the weld is nearly equal to the one nearby the melt blow-out. Since the herein shown measurement does not allow the investigation of the interaction between temperature field and squeeze-flow velocity, it is of great interest to build up a thermo-mechanically coupled process model, in order to get a deeper process knowledge.

The squeeze-flow leads to large deformations in the simulation, whereby finite elements get highly distorted. For this reason, the entire process cannot be computed properly by using a standard Lagrangian element formulation, as seen in previous studies [3]. This issue can be bypassed by employing an element formulation that bases on the Arbitrary-Lagrangian-Eulerian-Method (ALE).

By using ALE, each time-step is divided in a Lagrangian step and an advection cycle. In each Lagrangian step the mesh follows the deformation of the material. In the advection cycle, the mesh is transferred to a spatially fixed mesh by using an Eulerian technique. In the upcoming Lagrangian step the deformation of the material is calculated using a better mesh compared to simulations without a remapped mesh. By this, high element distortions, which are leading to a cancellation of the computation, can be avoided [4].

In this paper the element formulations Multi-Material-ALE (MMALE) and Single-Material-ALE with Void (SMALE-WV) are used to model the quasi-simultaneous laser transmission welding process. As an outlook, the potentials of the ALE-Method for modelling other welding processes are discussed.

PROCESS MODELLING USING MULTI-MATERIAL-ALE

In the following, two process models with Multi-Material-ALE formulation (MMALE) are described exemplarily for a typical quasi-simultaneous welding and compared with each other, in order to demonstrate the capabilities of the process models.

PROCESS MODEL WITH SOLID AND FLUID PARTS

In general, the MMALE allows the usage of multiple solid and fluid material models in one coherent ALE mesh. By this, the interaction of solid and fluid parts can be simulated, correctly. Thus, it offers the possibility to model the quasi-simultaneous laser transmission welding at a certain time, at which a specific proportion of solid and a fluid material phase is already given. The flow conditions as well as the shape of the resulting melt blow-out can be investigated.

In order to divide the joining partner in fluid and solid parts, a thermal simulation is performed beforehand, using ANSYS. The shape of the fluid material-phase is marked by the computed isotherm of the melting temperature, which can be extracted at a specific time. Due to the high feed rate, 2D Finite-Elements are used, since the temperature does not vary significantly in feed direction, as seen in previous studies [3]. The absorbed radiation, which is equal to a volumetric heat, is implemented in the analysis using Eqn. (1):

$$Q(\mathrm{y,z,t}) = \frac{8\cdot\alpha\cdot P}{\pi\cdot d^2}\cdot \exp\left(-\alpha\cdot z - 8\cdot \frac{(x_0 - v\cdot t)^2 + y^2}{d^2}\right) \tag{1}$$

In this formula Q is the local heat generation rate (W/mm³), P the total power of the laser (W), α the absorption coefficient of the material (1/mm), d the laser beam diameter (mm), x_0 the starting position of the laser (mm) and v the feed rate (mm/s).

One scan repetition of the laser is modelled in two steps. In the first step, the temperature field is calculated by considering the volumetric heat. In the second step only the heat transfer by heat conduction is calculated. This procedure is repeated alternately, until a simulation-time of 2.3 s is reached. At this time, it is known from the set-path course of the welding, that the stationary process state is reached. That is why this simulation time is chosen. The resulting temperature field is then used to model the shape of the solid and the fluid phase, since the melting temperature correlates with the change of solid to fluid behaviour (see Fig. 2). Thus, the below placed joining partner as well as the upper joining partner are separated into different parts. For each joining partner a solid and a fluid part is modelled, according to the precomputed temperature field (see Fig. 2).

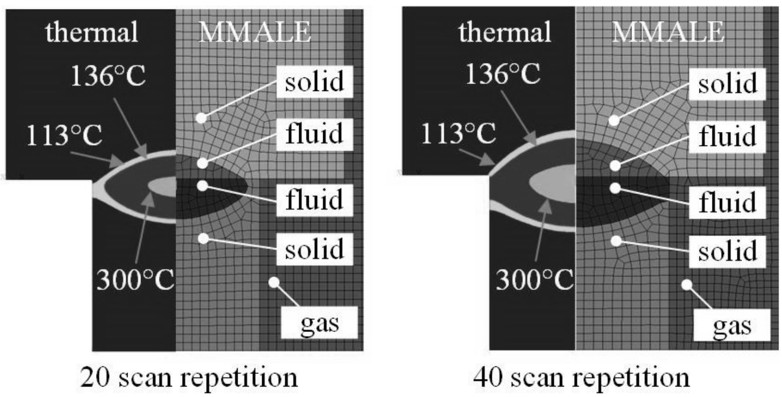

Fig. 2 Precomputed temperature field using ANSYS and the MMALE-Model with fluid and solid parts at two different scan repetitions (left and right).

