Numerical optimisation of the temperature field for the prevention of solidification cracking during laser beam welding using the multi-beam technique

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1 Introduction

The idea to use additional heat sources as a mean for prevention of the solidification cracking in welds was suggested in the 70-s [1-2]. On the basis of FEM-simulations some works [1, 3] have demonstrated, that introducing the additional heating "in a right place and at the right time [1]" leads to the "beneficial" compressive stress (or strain) in regions, which are critical with respect to the solidification cracking. The parameters of the additional heat sources were found either through trial and error or prescribed intuitively.

In spite of the apparent simplicity of the suggested idea, the additional heating has still not found the expected industrial application. The determination of "the right place and the right time", i.e. the optimal position, the size and the power of the additional heating spots, seems therewith the most important problem hindering the practical application of the suggested technique.

The problem of determination of the proper parameters for the additional heat sources relates to the class of optimization problems, since the solution (parameters of the additional heat sources) must be obtained from the prescribed results (compressive stress or strain in a certain place). In previous works the present authors have introduced the general methodology for solving the optimisation problems specific for welding [4]. In this work, on the basis of the simplified models we try to demonstrate how the optimisation approach can be applied for the solution of problems concerning the determination of the optimal parameters for the additional heat sources by the multi-beam laser welding.

2 Mechanism of the cracking prevention by multi-beam welding

Experimental observations of the crack surfaces [5-6] indicate that the solidification cracking occurs in the solid-liquid region of the weld, i.e. in the mushy zone (Fig. 1a). The reason is the critical tensile strain [5], which leads to the tearing of the not completely solidified grains of the base material. Prevention of the solidification cracking can be principally achieved due to the application of additional beams. An additional heating in the critical region would cause compressive strain in the mushy zone and suppress the crack initiation (Fig. 1b). It is obvious that the optimal parameters of the additional beams (position, size, power) should be found in order to achieve the maximal compression in the mushy zone. On the other hand, an additional heating "in not a right place" can even enhance the solidification cracking.

