Analysis of laser beam welding of the S650MC high strength steel using numerical simulation

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Abstract. Laser beam welding (LBW) is used in a wide range of industries, e.g. in the mechanical engineering, R&D, electronics, medical, aerospace or automotive industries. LBW technology is very popular not only for the well-known advantages comparing to another processes of fusion welding but also due to the fact that it can be easily integrated into the automated production lines. Modelling and numerical simulation of LBW processes provides a possibility to explore in detail technological principles and complex phenomena associated with this technology. The contribution is focused on the application of numerical simulation for the analysis and design of parameters for laser welding of S650MC high-strength steel sheets. For this purpose, simulation model of LBW process was developed and applied for numerical simulation of temperature fields in the program code ANSYS. A verification experiment was carried out using TruDisk 4002 disk laser. During the laser welding experiment, temperatures were measured using thermocouples of the K-type. The macrostructure of the produced weld joints was assessed by light microscopy. Measured temperatures and dimensions of welded joints were compared with results obtained by numerical simulation. Finally, using the verified simulation model, suitable parameters for laser welding of sheets from S650MC high-strength steel with the thickness of 4 mm were suggested.

1. Introduction
Development of advanced high-strength steels (AHSS) have been connected with the growing demands of designers and engineers for relatively cheap materials with special properties particularly high strength, ductility, toughness or fatigue properties. Advanced high-strength steels are complex, sophisticated materials, with carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes [1].

Generally, the AHSS microstructure is composed of a relatively soft ferrite matrix in combination with the reinforcing phase (martensite, bainite, precipitates) [2-3]. The production of AHSS using unconventional methods of thermal and thermo-mechanical processing leads to the formation of unique microstructures and microstructural components whose exceptional mechanical properties can be impaired by exposure to elevated temperatures [4-6]. This temperature sensitivity of AHSS can be taken into account in selection of welding methods for joining components from these steels. The localized heat input associated with fusion welding processes can cause significant changes in the local microstructure, and hence affect mechanical properties of AHSS in weld joint area. During laser beam welding, the energy needed for material joining is focused to a very narrow zone, which results in minimal degradation of initial properties of the base material, low residual stresses and distortions [7-10]. Moreover, the laser beam can be precisely located and the welding speeds can be very fast what makes the laser welding very attractive for many industrial applications including high-efficient production in the automotive sector.
This paper is focused on the numerical simulation of temperature fields during laser beam welding of high-strength steels. The main aim of the research is to design the appropriate parameters for butt laser welding of 4 mm thick sheets made of S650MC high-strength steel using numerical simulation of the welding process in the ANSYS program code.

2. Simulation model
To analyse the temperature fields during formation of butt joints of high-strength steel sheets by disc laser with the maximum power of 4 kW, simulation model of laser beam welding process was developed, experimentally verified and applied to fit proper welding parameters.

Numerical simulation of temperature fields is based on the numerical solution of Fourier-Kirchhoff partial differential equation in the form (1)

\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_x(T) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \lambda_y(T) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \lambda_z(T) \frac{\partial T}{\partial z} \right] + q_v \quad [\text{W.m}^{-3}] \]  

in which \( T \) is the temperature, \( \rho \) is the density, \( c_p \) is the specific heat, \( \lambda_x, \lambda_y \) and \( \lambda_z \) are the thermal conductivities in \( x, y \) and \( z \) directions, respectively and \( q_v \) is the volume heat source density, i.e. the heat generated per unit time in a unit volume [11]. Geometrical, physical, initial and boundary conditions are necessary to define to accomplish solution and numerical analysis.

2.1. Geometrical and finite element model
Geometrical model was suggested taking into account symmetry of the temperature fields during laser welding of high-strength steel sheets according to central plane of weld joint. Relatively small computation domain with dimensions of 15 mm \( \times \) 30 mm \( \times \) 4 mm (Figure 1) was considered to save computing time. On the other hand, this small-sized geometrical model was fully sufficient if only the temperature fields during laser welding were studied. Of course, in case of the stress-strain analysis, geometrical model should correspond to the real geometry of components to be welded.