The ambient air in the surrounding is modelled as a gas using *MAT_NULL. Since contact definitions between parts are not supported using the MMALE formulation in LS-DYNA [5], the only way to connect the parts is to merge the coincident nodes of all parts. A rigid body is used to implement the clamping force on the top side of the upper joining partner. The viscosity of each fluid part is extracted from literature. The solid parts are modelled using a simple elastic material model.

Fig. 3 shows the local velocity of the melt flow in the horizontal direction. The melt flow is more and more squeezed out with increasing simulation-time (see Fig. 3, bottom). The computation of an equilibrium-state, at which the deformation does not further increase would be ideal, but cannot be realized since an explicit solver has to be used. Hence, the simulation-time does not correspond with the physical time. By comparing the shape of the squeeze-flow with a thin-cut of the welding, a good match is seen.

In the beginning, mainly material of the below placed joining partner is squeezed out (Fig. 3, bottom left). Later on, melt of the upper joining partner is also squeezed out (Fig. 3, bottom right). In general, the fluid fraction of the below placed joining partner nearby the melt blow-out is significantly bigger compared to the one in the upper joining partner. By this, the squeezed out volume per time is much bigger in the below placed joining partner compared to the upper one. This seems to be realistic, since in quasi-simultaneous laser transmission welding the highest velocity is very close to the interface of the joining zone, since there are high temperatures. The squeeze-flow of the upper and the below placed joining partner are sticking together, once they get into touch, which is caused by adhesion forces. By this, the melt flow of the below placed joining partner is flowing around the one of the upper joining partner. This effect is also seen in the simulation results, even though the fluid parts are assigned with one single viscosity, which is not temperature-dependent (see Fig. 3, right).

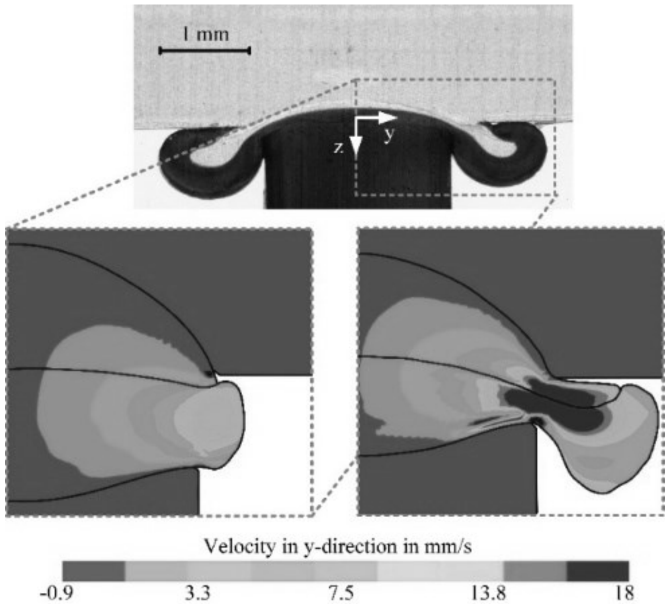

Fig. 3 Thin-cut of a weld (top) and the velocity in y-direction in early (bottom left) and later stage of analysis (bottom right), both computed in an Multi-Material-ALE simulation.

By using a MMALE simulation with predefined fluid and solid parts, the resulting shape of the melt blow out can be analysed in dependence of the used process parameters. However, a distinct disadvantage is that the material properties are approximated roughly by defining parts as either solid or fluid. Additionally, there is no coupling from the mechanical to the thermal analysis and the simulation-time only reproduces a fraction of the whole welding process.

PROCESS MODEL WITH TIME-DEPENDENT TEMPERATURE DISTRIBUTION

In order to compute the entire welding process more accurately, the time-dependent temperature distribution must be considered. By this, the time-dependent temperature field has to be implemented as a boundary condition using time-dependent temperature data. Here, the joining partners are modelled as two parts, which are described with a thermo-elastic material model. The geometry of the fluid and the solid material-phase is not user-defined, but derived by the model itself, using the already mentioned precomputed temperature field as a boundary condition.

