Analysis of temperature and stress-strain fields during laser beam welding of a TRIP steel

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Abstract. Transformation Induced Plasticity (TRIP) steels belong to the group of Advanced High Strength Steels (AHSS) that are characterized by good strength-strain combination and formability required for special applications in the automotive industry. The excellent combination of strength, ductility and formability of TRIP steels is achieved by a careful control of microstructure development in the process of their production. The microstructure of multiphase TRIP steels typically consists of ferrite, carbide-free bainite and metastable retained austenite, which can be transformed into martensite by plastic deformation. Upon crash, this feature allows the TRIP steels to absorb more energy, ensuring greater passenger safety. In the automotive industry, TRIP steels are mainly joined by resistance spot welding, laser or electron beam welding. Generally, the thermal cycle of a fusion welding process destroys the sophistically designed microstructure of these steels in fusion and heat-affected zones resulting in deterioration of mechanical properties of the weld joint. Negative consequences of the welding process can be eliminated using proper welding parameters. The paper deals with numerical simulation and analysis of the temperature and stress-strain fields developed during the laser beam welding of a CMnSiNb TRIP steel sheets with the thickness of 2 mm. Simulation model takes into account non-linear temperature and phase dependent material properties. The heat input during the laser beam welding is modelled using the conical volumetric heat source. The optimal welding parameters for production of butt joints of CMnSiNb TRIP steel sheets using the TruDisk 4002 disc laser with the maximum power of 2 kW are designed.

1. Introduction
Effort to reduce the fuel consumption and the weight of passenger cars leads to increased applications of advanced high-strength steels (AHSS). The use of AHSS in the automotive industry increases also the impact resistance of cars, ensuring greater passenger safety. However, maintaining a high degree of ductility of materials for the forming processes of car body components along with the effort to enhance the tensile strength requires the development of new materials [1-3]. These requirements led to the development of novel multiphase steels, including TRIP steels [4-5]. In the framework of the programme ULSAB - the Ultra Light Steel Auto Body, sheet steel producers from 35 companies and 18 countries cooperated on the research and production of new grades of AHSS, resulting in 25% decrease of weight and 14 % decrease of cost for the benchmarked four-door sedans [6].

The problem that arises in the area of application of AHSS and especially TRIP steels in the automotive industry is the formation of high-quality joints between the car body parts [7-8]. Welding represents currently the most applied technology for joining car body components.
TRIP steels are mainly joined by resistance spot welding, laser or electron beam welding [9-12]. Generally, the thermal cycle of a fusion welding process destroys the sophisticatedly designed microstructure of these steels in fusion and heat-affected zones, resulting in deterioration of mechanical properties of the weldments. In the process of laser beam welding (LBW), the temperature cycles are very short, so the material is exposed to maximum temperatures for a much shorter time compared to e. g. arc or resistance spot welding. Moreover, laser welding is also characterized by the formation of a narrow heat affected zone (HAZ). These advantages make LBW technology useful for welding difficult to weld materials such as TRIP steels. It has been proven that the setting of optimal technological parameters can ensure production of satisfactory weld joints of TRIP steels or even combinations of TRIP steels with another materials [8-16].

The paper is focused on the numerical simulation and analysis of the temperature and stress-strain fields developed during the laser beam welding of CMnSiNb TRIP steel sheets with the thickness of 2 mm. Using developed simulation model, appropriate welding parameters for production of butt joints of CMnSiNb TRIP steel sheets using the TruDisk 4002 disc laser with the maximum power of 2 kW are designed.

2. Problem description and simulation model
Analysis of temperature and stress-strain fields during laser welding of sheets made of the CMnSiNb TRIP steel with the chemical composition given in Table 1 was performed using the program code ANSYS Release 18.1 [17]. The application of continuous wave TRUMPF TruDisk 4002 disc laser with the maximum power of 2 kW, the wavelength of laser radiation of 1030 nm and the laser core diameter of 400 µm was supposed to produce butt joints of steel sheets with the thickness of 2 mm.

In the first step, simulation model for the thermal and static analyses of the laser beam welding process was developed.

