Numerical and experimental analysis of a laser welded joint made of dissimilar materials S355 and 304 steel

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Abstract. One of the latest trends in modern welding industry is joining materials with different physical properties. Performing such welded joints results from the needs of the modern industry (like aviation or automotive). It is required that welded joints have appropriate strength, anti-corrosion and heat properties. The welded joints of this type are quite troublesome due to the large differences between the materials being joined. This work presents numerical and experimental research of laser butt welding of dissimilar materials. Experimental tests were made for laser welding of S355 steel with 304 austenitic steel (X5CrNi18-10). Macroscopic research is performed. On the basis of experimental research numerical investigations of the thermomechanical phenomena of the welding process are carried out using commercial software. Numerical analysis takes into account temperature dependent thermomechanical properties of welded materials. The temperature distribution in the welded joint is determined on the basis of results of calculations. The shape of melted zone and heat affected zone are numerically estimated. Stress distributions and displacement field in welded joint are numerically determined. Obtained results of the numerical analysis are compared to the experimental results.

1. Introduction

In recent years there has been a rapid increase in the demand for dissimilar materials that can be performed by various methods. Dissimilar materials are most often produced by friction stir welding or laser welding process [1–3]. Presented work is limited to laser techniques. The main advantage of using laser welding is the increased efficiency of the welding process compared to conventional welding methods and the possibility of automation and robotization of the process [4–6]. The laser beam creates a smooth weld that does not require additional finishing treatment [6, 7]. Laser welded joints of dissimilar materials are widely used, among others, in aviation, automotive industry and power industry [8]. Depending on the place of application of such dissimilar materials, the requirements for individual elements of the structure are different, e.g. in power engineering, the ability to carry useful loads and high heat resistance.

It is difficult to weld dissimilar materials due to the differences between thermomechanical properties of the joined elements [9–11]. The main parameters affecting the weldability of materials are: chemical composition, thermal conductivity, melting point, and expansion coefficient. The weldability of two different materials is difficult when there are significant differences between any of

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these parameters. Therefore, numerical modelling is often used to analyze the process at the initial stage of construction design [6, 12, 13]. Conducting experimental research is quite expensive, as it requires tests to determine the proper process parameters [6, 7, 13].

The work concerns the numerical analysis of thermomechanical phenomena of the welding process of a laser butt joint made of different materials. The material of joined sheets is high carbon steel with S355 and austenitic steel 304 (X5CrNi18-10). In order to verify the results of simulation performed experimental studies. Numerical investigations were carried out in the ABAQUS FEA calculation software. The program developed a discrete model of the analyzed welded joint. In the material module of the Abaqus/CAE program, takes into account thermomechanical properties of the welded materials changing with temperature. The implementation of additional numerical subroutines into the calculation program enables modeling of the moveable welding source. The calculations assume the same parameters as in the experiment. Based on the simulation calculations carried out, the temperature distribution of the welded joint was determined. The shape and size of the melted zone and heat affected zone was numerically estimated. The stress state in the joint and the displacement were numerically determined. Selected results of numerical simulation are compared with experimental research.

2. Experiment
An important element of numerical modeling of the welding process is the experimental verification of developed mathematical and numerical models [2, 6, 13]. At the Welding Institute in Gliwice, experimental tests of laser welding of dissimilar materials were carried out. The tests were made using universal Trumpf Lasercell 1005 laser welding and cutting station equipped with a CO₂ laser, with a maximum laser beam power of 3800 W and a laser wavelength of 10.6 μm. An experimental butt weld was performed on two dissimilar sheets of measuring 70 × 70 × 4 mm (figure 1). The material of the first sheet is high carbon steel S355 with chemical composition (%): 0.2 C, 1.5 Mn, 0.2–0.5 Si, max 0.3 Ni, max 0.3 Cr, while the second sheet is made of 304 austenitic steel with the chemical composition (%): 0.06 C, 17–19 Cr, 11–13 Ni, N <0.11. Welding is carried out without the use of additional material, using shielding gas from the face of the weld in the form of helium with a capacity of 10 l min⁻¹. During the welding process of dissimilar materials the following technological parameters were used: beam power 3800 W, beam power with efficiency losses 3450 W, focal length 270 mm.