Compared to the before mentioned MMALE-model with predefined solid and fluid parts, it can be observed, that a smooth transition between solid and fluid material-phase is realized, which is a better approximation of the real conditions during welding.

Since in Multi-Material-ALE a Finite-Element can contain material of multiple parts, the predefined temperature is allocated to the material of both joining partners. The implementation of a thermal analysis in the MMALE-model would require, that every node has to store several temperatures for the different parts. Currently, LS-DYNA only allows the calculation of one temperature per node, by which a bi-directional thermo-mechanically coupled simulation cannot be realized[1].

PROCESS MODELLING USING SINGLE-MATERIAL-ALE WITH VOID

The Single-Material-ALE with void (SMALE-WV) is a special type of the Multi-Material ALE-Method, which only allows the use of one material model for ALE parts. Like in an ordinary Multi-Material formulation, Finite-Elements can be partially filled. The empty space within elements is defined as void, which does not interact with the material. Thereby, one Finite-Element can contain material and void. To obtain a proper thermal and mechanical behaviour of the joining partners in solid and fluid phase, a nonlinear thermal and a temperature dependent nonlinear mechanical material model are chosen.

COMPUTATION AND IMPLEMENTATION OF THE HEAT GENERATION RATE

For the mechanical simulation using ALE, only an explicit solver can be used, whereas for the thermal simulation an implicit solver is used. Thus, the applicable time steps between thermal and mechanical analysis differ significantly. The movement of the laser in quasi-simultaneous welding produces a time-dependent heat generation. Caused by the high feed rate of the laser beam, small time steps have to be used when implementing a time-dependent load.

To achieve a correct heat generation rate, which is independent from the thermal time step, an energy equivalent volumetric heat generation rate is computed by integrating Eqn. (1) over time, and refer it to a time t_P, in which the laser beam is guided once along the trajectory, coming to Eqn. (2).

$$Q_{eqv}(y,z) = \frac{1}{t_P} \int_0^{t_P} Q\,(y,z,t)\; dt \tag{2}$$

Using an equivalent volumetric heat generation rate in the simulation means that the entire weld trajectory is heated continuously and simultaneously. Since Eqn. (1) can be divided in a time-dependent and a time-independent term (see Eqn. (3))

$$Q\,(y,z,t) = \underbrace{\frac{8\cdot\alpha\cdot P}{\pi\cdot d^2}\cdot \exp\left(-\alpha\cdot z - 8\cdot \frac{y^2}{d^2}\right)}_{\text{time-independent}} \cdot \underbrace{\exp\left(-8\cdot \frac{(x_0 - v\cdot t)^2}{d^2}\right)}_{\text{time-dependent}} \tag{3}$$

, Eqn. (2) can be simplified, leading to Eqn. (4)

[1] According to a statement of LSTC Inc.

$$Q_{eqv}(y,z,t)=\underbrace{\frac{8\cdot\alpha\cdot P}{\pi\cdot d^2}\cdot\exp\left(-\alpha\cdot z-8\cdot\frac{y^2}{d^2}\right)}_{\text{time-independent}}\cdot\underbrace{\frac{1}{t_P}\int_0^{t_P}\exp\left(-8\cdot\frac{(x_0-v\cdot t)^2}{d^2}\right)dt}_{\text{time-dependent}} \tag{4}$$

, which is a combination of Eqn. (2) and Eqn. (3). The time-dependent term is named as equivalency factor γ and can be solved separately by computing Eqn. (5).

$$\gamma=\frac{1}{t_P}\cdot\int_0^{t_P}\exp\left(-8\cdot\frac{(x_0-v\cdot t)^2}{d^2}\right)dt \tag{5}$$

Since no analytic antiderivative for this term exists, it has to be solved by numerically or symbolically methods.

VERIFICATION OF THE THERMO-MECHANICAL COUPLING

Because the laser beam is larger than the width of the absorbent joining partner, the melt flow which leaves the joining zone is also heated during welding. By using SMALE-WV, the thermal energy is transported with the squeeze-flow, whereby the heating is taken into account. To check this, a T-joint geometry with an initial temperature of 150 °C in a square formed section is predefined (see Fig. 4, left).