![Figure 1. Geometrical model.](image)

The finite element model (Figure 2) was generated in ANSYS, Release 18.1 [12] using 3D elements of the SOLID70 type. The size of elements (mesh density) was chosen taking into account different temperature gradients expected in the individual regions of the weld joint and the base material. The highest mesh density was near the weld centreline. The smallest element size was 0.2 mm in the welding direction and 0.05 mm in the direction perpendicular to the welding direction. In other zones of the weld joint and the base material, progressive meshing was used. The generated finite element model consists of 82122 nodes and 103144 elements.
2.2. Material model

Thermo-physical properties of the S650MC high-strength steel in the dependence on temperature were computed using the JMatPro software [13] on the base of chemical composition of the steel presented in Table 1.

| Element | C   | Si  | Mn  | P   | S   | Al  | Nb  | V   | Ti  | Mo  | B   | Fe  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| [wt. %] | 0.12| 0.60| 2.00| 0.025| 0.015| 0.09| 0.20| 0.22| 0.50| 0.005| bal.|

Computed values of the thermal conductivity, density and specific heat of the S650MC steel vs. temperature are plotted in Figures 3-5. For the numerical simulation of temperature fields during fusion welding, the enthalpy changes during the solid-state transformations as well as during the melting of the investigated steel are necessary to take into account. The amount of latent heat associated with single phase transformations was defined using the method of equivalent specific heat capacity [8]. The solidus and liquidus temperatures of the S650MC steel were defined on the base of computation to be 1414 °C and 1500 °C, respectively.

Figure 2. Finite-element model with a detail of the mesh density near the weld centreline.

Figure 3. Thermal conductivity of the S650MC steel vs. temperature.
2.3. Initial conditions, boundary conditions and loads

The initial temperature of the welded sheets was 20 °C. In performed numerical simulations, the heat dissipation from the samples to the environment was not considered due to the high welding speeds and consequently very short time periods for sample cooling during the welding process [14].

For the accurate computation of temperature field, substantially more significant is the modelling of the laser heat source [15]. In this case, the conical volumetric model of a heat source with Gaussian heat flow distribution was chosen (Figure 6). The conical volumetric heat source model is defined by the geometrical parameters of \( r_e, r_i, z_e \) and \( z_i \) according to Figure 6 together with the heat output of the laser beam source \( \Phi \) and laser efficiency \( \eta \) [16].

\[
q_e(x, y, z) = \frac{9\eta \Phi e^3}{\pi(e^3 - 1)} \times \frac{1}{(z_e - z_i)(r_e^2 + r_e r_i + r_i^2)} \exp \left( \frac{3(x^2 + y^2)}{r_0^2(z)} \right)
\]  
\[
where \quad r_0(z) = r_e + \frac{r_i - r_e}{z_i - z_e}(z - z_e)
\]

Based on previous experience [18], the following values of the parameters were applied in this simulation: \( r_e = 0.079 \) mm, \( r_i = 0.072 \) mm, \( z_e = 4 \) mm and \( z_i = 0 \) mm. The efficiency of the laser heat source was supposed to be 85 %.

Figure 4. Density of the S650MC steel vs. temperature.

Figure 5. Specific heat of the S650MC steel vs. temperature.

Figure 6. Conical volumetric heat source model [17].
Numerical simulation of temperature fields during laser welding of sheets made of the S650MC steel were performed using the ANSYS program code, Release 18.2 by means of the solution of a transient, non-linear thermal problem.

3. Verification experiment

To verify the developed simulation model, verification experiment was carried out in the Center of Excellence of the 5-axis machining at the Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology (MTF SUT) in Trnava. The continuous wave TRUMPF TruDisk 4002 disc laser with the maximum power of 2 kW was used to prepare butt weld joints of samples from the S650MC steel sheet with dimensions of 50 mm × 100 mm × 4 mm. The wavelength of laser radiation was 1030 nm and the beam quality (BPP) 8 mm mrad. Laser beam was transported to the BEO D70 focusing optics via laser light cable with the core diameter of 200 µm. The focusing optics was mounted on the Fanuc M-710iC/50 6-axis robot. The disk laser beam was focused at +2 mm and +3 mm above the surface of the samples to be welded. Argon with the flow rates of 24 L.min⁻¹ and 30 L.min⁻¹ was used as a shielding gas. Both, weld bead and weld root were protected during laser beam welding. The laser power of 1500 W and 2000 W along with the welding speed from the range of 15 mm.s⁻¹ to 30 mm.s⁻¹ was exploited. Altogether, seven butt weld joints of samples were prepared experimentally using the welding parameters listed in detail in Table 2.

