NUMERICAL MODELING OF SINGLE-SIDED LASER BEAM WELDING T-JOINT

Zbigniew SATERNUS, Wiesława PIEKARSKA

Czestochowa University of Technology, Institute of Mechanics and Machine Design Foundations, Czestochowa, Poland, EU
saternus@imipkm.pcz.pl, piekarska@imipkm.pcz.pl,

Abstract

The paper concerns numerical modeling of single-side T-joint welding using the laser beam. The purpose of performed analysis is the determination of the temperature field in the welded joint, stress state and the estimation of welding deformation. Numerical analysis of laser welding phenomena is carried out in Abaqus/FEA software. The position of the beam in relation to the connected edges of the T-joint is selected in the developed three-dimensional discrete model to ensure full melting of the contact area of joined surfaces. The calculation model has been extended with additional subroutines that allow perform a full analysis of thermomechanical phenomena. The power distribution of a moving welding source is modeled in subroutines using mathematical formulas based on transformational equations for relative positioning of the heat source to the joined elements. Changing with temperature thermomechanical properties of welded elements made of austenitic steel are considered in the material module of Abaqus/CAE software. Temperature distribution in analyzed joint, stress state and welding deformations are determined on the basis of numerical simulations. The experimental research available in domestic and foreign literature is used to verify obtained simulation results.

Keywords: Laser welding, Single-side T-joint, Numerical modelling, Abaqus/FEA software, movable welding source

1. INTRODUCTION

One commonly used type of welded joints in the construction of large structures of welded connections are T-joints. Classically performed using arc methods for fillet welds, in which it is necessary to use additional material during the welding process [1]. Such joints are characterized by a huge heat input entering the joint, which has a significant impact on its strength properties [2]. The application of modern welding technologies based on a laser beam into production process has significantly increased the implementation of T-joints. Laser technology allowed performing precision welds with at a very high welding speed, where joints do not require additional post processing [3, 4]. Concentrated heat source of the laser beam provides a narrow melting zone and a small heat affected zone, which affects the size of the resulting deformation of welded structures and in consequence the size of resulting deformation of welded construction [2, 5]. Laser methods allow making T-joints with various welding techniques (**Figure 1**), such as: classic joints with fillet welds with or without additional material (**Figures 1a** and **1b**) [6], butt welded T-joint (**Figure 1c**) [5] and it is possible to make an I-core type weld where laser beam penetrates the faceplate, joining it with a core (**Figure 1d**) [7].

In the case of welded joints without additional material it is necessary to precisely assemble the joined elements (the gap between joined elements must be near zero). The gap between joined flat can lead to the formation of a concave weld face, which consequently is detrimental to the welded joint [8].

During the laser welding process in the welded joint there are coupled thermomechanical phenomena that occur over a wide temperature range and have a direct impact on the quality of the joint [2, 9]. Numerical modeling of laser welding process requires the adoption of mathematical models and numerical representation to the actual conditions of the welding process. Important element of numerical modeling is the adoption of appropriate mathematical model of the heat source power distribution and the process parameters.

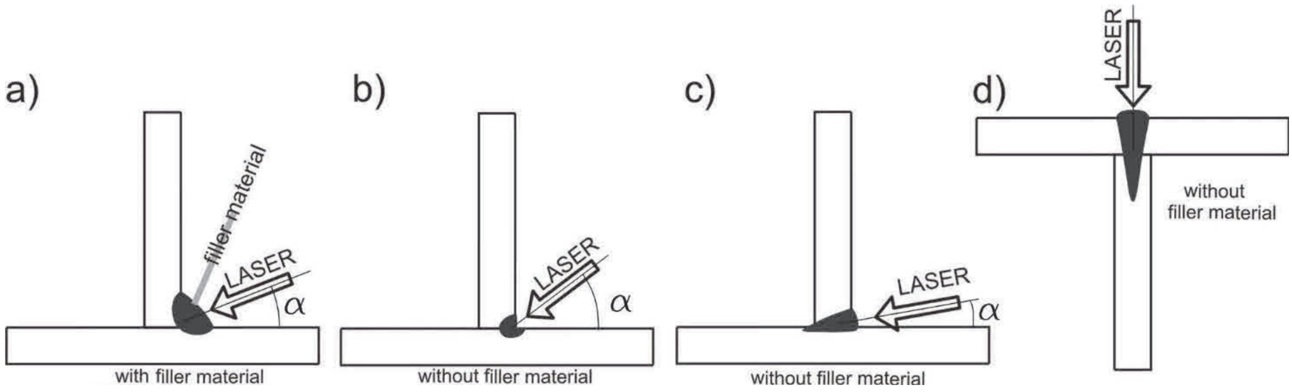

Figure 1 Laser welded T-joint: a) with filler material, b) without filler material, c) butt welded joint, d) I-core T-joint