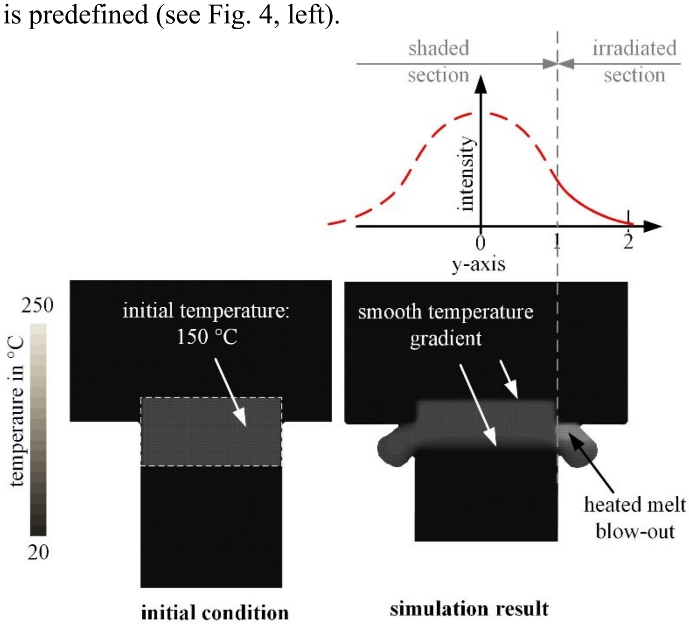

Fig. 4 Temperature field of a T-joint geometry with an initial temperature of 150 °C in a square formed section and 20 °C in the surrounding (left) as well as the resulting temperature field after the melt is squeezed out of the joining zone and heated on the right-sided melt blow-out (right).

The thermo-mechanically coupled simulation is solved, whereby a typical clamping force and a heat generation only on the right-sided melt blow-out is applied (see Fig. 4, right). In reality this would mean, that the rest of the joining zone is shaded, as can be seen on the solid and dashed line of the intensity distribution (see Fig. 4, top right).

The melt flow is squeezed out of the joining zone and again heated outside of the initial geometry (see Fig. 4, right). Also the steep gradient on the boundary of the initially assigned temperature is smoothed due to heat conduction (see Fig. 4, right). In conclusion it can be stated, that a bi-directional coupling is realized.

COMPARISON BETWEEN COMPUTED AND MEASURED DATA

In order to verify the process model, the measured set-path progression is used for a comparison with the computed deformation. Fig. 5 shows the measured set-path (s) for a welding with typical process parameter settings in comparison to the computed deformation. The characteristic course in the three process states (non-stationary, stationary and cooling) are also reproduced in the simulation. At first, the set-path is reaching a negative value, caused by the thermal expansion. With increasing irradiation time the material nearby the joining zone is more and more softened until it is squeezed out, which corresponds with a positive progression of the set-path. The typical linear trend of the set-path is represented as well as the decreasing course in the cooling state, in which the laser is switched off.