![Figure 1. Laser butt welded joint of dissimilar materials of S355 steel with 304 austenitic steel: a) general view, b) weld face, c) weld ridge.](image-url)
In the next stage of the experimental tests metallographic testing is performed to assess the quality of obtained welded joint (figure 2). On the basis of received photos of metallographic specimens, the shape and size of the melted zone and the boundary of the heat affected zone (HAZ) are determined.

![Image of welded joint and metallographic view](image-url)

**Figure 2.** Sample and macroscopic view of the cross section of the weld.

The macroscopic picture (figure 2) shows joint zones. Different melting zones and the absence of heat affected zone in the case of austenitic steel (304 steel) can be observed in the case of welding of dissimilar materials.

### 3. Mathematical model

The heat flow equation in the Abaqus program is made on the basis of the energy conservation equation and Fourier law, expressed in the criterion of weighted residuals method. The notation of the equation in the program is as follows [13, 14]:

\[
\int_V \rho \frac{\partial U}{\partial t} \frac{\partial T}{\partial x} dV + \int_V \left( \frac{\partial T}{\partial x} \frac{\partial T}{\partial x} \right) dV = \int_S \delta T q_s dS + \int_S \delta T q_v dS
\]

where: \( \lambda \) is a thermal conductivity (W m\(^{-1}\) °C\(^{-1}\)), \( U = U(T) \) is an internal energy (J kg\(^{-1}\)), \( q_v \) is a laser beam heat source (W m\(^3\)), \( T = T(x_a, t) \) is a temperature (°C), \( q_s \) is a boundary heat flux (W m\(^{-2}\)), \( \delta T \) is a variational function, \( \rho \) is a density (kg m\(^{-3}\)), \( T = T(x_a, t) \) is temperature (°C).
Equation (1) is completed by the initial condition \( t = 0 : T = T_0 \) and boundary conditions of Dirichlet and Neumann type. While the heat exchange with the environment is performed by Newton's condition, which takes into account the loss of heat by convection, radiation and evaporation [6, 15].

Most often in the literature on the numerical modeling of the laser beam welding process to describe the power distribution of the welding source, the Gaussian mathematical model of the volumetric heat source is adopted (2):

\[
q_r(r,z) = \frac{Q}{\pi r_o^2 h} \exp \left(1 - \frac{r^2}{r_o^2}\right) \left(1 - \frac{z}{h}\right) \text{ where } r_o = r_i - (r_b - r_i) \frac{z}{h}
\]

where: \( Q \) is a laser beam power (W), \( \eta \) is process efficiency, \( h \) is the laser heat source penetration depth (m), \( z \) is actual depth (m), \( r_i \) is a beam radius for \( z = 0 \), \( r_b \) is a beam radius for \( z = h \) and \( r \) is actual radius (m), where \( r = \sqrt{x^2 + y^2} \). This model takes into account the linear decrease of energy intensity along material penetration depth [16]. The shape of heat source is assumed as the shape of a truncated cone (figure 3) [17].

**Figure 3.** Change in the volume of the heat source.

In Abaqus FEA, the moveable welding source is simulated using an additional DFLUX numerical subroutine written in the Fortran programming language [13]. The subroutine takes into account the power distribution of the beam, its location, beam movement and motion direction. The location of the center of the source is determined for each time step depending on the adopted source speed.