In the first trial, the laser welding with the laser power of 1500 W, the welding speed of 20 mm.s⁻¹ and focusing +3 was performed. As this laser power was not sufficient to achieve the full weld root melting, the laser power was increased to 2000 W.

![Figure 7. Laser workplace in the Center of Excellence at MTF SUT in Trnava.](image)

| Sample number | Laser power $P$ [W] | Welding speed $w$ [mm.s⁻¹] | Focusing | Argon gas flow [L.min⁻¹] |
|---------------|----------------------|---------------------------|----------|-------------------------|
| 1             | 1500                 | 20                        | +3       | 24                      |
| 2             | 2000                 | 20                        | +3       | 24                      |
| 3             | 2000                 | 15                        | +2       | 30                      |
| 4             | 2000                 | 20                        | +2       | 30                      |
| 5             | 2000                 | 20                        | +2       | 30                      |
| 6             | 2000                 | 25                        | +2       | 30                      |
| 7             | 2000                 | 30                        | +2       | 30                      |
According to visual evaluation of the prepared weld joint, the fusion and heat affected zones seemed to be relatively wide. In this reason, the focusing value was reduced to +2 and the next five weld joint were produced using the laser power of 2000 W and varying welding speeds.

During the welding process of the sample No. 5, experimental temperature measurement was carried out. Two thermocouples of the K-type were resistance welded to the experimental sample in the positions according to Figure 8. In this figure, the time dependence of temperatures measured by thermocouples during experiment is shown as well. The maximum temperature measured by the thermocouple 1 in the depth of 2 mm from the surface at the distance of 1.95 mm from the weld centreline is higher than the surface temperature measured by the thermocouple 2 distant from the weld centreline of 3.2 mm.

4. Comparison of results obtained by numerical simulation and verification experiment
Applying simulation model described in section 2, temperature fields during the laser welding with parameters provided in Table 2 were computed. The computed dimensions of fusion zones (weld pool) were compared with experimentally measured dimensions of fusion zones (FZ) and heat-affected zones (HAZ) on the macrostructures from the produced weld joints (samples No. 1 – 7). Moreover, for the sample 5, comparison of computed and experimentally measured temperatures was accomplished.

Figure 9 illustrates the temperature fields in the chosen times during the laser welding of the experimental sample No. 5. The fusion zone as well as HAZ are very narrow and the temperatures of the base metal distant from the weld centreline do not change during investigated time; they remain equal to the initial temperature of the sample. This indicate that the computation domain is large enough to evaluate the temperature fields during the studied process of laser welding. The statement can be confirm also by the Figure 10 illustrating the time-history of temperatures in central points at different distances from the welding start point. Already at the distance of 5 mm from the sample beginning, the welding process is in so-called regular mode, i. e. the computing domain supposed in the welding direction is sufficiently long.
Figure 9. Temperature distribution in chosen times during the laser welding process (sample No. 5 - laser power of 2000 W, welding speed of 20 mm.s$^{-1}$).

Figure 10. Time history of temperatures in central nodes at different distances from the welding start point.

In Figures 11-15, the temperature distribution and shapes of weld pool for weld joints No. 1, No. 3 and No. 5-7 are depicted using the sample top view, bottom view (or longitudinal cross-section view) and the 3D image of a fusion zone. The dark blue color represents material in solid state with temperatures below the solidus temperature of 1414 °C. In gray zones, temperatures are higher than the liquidus temperature for the S650MC steel ($T_L = 1500 ^\circ C$) and the material is fully melted. For comparison, macrostructures of prepared weld joints are presented in these figures as well. Macrostructural analysis was carried out using the Stemi 2000-C light microscope. The dimensions of
FZ and FZ+HAZ were evaluated according to the scheme in Figure 16. Table 3 summarizes the measured and computed dimensions of FZ and FZ+HAZ for all weld joint samples.