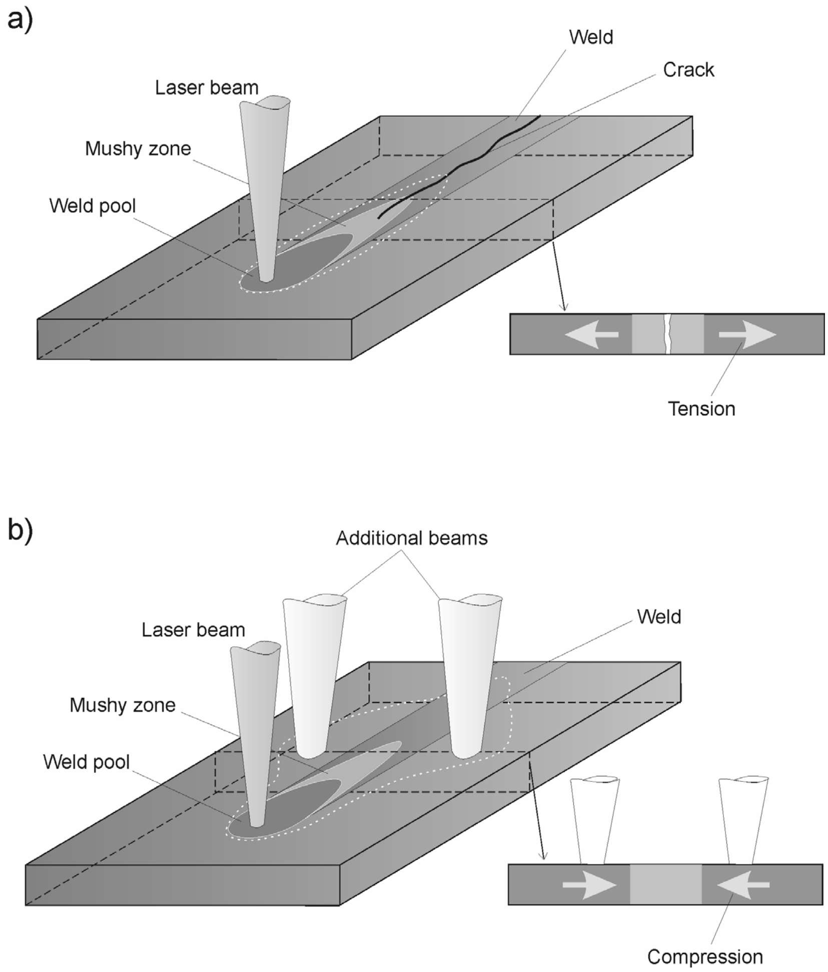

Figure 1: An initiation of the solidification crack in the mushy zone due to the transverse strain by the conventional laser welding (a) and prevention of the crack initiation due to the local heating by the multi-beam laser welding (b).

3 Model

3.1 Temperature field

The temperature field by the multi-beam laser welding process is simulated using a semi-analytical solution which takes into account the influence of additional heat sources. Two additional beams are assumed to move behind the main beam with the same velocity as shown in Fig. 2. The net power of each additional beam q_{add} is evenly distributed over a circular heating spot (domains D_1 and D_2, Fig. 2). The temperature field can be expressed using the method of the Green's functions [7] as follows:

$$T(x,y) = \frac{q/s}{2\pi\lambda}\exp(\frac{vx}{2a})K_0\left(\frac{v\sqrt{x^2+y^2}}{2a}\right) + T_{add}(x,y) + T_0 \tag{1}$$

where $T_{add}(x,y)$ is the temperature increase due to the additional heat sources:

$$T_{add}(x,y) = \frac{1}{2\pi\lambda}\frac{q_{add}/s}{\pi r_{add}^{\ 2}}\iint_{D_n}\exp(\frac{v(x-\xi)}{2a})K_0\left(\frac{v\sqrt{(x-\xi)^2+(y-\eta)^2}}{2a}\right)d\xi d\eta \tag{2}$$

where r_{add} is the radius of a heating spot, $D_n = D_1 \cup D_2$ is the total domain of additional heating spots.

Using equations (1) and (2) the values of temperature are calculated numerically for each point of the welded plate.

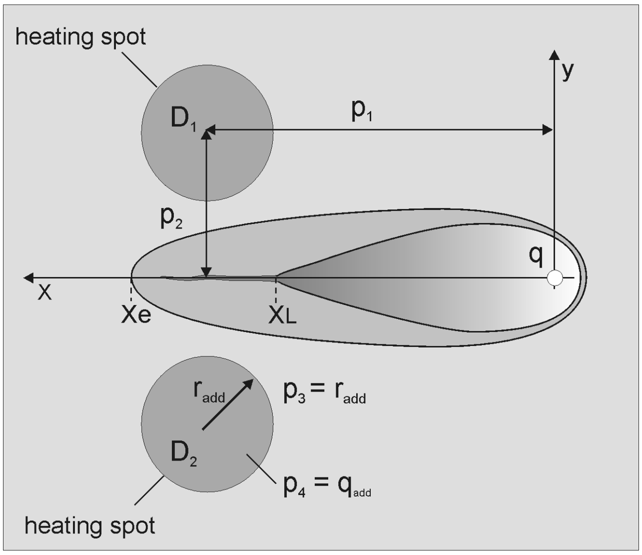

Figure 2: Parameters of the multi-beam laser welding.

3.2 Strain accumulated in the mushy zone

The transverse strain, which is accumulated in the mushy zone, can be roughly evaluated using the strip expansion technique [8-9] as shown in Fig. 3. According to this method the welded plate is divided into narrow stripes. Each strip is assumed to deform independently. It is further assumed that the boundaries of the mushy zone are defined by two isotherms, which correspond to the liquidus and to the eutectic temperature. The last assumption applies to an eutectic alloy system and takes into account the effects of segregation in the mushy zone. The half value of the transverse strain Y_{op} (opening) accumulated in the mushy zone along the weld centreline can be obtained using the following expression (see Fig. 3):

$$\mathrm{Y}_{\mathrm{op}}(x\ ) \ = \ \int_0^B \left[\alpha T(x_L, y) - \alpha T(x\ , y)\right]\, dy \tag{3}$$

where x_L is the x-coordinate of the liquidus boundary; B is the distance from the centreline to the restraint and α is the thermal expansion coefficient (it can be temperature dependent).