Table 1. Chemical composition of the TRIP steel.

| Element | C  | Mn  | Si  | P  | S  | Cr  | Ni  | Cu  | Al  | Nb  | Mo  | Fe  |
|---------|----|-----|-----|----|----|-----|-----|-----|-----|-----|-----|-----|
| [wt. %] | 0.21 | 1.449 | 1.797 | 0.008 | 0.005 | 0.008 | 0.072 | 0.058 | 0.006 | 0.06 | 0.02 | bal. |

2.1. Mathematical model
Numerical simulation of temperature fields is based on the solution of Fourier-Kirchhoff partial differential equation in the form [18]

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q_v.$$  

(1)

in which $T$ is the temperature, $\rho$ is the density, $c_p$ is the specific heat, $\lambda$ is the tensor of thermal conductivities and $q_v$ is the volumetric heat source density, i.e. the heat generated per unit time in a unit volume. Geometrical, thermo-physical, initial and boundary conditions are necessary to define to accomplish solution of the Eq. 1 and numerical simulation.

Analysis of stress-strain fields during laser beam welding is based on the equilibrium condition given by the equation [19-20]

$$\nabla \cdot \bar{\sigma} + f = 0$$  

(2)

where $\bar{\sigma}$ is the stress tensor and $f$ is the vector of external volumetric forces. The constitutive model describing the mechanical behavior of TRIP steels generally supposes that the total strain rate $\dot{\varepsilon}^{tot}$ is given as the sum of the elastic $\dot{\varepsilon}^e$, plastic $\dot{\varepsilon}^p$ and transformation $\dot{\varepsilon}^\alpha$ parts

$$\dot{\varepsilon}^{tot} = \dot{\varepsilon}^e + \dot{\varepsilon}^p + \dot{\varepsilon}^\alpha.$$  

(3)

Stress and strain tensors are interrelated through material properties: Young modulus and Poisson ratio. The thermal stresses are dependent on the coefficient of thermal expansion. A detail description of the constitutive model can be found in [19-21].
2.2. Geometrical and finite element model
Taking into account geometrical symmetry and symmetry of boundary conditions, the proposed geometrical model consists of a sheet with the dimensions of 15 mm × 30 mm × 2 mm (Figure 1). The finite element mesh was generated in the program code ANSYS, Release 18.1 [17] using 3D elements of the SOLID70 type (thermal analysis). For structural analysis, the element type was switched to SOLID185. The progressive mesh density was defined with respect to the expected different temperature gradients directly in and near the area of the weld joint and in the distant regions of the thermally unaffected base material. The highest mesh density was near the weld centreline where the element size was 0.1 mm in the welding direction, 0.05 mm in the direction perpendicular to the welding line and 0.125 mm along the sheet thickness. The generated finite element model consists of 110019 nodes and 140968 elements.

![Figure 1. Geometrical model and finite element model with a detail of the mesh density near the weld centreline.](image1)

2.3. Material model
Microstructure and material properties of the applied CMnSiNb TRIP steel are influenced by the processing conditions of its thermo-mechanical treatment [22]. Mechanical and thermo-physical properties of the CMnSiNb TRIP steel in the dependence on temperature were computed using the JMatPro software [23]. Obtained thermal properties - values of the thermal conductivity, density and specific heat v. s. temperature are plotted in Figure 2. The solidus and liquidus temperatures of the CMnSiNb TRIP steel were computed to be 1422.4 °C and 1481.7 °C, respectively.

![Figure 2. Thermal properties of the CMnSiNb TRIP steel in the dependence on temperature.](image2)
The latent heat associated with the solid-liquid phase transformation ($l_v = 297.8$ kJ/kg) was taken into account using the method of equivalent specific heat capacity [17, 24].

Mechanical properties including the Young modulus, Poisson ratio and the thermal expansion coefficient in the dependence on temperature are depicted in Figure 3. Non-linear stress-strain curves for chosen temperatures applied for static analysis are shown in Figure 4.

**Figure 3.** Mechanical properties of the CMnSiNb TRIP steel in the dependence on temperature.

**Figure 4.** Stress-strain curves of the CMnSiNb TRIP for chosen temperatures.

**2.4. Initial conditions, boundary conditions and loads**

The initial temperature of the welded sheets was 20 °C. In performed numerical simulations, the heat extraction due to the convection and radiation to the surroundings was taken into account [25]. To model the heat input due to the moving laser beam source, the conical volumetric model of a heat source with the Gaussian heat flow density distribution was exploited (Figure 5).

$$q_e(x, y, z) = \frac{9 \eta P e^3}{\pi (e^3 - 1)} \frac{1}{(y_e - y_i)(r_e^2 + r_e r_i + r_i^2)} \exp \left( \frac{3(x^2 + z^2)}{r_0(y)} \right)$$

where $r_0(y) = r_e + \frac{y_i - y_e}{y_i - y_e}(y - y_e)$

$$r_e = \sqrt{y_i^2 + z_i^2}$$
Figure 5. Conical volumetric heat source model.