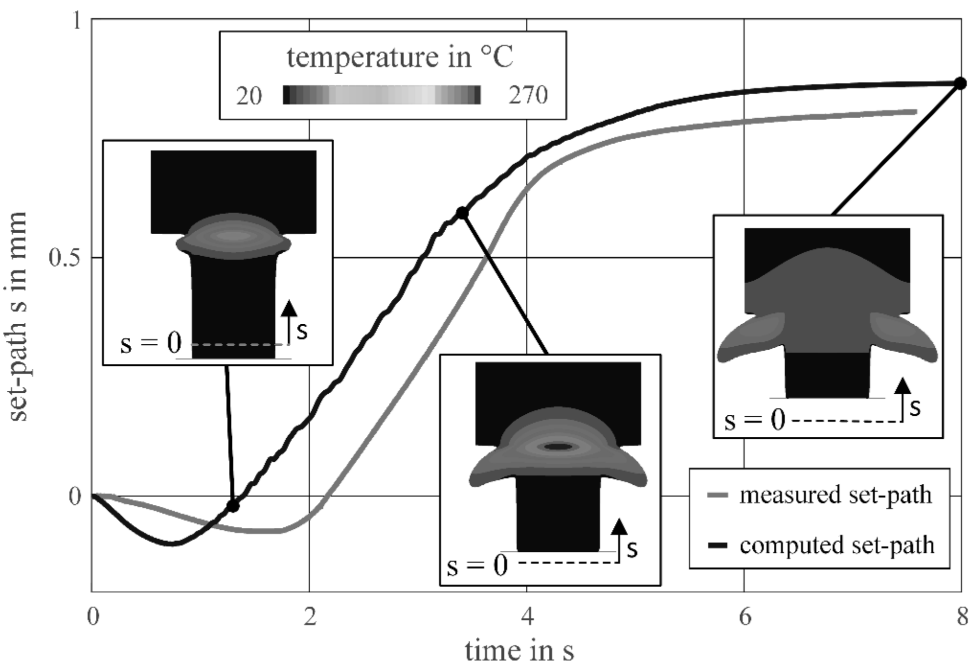

Fig. 5 Comparison of the measured set-path during quasi-simultaneous laser transmission welding with the computed deformation using Single-Material-ALE with Void.

Since the coincident nodes of both parts have to be merged, no separation between the joining partners is allowed. However, previous studies (see Ref. [6]) show, that gaps between the joining partners arise. This is caused by a higher thermal expansion in the centre of the welding, compared to the boundary. Since no separation between the joining partners is allowed by using SMALE-WV, tensile stresses appear in the contact zone and prevent the gap from opening. As a consequence, more heat will be transferred from the below placed joining partner to the upper joining partner using SMALE-WV compared to the real welding, caused by the larger contact area. This effect might be negligible, if the intensity distribution in the joining zone is quite homogenous, whereby almost no significant gap area exists.

It is seen in thin-cuts (see Fig. 3), that the squeeze-flow is concentrated very close to the joining interface, which is not reproduced in SMALE-WV as realistic as in Multi-Material-ALE, as seen by comparing the shape of the melt blow-out in Fig. 3 and Fig. 5. This is also mainly caused by merging coincident nodes.

Nevertheless, all process states are reproduced properly using SMALE-WV, since a bi-directional coupling can be realized in contrast to MMALE. This makes the SMALE-WV to a promising tool for investigations concerning temperature field, flow condition and residual stresses.

POTENTIALS OF THE ALE-METHOD TO MODEL WELDING PROCESSES

In some welding processes for metals (e.g aluminium or steel) the same deformation is seen like in quasi-simultaneous laser transmission welding of thermoplastics. For instance, stud welding, friction welding or flash welding are welding processes where also material is heated and squeezed out during welding. If the commonly used Finite-Element-Method with standard Lagrangian element formulation is applied to model these processes, the deformation of the mesh is inherently limited by the simulation technique itself, as it is demonstrated for friction welding in Ref. [7]. As a result, the shape of the welding bulge does not fit to the real shape very well, as reported by PETROPOULOS et. al [8]. Especially for stud welding the subsidence of the bolt in the molten pool of the component is of interest (see Ref. [9, 10]), but actually not modelled in a sufficient accuracy by using the Finite-Element-Method.

Using the Arbitrary-Lagrangian-Eulerian element formulation, which is commercially still available, one can overcome the limitations caused by high distortion of the mesh, which makes it to a promising tool for modelling welding processes in which a squeeze-flow of molten material occurs.

SUMMARY

Modelling the squeeze-flow of molten material in quasi-simultaneous laser transmission welding is crucial, in order to realize a process model with a high accuracy. However, the Finite-Element-Method with standard Lagrangian element formulation restricts the process modelling, since the mesh is highly distorted as far as a squeeze-flow occurs, which leads to a cancellation of the simulation. By using the Arbitrary-Lagrangian-Eulerian element

formulation, this limitations are no longer given. In this paper the so called Multi-Material-ALE (MMALE) and the Single-Material-ALE with void (SMALE-WV) are used to model the quasi-simultaneous laser transmission welding. It is found that by using both techniques, the squeeze-flow can be analysed. The MMALE is restricted to a uni-directional thermo-mechanically coupling, whereas the SMALE-WV allows the realization of a bi-directional coupling. This means, that the initial temperature of the melt is transported by the squeeze-flow and can be reduced by heat conduction or increased again by an absorbed laser radiation. A verification study has shown, that the typical process states, indicated by the course of the set-path, are also seen in the computed deformation.

In an upcoming step the simulation has to be validated on several process parameter settings, in order to evaluate a suitable material model and parameterize it precisely. The aim is to compute the temperature field, the deformation as well as the residual stresses and link it to the joint strength, in order to identify the best process parameter setting. Since in many welding processes a squeeze-flow of molten material is also seen, the ALE-Method is found to be a promising technique to model such welding processes.

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