Numerical integration of the equation (3) using equations (1) and (2) gives the values of the strain accumulated in the mushy zone by the given thermal conditions.

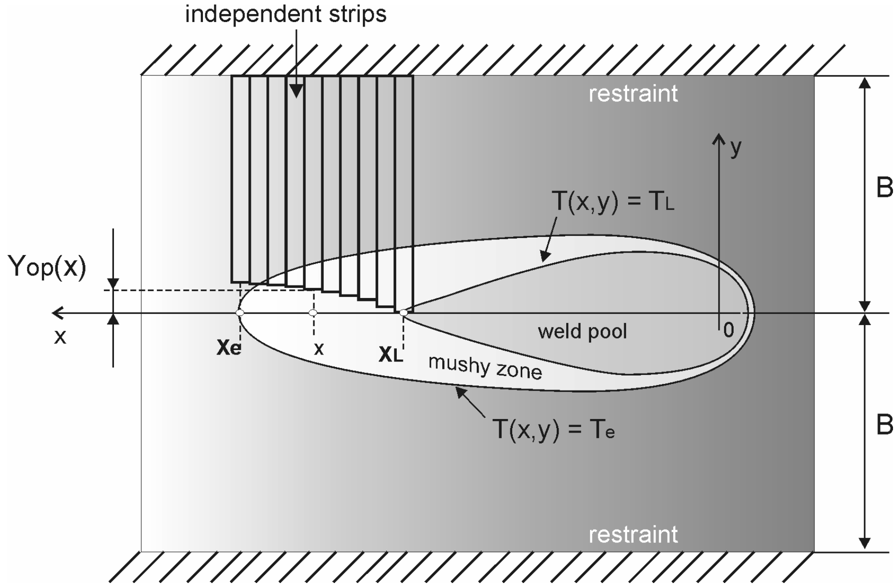

Figure 3: Schematical illustration of the strip expansion technique.

4 Optimisation problem and results

In order to find the optimal position and parameters of the additional beams, the following optimisation problem was solved. The strain accumulated in the last point of the mushy zone $Y_{op}(x_e)$, where x_e is the x-coordinate of the eutectic boundary, was taken as an objective function. The optimisation task was to minimise the objective function $Y_{op}(\boldsymbol{p})$, where $\boldsymbol{p}$ is the vector of design variables, $\boldsymbol{p} = \{p_1, p_2, p_3, p_4\}$, which specifies the position, the size and the power of the additional heat sources (see Fig. 2). In addition, the following constraints were introduced in the calculation algorithm:

1) $p_2 \geq p_3$

2) $\mathrm{p}_2 + \mathrm{p}_3 \leq \mathrm{B}$

3) $\mathrm{T}_{\max}(\mathrm{x},\mathrm{y}) \leq \mathrm{T}_{\mathrm{S}} \qquad x, y \in D_n$

Inequality constraints 1 and 2 describe the separation of the heating spots from one another and from the mechanical restraint (Fig. 3). Constraint 3 requires non-melting in the region of additional heating.

The non-linear optimisation problem described above is solved in iterative fashion [4]. The temperature fields for the welds with and without additional heat sources are shown in Fig. 4. The half value of the transverse strain, which is accumulated along the weld centreline, is calculated for these welds from the beginning to the end of the mushy zone (Fig. 5).