This heat source model is defined by geometrical parameters \( r_e \), \( r_i \), \( y_e \) and \( y_i \) according to Figure 5 together with the laser power \( P \) and laser efficiency \( \eta \) [26]. The efficiency of the laser heat source was supposed to be 75%. The following values of parameters were applied in this simulation: \( r_e = 0.79 \text{ mm}, \ r_i = 0.7 \text{ mm}, \ y_e = 2 \text{ mm} \) and \( y_i = 0 \text{ mm} \).

In the static analysis, the symmetry boundary condition was defined on the area in the centre of the weld joint. In accordance with supposed location of welded samples in a fixture, the displacements in \( y \) direction in the nodes on the bottom red line (Figure 1) were prescribed as \( u_y = 0 \). In the node P in the middle of the sample length, all degrees of freedom were removed.

3. Results and discussion

Applying simulation model described in section 2, eighteen numerical experiments (simulations) were performed using the laser welding parameters summarized in Table 2.

Table 2. Welding parameters considered in simulations and the maximum weld pool temperatures.

| Simulation No. | \( P \) [W] | \( w \) [mm.s\(^{-1}\)] | \( T_{\text{max}} \) [°C] |
|---------------|----------------|----------------|----------------|
| 1             | 1600           | 30             | 2494           |
| 2             | 40             | 2108           |
| 3             | 50             | 1824           |
| 4             | 60             | 1610           |
| 5             | 70             | 1484           |
| 6             | 30             | 2764           |
| 7             | 40             | 2341           |
| 8             | 50             | 2027           |
| 9             | 60             | 1791           |
| 10            | 70             | 1607           |
| 11            | 80             | 1492           |
| 12            | 40             | 2571           |
| 13            | 50             | 2231           |
| 14            | 60             | 1980           |
| 15            | 2000           | 70             | 1767           |
| 16            | 80             | 1604           |
| 17            | 90             | 1496           |
| 18            | 100            | 1463           |
Figure 6 illustrates the temperature fields in chosen times during the laser beam welding of CMnSiNb sheets with the laser power of 2000 W and the welding speed of 70 mm.s\(^{-1}\) (simulation No. 15). The fusion zone is very narrow and the temperatures of the base metal distant from the weld centreline remain practically unchanged.

![Temperature distribution](image)

**Figure 6.** Temperature distribution in chosen times during the laser welding process (simulation No. 15: laser power of 2000 W, welding speed of 70 mm.s\(^{-1}\)).

In the first step, the influence of welding parameters on the maximum temperature of a weld pool was evaluated. The computed maximum temperatures of a weld pool are summarized in Table 2 and graphically presented in the dependence on welding speed for different values of laser power in Figure 7. Based on this type of results, those combinations of welding parameters (laser power & welding speed) that would lead to the formation of poor quality weld joints can be excluded. If the temperatures of a weld pool are too low, the material melting in the zone of weld joint is insufficient. On the other hand, at too high weld pool temperatures undesirable material evaporation can occur. In this reason, the further results of simulations No. 1, 6, 7, 11, 12, 13 and 18 were not processed.
Figure 7. Dependence of the maximum weld pool temperature on the welding speed for considered values of laser power.

| Welding Speed [mm.s\(^{-1}\)] | Laser Power [W] |
|--------------------------------|----------------|
| 30                             | 1481.7 °C      |
| 40                             | 1600 W         |
| 50                             | 1800 W         |
| 60                             | 2000 W         |

Figure 8. Temperature fields in transversal sections of weld joints for chosen welding parameters.
The width of fusion zone can be proposed according to the temperature fields in the transversal sections of weld joints. Figure 8 shows the temperature fields in the transversal sections of weld joints computed using chosen welding parameters, laser powers and welding speeds. Application of a higher laser power at the same welding speed results in the increased width of fusion zone. The combination of parameters: the laser power of 1600 W and welding speed of 70 mm.s\(^{-1}\) or the laser power of 2000 W and welding speed of 90 mm.s\(^{-1}\) cannot lead to the production of a sound weld joint as the weld root is not molten.