Sample No. 1 was produced with the laser power of 1500 W, focusing +3 and the welding speed of 20 mm.s\(^{-1}\) (Table 2). In this case, the base sheets with the thickness of 4 mm were not completely melted, i.e. incomplete root fusion occurred. The base material was melted only to the depth of 2.78 mm while the width of fusion zone at the top side was 1.50 mm. According to computation, the depth of fusion zone was 2.87 mm, the width and the length of fusion zone were 1.56 mm and 4.0 mm, respectively (Table 3), corresponding to the relative error at the level from 3 % to 4 %.

When the laser power was increased to 2000 W, the weld pool was relatively wide at the top side but too narrow at the bottom side (only 0.24 mm). After the focus adjustment, further weld joints were prepared with the maximum possible laser power of 2000 W and different welding speeds. With increased welding speed, the dimensions of FZ and HAZ decreases. Incomplete root penetration was achieved using the welding speed of 30 mm.s\(^{-1}\) (Figure 15).

![Figure 11. Temperature distribution during the laser welding of the sample No. 1 (top, bottom and 3D view of the weld pool) and macrostructure of the weld joint (P = 1500 W, w = 20 mm.s\(^{-1}\)).](image1)

![Figure 12. Temperature distribution during the laser welding of the sample No. 3 (top, bottom and 3D view of the weld pool) and macrostructure of the weld joint (P = 2000 W, w = 15 mm.s\(^{-1}\)).](image2)

![Figure 13. Temperature distribution during the laser welding of the sample No. 5 (top, bottom and 3D view of the weld pool) and macrostructure of the weld joint (P = 2000 W, w = 20 mm.s\(^{-1}\)).](image3)
Figure 14. Temperature distribution during the laser welding of the sample No. 6 (top, bottom and 3D view of the weld pool) and macrostructure of the weld joint \((P = 2000 \text{ W}, w = 25 \text{ mm.s}^{-1})\).

Figure 15. Temperature distribution during the laser welding of the sample No. 7 (top, bottom and 3D view of the weld pool) and macrostructure of the weld joint \((P = 2000 \text{ W}, w = 30 \text{ mm.s}^{-1})\).

Figure 16. Scheme of the experimental measurement of the width of FZ and FZ+HAZ.

Table 3. Comparison of experimentally measured and calculated dimensions FZ and FZ+HAZ.

| Sample No | \(P\) [W] | \(w\) [mm.s\(^{-1}\)] | Focus | FZ \(a_1\) [mm] | FZ \(a_2\) [mm] | FZ+HAZ \(b_1\) [mm] | FZ+HAZ \(b_2\) [mm] |
|-----------|-----------|----------------|-------|----------------|----------------|----------------|----------------|
| 1         | 1500      | 20             | +3    | 1.50           | 1.56           | 2.31           | 2.87           |
| 2         | 1500      | 20             | +3    | -              | 0.24           | 2.58           | -              |
| 3         | 2000      | 15             | +2    | 1.42           | 1.60           | 1.46           | 2.69           |
| 4         | 2000      | 20             | +2    | 1.09           | 1.26           | 1.06           | 2.2            |
| 5         | 2000      | 20             | +2    | 1.26           | 1.26           | 1.06           | 2.33           |
| 6         | 2000      | 25             | +2    | 1.17           | 1.14           | 0.81           | 0.66           |
| 7         | 2000      | 30             | +2    | 1.12           | 1.28           | 2.08           | 1.86           |

\(b_2\) \(\ast\) \text{ penetration depth (full penetration was not achieved)}
In Figure 17, correlation between temperatures experimentally measured during the preparation of weld joint No. 5 and temperatures computed in nodes approximately corresponding to the position of thermocouples is shown. Considering the mesh generation and applied numerical method (FEM), it was not possible to obtain the time dependencies of calculated temperatures exactly in nodes of the thermocouple localization, therefore the compliance of measured and calculated temperatures can be considered as good. As it can be seen from calculated results, the temperature differences near the weld pool are significant even at very small distances, e.g. in the depth of 2 mm under the surface, the maximum temperature reached during the laser welding drops by more than 150 °C at the distance of 0.2 mm. Faster temperature decrease measured by thermocouple 2 in the depth of 2 mm can be caused by the heat extraction from the bottom surface of the welded sample to the fixture which was not considered in the numerical simulation.