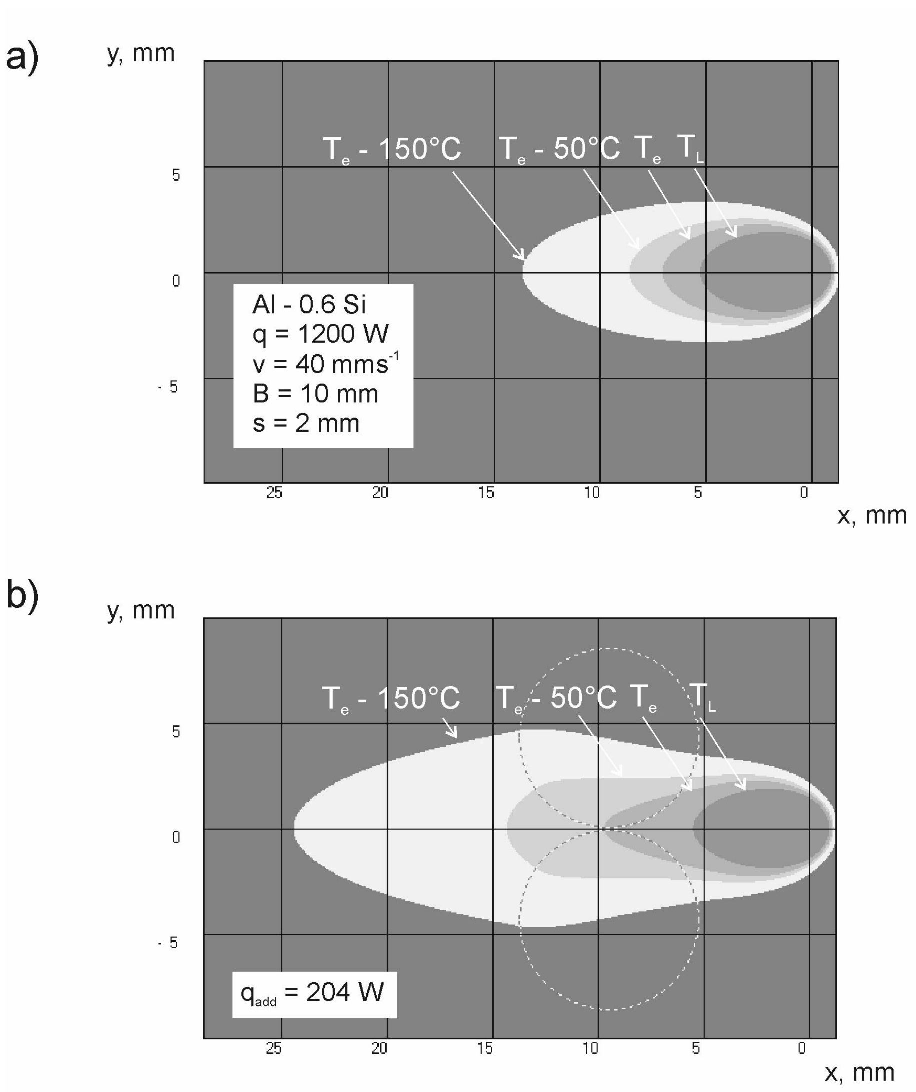

Figure 4: Calculated temperature fields for a weld produced (a) without and (b) with additional heating under the optimized parameters of the additional beams (the parameters of the main beam are constant for both cases).

Although the total amount of power introduced by the additional beams is less than 20% of the main beam power, the effect on the transverse strain in the mushy zone is drastic. In the weld produced without additional heating, the transverse strain increases from the beginning to the end of the mushy zone. If the additional beams are applied, the accumulated strain quickly reaches negative values and experiences the further decrease. This means an achievement and increase of the compression in the mushy zone, i.e. the condition required for the suppression of crack initiation.