The paper presents numerical modeling of single-sides welding of T-joint using a laser beam. The work involved the thermal and mechanical analysis of the T-joint consisting of two flat elements made of austenitic steel 304 (X5CrNi18-10). The calculations take into account thermomechanical properties of austenitic steel chancing with the temperature. Numerical calculations are carried out in the Abaqus FEA software. The program is extended with additional subroutines introduced to the computing solver. This allow for the analysis of thermomechanical phenomena occurring in welding process. The power distribution of the movable welding source is modeled in these subroutines using mathematical equations taking into account transformation equations based on the relative positioning of the joined elements. Numerical studies conducted in the literature [9] concerned the analysis of the impact of slope change in laser beam on the shape and size of the melted zone in the laser welded T-joint. On the basis of obtained results in this study it was concluded that the best quality of the weld is obtained when the lowest slope of the laser beam relative to the joined surface is used. The small angles of inclination of the laser beam allowed obtaining butt welds in accordance with experimental investigations carried out at the Welding Institute in Gliwice, Poland [8]. In order to verify the developed mathematical and numerical models the simulation is performed for single-sided welds using experimental data from [8]. Three-dimensional discrete model of the T-joint is developed. Identical technological parameters of the welding process are assumed in numerical simulations and the experiment.

Temperature distribution in the joint and the shape of the melted zone are estimated on the basis of numerical simulations, verified by metallographic studies from [8]. The state stress and welding deformation are determined for numerically designated welded joint.

2. NUMERICAL ANALYSIS OF TERMOMECHANICAL PHENOMENA

Numerical modeling of thermomechanical phenomena occurring in the welding process requires the definition of mathematical and numerical models necessary to reflect the conditions of process. Engineering software based on finite element method require adaptation additional procedures in order to take into account specific parameters of the welding process. Numerical analysis of thermal phenomena in the Abaqus software is based on the classical equation of the temperature field, which is obtained by the solution of energy conservation equation together with Fourier law [10].

$$\int_V \rho \frac{\partial U}{\partial t} \delta T\, dV + \int_V \frac{\partial \delta T}{\partial x_\alpha} \cdot \left(\lambda \frac{\partial T}{\partial x_\alpha} \right) dV = \int_V \delta T\, q_V dV + \int_S \delta T\, q_S dS \qquad (1)$$

where:

$\lambda = \lambda(T)$ - the thermal conductivity (W / (m K))

$U = U(T)$ - the internal energy (J / kg)

q_v - the laser beam heat source (W / m^3)

q_S - the heat flux toward elements surface (W / m^2)

δT - the variational function

ρ - the density (kg / m^3)

The presented heat transfer equation is expressed in the criterion of weighted residuals method. Equation (1) is completed by the initial condition and boundary conditions of Dirichlet, Neumann and Newton type [2].

The use of an additional author numerical subroutine DFLUX allowed the simulation of the welding process using a movable heat source. In the procedure, the shape and size of the heating source is determined using the mathematical equation of the volumetric heat source with Gaussian distribution (2) [11]. Position of the heat source is determined during the analysis in each time step in correspondence with welding speed.

$$Q_v(r,z) = \frac{Q \cdot \eta}{\pi r_o^2 h} \exp\left[1 - \frac{r^2}{r_o^2}\right]\left(1 - \frac{z}{h}\right) \tag{2}$$

where:

Q - the laser beam power (W)

η - the efficiency of the process (-)

h - the heat source penetration depth (m)

z - the actual depth (m)

r_0 - the beam radius (m)

r - the actual radius (m), where $r = \sqrt{x^2 + y^2}$

In the DFLUX numerical subroutine, additionally transformational formulas are applied in order to position the laser beam power distribution with respect to the connected edges of flat elements. In the case of analyzed T-joint it is necessary to obtain the slope angle α of laser beam to the the stringer in T-joint [9].

$$A_{i'} = \gamma_{i'j} A_j \quad \text{where} \quad \gamma_{i'j} = \mathbf{e}_{i'} \cdot \mathbf{e}_j \tag{3}$$

Using the transformation formulas (3) for the adopted coordinate system, a transformation matrix is obtained which solves the transition between two systems:

- $$\gamma_{i'j} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \Rightarrow \begin{cases} x = x_o \\ y = \cos\alpha \cdot y_1 + \sin\alpha \cdot z_1 \\ z = -\sin\alpha \cdot y_1 + \cos\alpha \cdot z_1 \end{cases} \tag{4}$$

In the case of the analysis of mechanical phenomena, the calculations are based on the classic equilibrium equations and the analysis is described in the elastic-plastic range:

- $$\begin{gathered} \nabla \circ \dot{\boldsymbol{\sigma}}(x_\alpha, t) = 0, \quad \dot{\sigma}_{ij} = \dot{\sigma}_{ji} \\ \dot{\boldsymbol{\sigma}} = \mathbf{D} \circ \dot{\boldsymbol{\varepsilon}}^e + \dot{\mathbf{D}} \circ \boldsymbol{\varepsilon}^e, \quad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^{Th} \end{gathered} \tag{5}$$

where:

$\boldsymbol{\sigma} = \boldsymbol{\sigma}(\sigma_{ij})$ - the stress tensor

x_α - the location of considered point (material particle)

(∘) - the inner exhaustive product

D = **D**(T) - the a tensor of temperature dependent material properties

$\boldsymbol{\varepsilon}$ - the total strain (where $\boldsymbol{\varepsilon}^e$ - elastic strain, $\boldsymbol{\varepsilon}^p$ - plastic strain and $\boldsymbol{\varepsilon}^{Th}$ - thermal strain)

Equilibrium equations (5) are complemented by initial conditions and boundary conditions are prescribed for preventing rigid body motion [2].

- $\boldsymbol{\sigma}(x_\alpha, t_0) = \boldsymbol{\sigma}(x_\alpha, T_S) = 0, \quad \boldsymbol{\varepsilon}^e(x_\alpha, t_0) = \boldsymbol{\varepsilon}^e(x_\alpha, T_S) = 0$ (6)

3. NUMERICAL MODEL

Numerical simulations of thermomechanical phenomena of the laser beam welding process are carried out in the Abaqus FEA software. Three-dimensional discrete model of analyzed welded T-join is developed consisting of flat with dimensions 30 mm x 100 mm x 3mm and 30 mm x 100 mm x 1 mm, according to the diagram shown in **Figure 2.** The geometrical dimensions of the numerically analyzed T-joint and technological parameters are taken from the literature [8]. In experimental studies conducted by the authors [8] technological parameters of the welding process are: beam power Q = 2200 W, welding speed v = 3 m/min, the angle of inclination of the laser beam relative to the connected elements $\alpha = 16^\circ$. The calculations assume also: the efficiency of the welding process η = 75 % (literature efficiency for laser welding), beam radius r = 0.35 mm and penetration depth h = 4 mm. The material model of steel 304 (X5CrNi18-10) is included in the "Property" module of the Abaqus program which takes into account changing with temperature thermophysical properties of steel [2, 9]. Assumed are: solidus temperature T_S = 1400 °C, liquidus T_L = 1455 °C, latent heat of fusion H_L = 260 × 10^3 [J / kg], ambient temperature T_0 = 20 °C and the convective coefficient α_k = 50 W / m^2.