In Figure 9, the temperature distribution and shapes of weld pools for the welding speed of 70 mm.s\(^{-1}\) and different values of laser power are depicted. In gray zones inside the weld pool, the temperatures are higher than the liquidus temperature of the CMnSiNb steel (\(T_L = 1481.7 \, ^\circ C\)) and the material is fully melted. Based on this type of simulation results, the dimensions of fusion zones at different welding conditions were predicted. The obtained dimensions of welding pool are summarized in Table 3.

| Simulation No. | \(P\) [W] | \(w\) [mm.s\(^{-1}\)] | Top width [mm] | Bottom width [mm] | Top length [mm] | Bottom length [mm] |
|---------------|----------|----------------|----------------|------------------|----------------|--------------------|
| 3             | 1600     | 50             | 0.686          | 0.428            | 1.895          | 1.142              |
| 4             | 1600     | 60             | 0.412          | 0.108            | 1.136          | 0.333              |
| 8             | 1800     | 50             | 0.774          | 0.562            | 2.419          | 1.675              |
| 9             | 1800     | 60             | 0.576          | 0.384            | 1.773          | 1.073              |
| 10            | 1800     | 70             | 0.394          | 0.066            | 1.148          | 0.283              |
| 14            | 2000     | 60             | 0.754          | 0.572            | 2.590          | 1.739              |
| 15            | 2000     | 70             | 0.576          | 0.364            | 1.784          | 1.084              |
| 16            | 2000     | 80             | 0.364          | 0.056            | 1.178          | 0.262              |
| 17            | 2000     | 90             | 0.138          | 0               | 0.536          | 0                  |

**Figure 9.** Top and bottom view of fusion zones at welding speed of 70 mm.s\(^{-1}\) and different values of laser power.

**Table 3.** Dimensions of fusion zones for the different combinations of laser power and welding speed.
| \( w \) [mm.s\(^{-1}\)] |  |  |  |
|---|---|---|---|
| 90 | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 80 | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 70 | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| 60 | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 50 | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |
| 40 | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) |

| \( P \) [kW] | 1600 | 1800 | 2000 |
|---|---|---|---|

**Figure 10.** 3D view of fusion zones for analysed combinations of laser power and welding speed.
Figure 10 provides the 3D views of computed dimensions and shapes of welding pools for analysed laser power and welding speed values. Based on the obtained results of thermal analyses, the following combinations of welding parameters can be recommended for the laser welding of 2 mm thick sheets of CMnSiNb TRIP steel:

1. welding speed of 50 mm.s\(^{-1}\) and laser power of 1600 W,
2. welding speed of 60 mm.s\(^{-1}\) and laser power of 1800 W or
3. welding speed of 70 mm.s\(^{-1}\) at the laser power of 2000 W.

In terms of the required high productivity and production efficiency in the automotive industry, the laser welding with the highest welding speed and the use of the maximum power of applied TRUMPF TruDisk 4002 disc laser is expected.

For these welding parameters corresponding to the simulation No. 15, the static analysis was carried out. The distribution of equivalent von Mises stresses are shown in Figure 11 along with the details of stress fields in the weld longitudinal and transversal sections. The maximum von Mises stresses reach the values at the level of 665 MPa in front of the fusion zone. According to experimental results [22], the ultimate tensile strength of welded CMnSiNb TRIP steel depends on the parameters of its thermo-mechanical treatment, achieving the values more then 800 MPa.

![Figure 11](image)

**Figure 11.** Equivalent von Mises stress computed during the laser welding at the welding speed of 70 mm.s\(^{-1}\) and the laser power of 2000 W with details in the longitudinal and transversal sections.

4. Conclusions
The paper deals with numerical simulation of the laser beam welding of CMnSiNb TRIP steel sheets with the thickness of 2 mm with the aim to predict the temperature and stress-strain fields arising during the welding process.

Using the developed simulation model, the effect of welding parameters including the welding speed and the laser power on the shape and dimensions of fusion zone was analysed. Based on the obtained results of thermal and static analyses, the proper welding parameters for production of butt joints of CMnSiNb TRIP steel sheets using the TruDisk 4002 disc laser with the maximum power of 2 kW were designed. The indicative operating diagram, laser power vs. welding speed, was prepared. This diagram
contains recommended combinations of welding parameters covering the values of laser power from 1600 W to 2000 W and the welding speeds from the range of 50 mm.s⁻¹ to 70 mm.s⁻¹.

To verify the developed simulation model and results of numerical simulations, the experimental butt weld joints of CMnSiNb TRIP steel sheets will be prepared applying the laser beam welding. The weld quality will be evaluated using microstructural analyses and mechanical testing.

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