In the case of analysis of mechanical phenomena, the Abaqus FEA calculation program is based on classical equilibrium equations (3). These equations are complemented by constitutive relationships (4), initial conditions (5) and boundary conditions. The mechanical analysis in elastic-plastic range [15]:

\[
\nabla \cdot \mathbf{\sigma}(x_\alpha, t) = 0, \quad \mathbf{\sigma} = \mathbf{\sigma}^T
\]

\[
\dot{\mathbf{\sigma}} = \mathbf{D} \cdot \dot{\mathbf{\varepsilon}} + \mathbf{D} \cdot \mathbf{\varepsilon}^p + \mathbf{D} \cdot \mathbf{\varepsilon}^T
\]

\[
\mathbf{\sigma}(x_\alpha, t_0) = \mathbf{\sigma}(x_\alpha, T_v) = 0, \quad \mathbf{\varepsilon}^p(x_\alpha, t_0) = \mathbf{\varepsilon}^p(x_\alpha, T_v) = 0
\]

where: \( \mathbf{\sigma}(\mathbf{\sigma}_0) \) is stress tensor, \( x_\alpha \) describes location of considered point (material particle), (\( ^\circ \)) is inner exhaustive product, \( \mathbf{D} = \mathbf{D}(T) \) is a tensor of temperature dependent material properties. The total strain is defined as a sum of elastic \( \mathbf{\varepsilon}^e \), plastic \( \mathbf{\varepsilon}^p \) and thermal \( \mathbf{\varepsilon}^T \) strains (6):

\[
\mathbf{\varepsilon}^{\text{total}} = \mathbf{\varepsilon}^e + \mathbf{\varepsilon}^p + \mathbf{\varepsilon}^T
\]

In the simulation, elastic deformations are modeled for an isotropic body using Hooke's law. The plastic strain is calculated using plastic flow model obeying Huber-Mises plasticity condition [6].
4. Numerical modelling

Discrete numerical model of laser butt-welded joints made of dissimilar materials is created in Abaqus/CAE module. The considered system consists of two sheets measuring 70 mm × 35 mm × 4 mm made of S355 steel and 304 austenitic steel. The developed discrete model of the system is shown in figure 4.

![Figure 4. Scheme of analysed domain with the finite element mesh.](image)

In the presented numerical model in the welding line, a significant density of the finite element mesh was used due to the effect of a large temperature gradient. However, in the distance from the welding line finite element mesh grid size is much greater. At the junction of the joined elements in the place of melted zone, perfect contact between two joined surfaces was assumed.

Numerical analysis of thermomechanical phenomena of the butt welding process in the Abaqus FEA program has been divided into the analysis of thermal phenomena and the analysis of mechanical phenomena. In the first analysis, the temperature field of welded joint was determined. The shape and width of the melted zone and heat affected zone were determined. In the next stage, an analysis of mechanical phenomena was carried out, in which the results from the previous analysis were input data. The scheme of the analysis of thermomechanical phenomena of the welding process in the Abaqus FEA program is shown in figure 5.

![Figure 5. Scheme of termomechanical analysis of welding processes in Abaqus software.](image)
In the mechanical analysis, the boundary conditions assumed in calculations are chosen to provide a static determination of considered system [6]. Thermomechanical properties of the welded materials changing with temperature of steels S355 and 304 stainless steel (figures 6 and 7) are implemented for the simulation calculations.

![Thermal properties of welded S355 steel](image)

**Figure 6.** Termomechanical properties of welded S355 steel.

Solidus and liquidus temperatures of S355 steel are set to: $T_S = 1477 \, ^\circ C$ and $T_L = 1527 \, ^\circ C$. Latent heat of fusion equals $H_L = 270 \cdot 10^3 \, J \, kg^{-1}$.