![Figure 17. Comparison of time dependences of the temperatures measured during laser welding of the sample No. 5 and the temperatures calculated in selected nodes.](image)

Based on the results of verification experiment, it can be concluded that the simulation model has been developed correctly and it can be used for further numerical analysis of the S650MC high-strength steel welding process.

5. Design of welding parameters for the laser welding of S650MC high-strength steel sheets

Design of appropriate welding parameters for production of high quality butt weld joints of S650MC high-strength steel sheets was carried out using numerical simulation with required laser power of 4000 W, focusing +2 and the welding speeds from the interval from 50 mm.s\(^{-1}\) to 100 mm.s\(^{-1}\). The laser efficiency was supposed to be 85 %.

Figures 18 and 19 illustrate the shapes and dimensions of FZ computed in numerical experiments 1 – 6 for considered welding speeds by means of 3D views of molten zones and temperature fields in the cross-sections perpendicular to the welding direction. In Table 4, dimensions of FZ for welding parameters taken into account in numerical simulations are summarized together with computed maximal weld pool temperature. The increase in welding speed results in the decrease of FZ volume. Moreover, for the welding speed of 100 mm.s\(^{-1}\), the laser power of 4000 W is not sufficient for complete root fusion.
Based on the results of numerical simulation, the welding speed of 70 mm.s\(^{-1}\) along with the laser power of 4000 W can be recommended for production of sound weld joints of 4 mm thick sheets made of the S650MC high-strength steel. This welding parameters can provide narrow weld joint with comparable weld width over the whole thickness of welded sheets. In addition, the weld pool temperatures are homogeneous. The computed maximal temperature of the weld pool is the lowest at the welding speed of 70 mm.s\(^{-1}\) (Table 4).

![3D view of fusion zones for welding speeds considered in numerical simulations.](image)

**Figure 18.** 3D view of fusion zones for welding speeds considered in numerical simulations.

![Temperature distribution in the weld joint cross-sections perpendicular to the welding direction for welding speeds from the range from 50 mm.s\(^{-1}\) to 100 mm.s\(^{-1}\).](image)

**Figure 19.** Temperature distribution in the weld joint cross-sections perpendicular to the welding direction for welding speeds from the range from 50 mm.s\(^{-1}\) to 100 mm.s\(^{-1}\).

| Experiment No. | \(P\) [W] | \(w\) [mm.s\(^{-1}\)] | FZ | \(a_1\) [mm] | \(a_2\) [mm] | \(T_{\text{max}}\) [°C] |
|---------------|----------|----------------|---|-------------|-------------|------------------|
| 1             | 4000     | 50            |   | 0.54        | 0.46        | 2520             |
| 2             |          | 60            |   | 0.45        | 0.38        | 2200             |
| 3             |          | 70            |   | 0.38        | 0.30        | 1970             |
| 4             |          | 80            |   | 0.38        | 0.20        | 1970             |
| 5             |          | 90            |   | 0.38        | 0.10        | 2070             |
| 6             |          | 100           |   | 0.38        | 0.38        | 2090             |

**Table 4.** Dimensions of fusion zone and the maximum temperature of a weld pool for welding parameters considered in numerical simulations.
6. Conclusions

The paper deals with numerical simulation of the laser welding of S650MC high-strength steel sheets with the thickness of 4 mm. The developed simulation model includes geometrical model with dimensions of 15 mm × 30 mm × 4 mm and finite element model generated in ANSYS program code using SOLID70 element type. Applying the JMatPro software, the material properties of S650MC steel in the dependence on temperature were calculated. A conical volumetric heat source was chosen to model the heat input during the laser welding. The experiment in the Center of Excellence MTF SUT in Trnava was carried out to verify the developed simulation model. Seven butt weld joints were produced using TruDisk 4002 disk laser with the maximum power of 2000 W and various welding parameters. During experiments, temperatures were measured by two thermocouples and consequently compared with results obtained by numerical simulations. The quality assessment of prepared weld joints was accomplished based on the macrostructure evaluation of welded samples and the measured dimensions of the FZ and HAZ. Finally, six numerical experiments (simulations) were performed using the developed and verified simulation model to design appropriate welding speed for the laser welding of S650MC high-strength steel sheets by a laser with the power of 4000 W. Based on the results of numerical simulations, the welding speed of 70 mm.s\(^{-1}\) can be recommended to produce required butt weld joints.

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