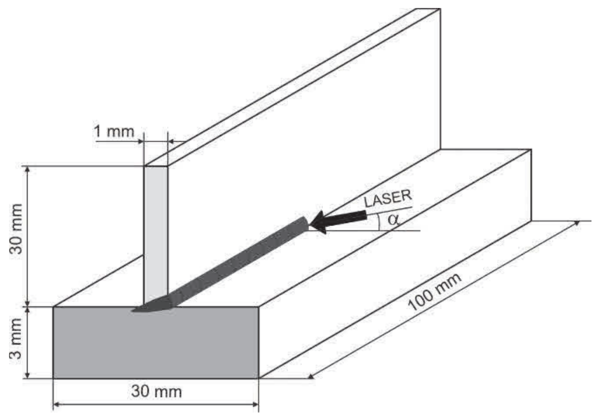

Figure 2 Scheme of considered system

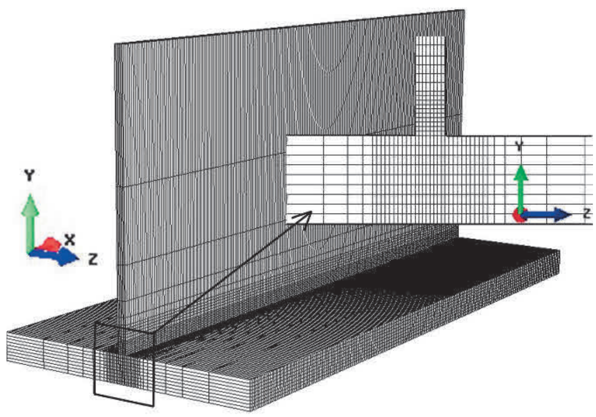

Figure 3 Discretization of analyzed domain

Figure 3 shows the discrete model of the analysed system. In the numerical model of the finite element mesh is chosen to reduce the duration of the numerical simulation. In the discrete model of T-joint perfect contact between the connected elements is assumed. Numerical analyses of thermal and mechanical phenomena are carried separately. First calculations of thermal phenomena are performed and then mechanical calculations based on the results of the thermal analysis. The mechanical boundary conditions are prescribed for preventing rigid body motion.

4. RESULTS AND DISCUSSION

On the basis of the numerical simulation of thermal phenomena the temperature field and shape and size of the melted zone are determined (**Figure 4a**). The numerically estimated shape of melted zone compared to the area of the weld cross-section of the welded joint is presented in **Figure 4b**. In this figure the solid line points out the boundary of melted zone (isoline $T_L \approx 1455$ °C). Comparing the numerically predicted shape of melted zone with the experiment, it can be seen a good agreement of the results with the real welded joint.

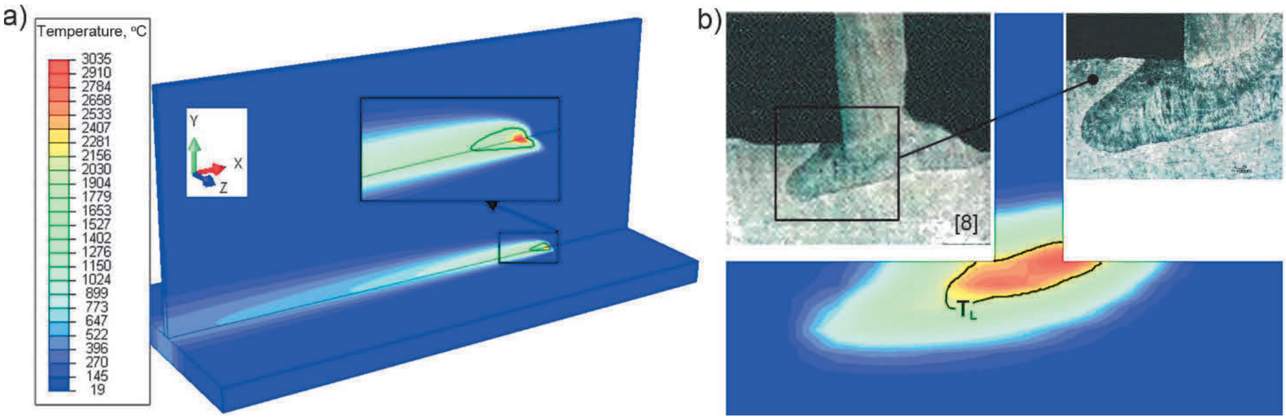

Figure 4 Temperature distribution in the welded T-joint a), Compare of the numerically predicted shape of melted zone with the experiment b)