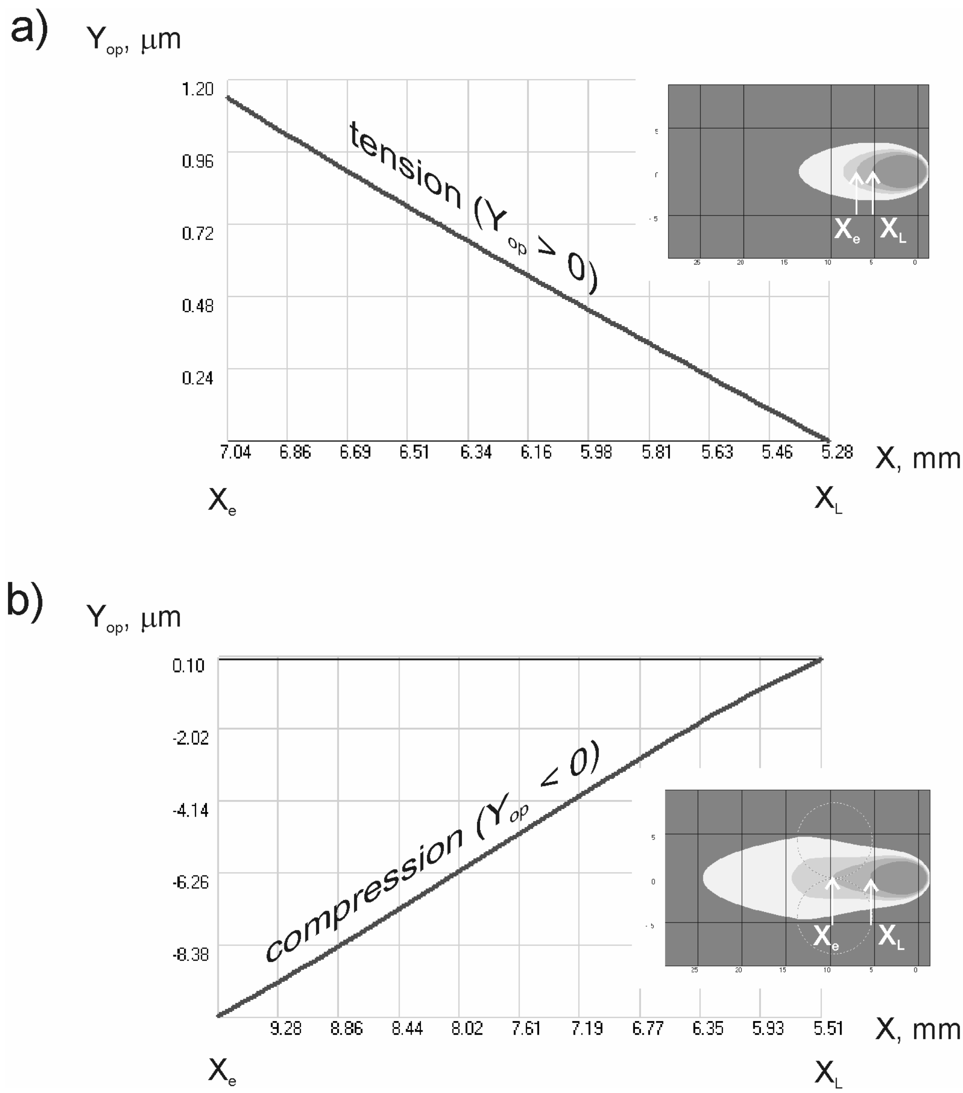

Figure 5: Calculated half values of the transverse strain accumulated in the mushy zone along the weld centerline for a weld produced (a) without and (b) with additional heating under the optimised parameters of the additional beams.

5 Summary and future developments

The presented results emphasise the high potential of the multi-beam technique for the prevention of solidification cracking in laser beam welds, since the conditions for the crack suppression seem to be achievable due to the relatively small additional power input (which is of the order of 20% relatively to the main beam power). The optimisation approach presented in this work can be effectively used in order to decrease the costs for experiments required for determination of the optimal parameters of the additional beams. For the solution of the real practical problems, the optimisation should be carried out on the basis the more precise FEM-calculations, which is the subject for the future development.

5 Acknowledgments

This work was carried out in the framework of the project ”Optimisation of Weldability” sponsored by the Bavarian Government, the Oberfranken Foundation, Allianz-Zentrum für Technik GmbH, AUDI AG, EADS Deutschland GmbH, Linde AG and MTU Motoren- und Turbinen-Union GmbH. The authors would like to thank all partners for the active support of the investigation as well as for very useful “feed-back” discussions.

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