![Thermal properties of welded 304 stainless steel](image)

**Figure 7.** Termomechanical properties of welded 304 stainless steel.

Solidus and liquidus temperatures of 304 stainless steel are set to: $T_S = 1400 \, ^\circ C$ and $T_L = 1455 \, ^\circ C$. Latent heat of fusion equals $H_L = 260 \cdot 10^3 \, J \, kg^{-1}$. Real process parameters used in the experiment are assumed in numerical calculations.
Table 1. Process parameters used in computer simulations.

| Laser beam power (W) | Efficiency (%) | Welding speed (m min⁻¹) | Beam radius (mm) | Penetration deep (mm) |
|----------------------|----------------|-------------------------|------------------|-----------------------|
| 3800                 | 90             | 1                       | \( r_t = 0.4 \)  | \( r_b = 0.2 \)       |
|                      |                |                         | \( H = 6 \text{ mm} \) |                       |

Based on the numerical verification, the beam radius values \((r_o)\) and source penetration depth \((h)\) is determined. The ambient temperature \(T_0 = 20\, ^\circ\text{C}\) and convective coefficient \(\alpha = 100\, \text{W m}^{-2} \text{°C}^{-1}\).

5. Results and discussion

In the Anaqus/Standard simulation module, numerical calculations are made using the presented mathematical models. In the first stage, numerical calculations of thermal phenomena are performed. Figure 8 shows the temperature field in a laser welded joint made of different materials. The results are presented for two selected simulation times. The duration of the simulation lasted 200 s after passing the heating source, the welded joint was cooling to ambient temperature.

![Fig. 8](image_url)

**Figure 8.** Temperature distribution of the laser welded joint.

![Fig. 9a](image_url_a)  
![Fig. 9b](image_url_b)

**Figure 9.** Temperature distribution in the cross section of the laser welded dissimilar materials a) comparing the numerically predicted shape of melted zone with the experiment b).

The figure 9 shows the temperature field in the cross section of the joint. This figure shows lines of solidus and liqudus temperatures for assumed materials. Red lines represent the melted zone boundary. The dashed line indicates the boundary of the heat affected zone. The following figure 9b presents
a comparison of numerical calculations with the results of experimental tests. Quite good agreement of results can be observed.

Figure 10 presents the results of numerical calculations of mechanical phenomena. Figures 10a and 10b present temporary reduced stresses, while figure 10c presents residual stresses. During welding process of two dissimilar materials, we can notice the different values in the range of maximum temporary and residual stresses. The maximum value of these stresses not exceed 290 MPa. The maximum concentration of stresses occurs in the welding line.

Figure 11 presented the displacement field of the welded joint (figure 11a) and numerically estimated displacements in the transverse direction to the welding line (figure 11b).

![Figure 10](image1.png)

**Figure 10.** Residual temporary reduced stress a) b) and reduced residual stress c) of laser welded joint.

![Figure 11](image2.png)

**Figure 11.** Numerically estimated deflection $U_z$ a) displacement field, b) displacement in cross section of the welded line.

In the numerically estimated welded joint, much greater displacement values occur in the transverse direction than longitudinal direction. It can be seen that two different sheets have undergone completely different deformations. The maximum displacement at ends of laser welded sheets is small and amounts to 0.05 mm for 304 stainless steel and 0.03 mm for S355 steel.
6. Conclusions
Numerical modeling of the laser welding process of butt welded joint made of dissimilar materials is most difficult to carry out. It requires taking into account in the material model two different thermomechanical values of joined sheets to each other and adopting the appropriate mathematical model of the heat source power distribution. Reliable mapping of the actual process conditions in the calculation program guarantees that accurate simulation results are obtained.

The comparison of the obtained results of numerical simulation of melted zone and HAZ forecasting with experience shows that the correct mathematical and numerical models have been adopted. The developed numerical model of the welding process for dissimilar materials can be a useful tool for determining the process parameters at the initial stage of the manufacturing process. Based on the obtained results of the simulation of mechanical phenomena, it can be stated that in two different materials there are different stress fields. Joined sheets are subject to completely different deformations (figure 11). The simulation results can be the basis for further work in the field of laser welding analysis of dissimilar materials.

7. References
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