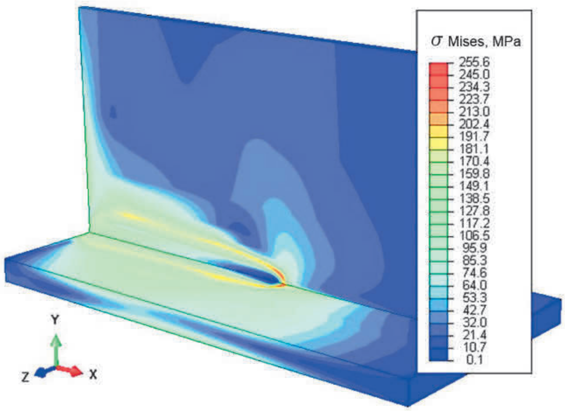

Figure 5 Residual temporary reduced stress σ of welded T-joints

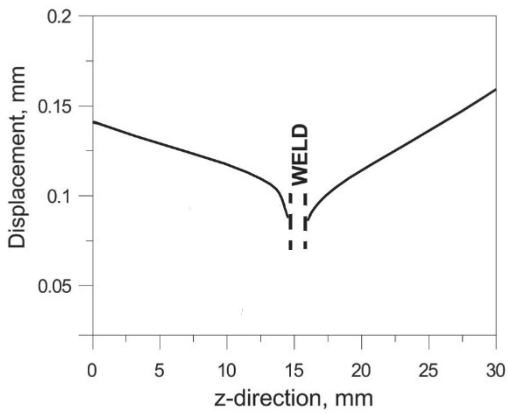

Figure 6 Numerically estimated deflection U_y in cross section of welded T-joint

Figure 5 presents the distribution of residual stresses. The maximum value of stresses does not exceed 255 MPa. **Figure 6** shows the displacement field of the laser welded T-joint. Much larger values of displacement occur in the transverse direction to the welding line than in the longitudinal direction. For the analysed T-joint, the maximum displacement value occurs in the transverse direction and does not exceed 0.17 mm.

5. CONCLUSIONS

The Abaqus software adopted for calculations required the introduction of additional numerical procedures necessary for modeling the phenomena of the welding process. In calculation the transformation model allowed simulate the T-joint welding process. Developed numerical model in Abaqus software allows simulate the welded process for any heating source inclined at any angle relative to the connected edges.

In the analyzed laser welded T-joint the highest stresses occur on the welding line and the maximum value does not exceed 255 MPa. The welded joint is deformed in both transverse and longitudinal directions. The largest displacements are at the ends of welded elements where the maximum value is 0.17 mm. The comparison of numerical simulations results with the experimental studies shows that a good agreement was obtained (**Figure 4b**). Developed numerical model can be a useful tool for engineers to design welded T-joints.

REFERENCES

[1] YONGZHI, L., KAIYUN, W., JIN, M., XU. L., HAO, L. Prediction of welding deformation in stiffened structure byintroducing thermo-mechanical interface element. *Journal of Materials Processing Technology,* 2015. vol. 216, pp. 440-446.

[2] PIEKARSKA, W., KUBIAK, M., SATERNUS, Z., STANO, S., DOMAŃSKI, T. Numerical prediction of deformations in laser welded sheets made of X5Cr 18-10 steel. *Archives of Metallurgy and Materials*, 2015. vol. 60 no. 3, pp. 1965-1972.

[3] DE, A., MAITI, S.K., WALSH, C.A., BHADESIA, K.D.H. Finite element simulation of laser spot welding. *Science Technology of Welding and Joining*, 2003, vol. 8, no. 5, pp. 377-384.

[4] UNTA, .A., POUTIAINEN, I., SALMINEN, A. Effects of sealing run welding with defocused laser beam on the quality of T-joint fillet weld. In *Physics Procedia: 8th International Conference on Photonic Technologies. Lane 2014*. 2014. vol. 56, pp. 497-506.

[5] OLIVEIRA, A.C., SIQUEIRA, R.H.M., RIVA, R., LIMA, M.S.F. One-sided laser beam welding of autogenous T-joints for 6013-T4 aluminium alloy. *Materials and Design,* 2015. vol. 65, pp. 726-736.

[6] SHANMUGAM, N., Siva, B., SANKARANARAYANASAMY, K.., KUMAR, S., Ramesh. S. A transient finite element simulation of the temperature and bead profiles of T-joint laser welds; *Materials & Design.* 2010. vol. 31, pp. 4528-4542.

[7] KOZAK, J. All steel sandwich panels - new possibilities introduced by laser welding techniques; *Przegląd Spawalnictwa*, 2007, vol. 10, pp. 53-59.

[8] STANO, S., ADAMIEC, J., DWORAK, J., URBAŃCZYK, M. Badania procesu spawania laserowego złączy teowych z cienkich blach ze stali austenitycznej. *Biuletyn Instytutu Spawalnictwa*, 2016. vol. 5, pp. 141-151.

[9] PIEKARSKA, W., SATERNUS, Z., KUBIAK, M., DOMAŃSKI, T. Numerical analysis of the influence heat source slope on the shape and size of fusion zone in laser welded T-joint.In *METAL 2016: 25th International Conference on Metallurgy and Materials,* Ostrava: *TANGER, 2016,* pp 688-693.

[10] DASSAULT SYSTEM, *Abaqus theory manual*. Version 6.7, SIMULIA, 2007.

[11] TSIRKAS, S.A., PAPANIKOS, P., KERMANIDIS, Th. Numerical simulation of the laser welding process in butt-joint specimens. *Journal of Materials Processing Technology*, 2003, vol. 134, pp. 59-69.