NUMERICAL ANALYSIS OF THE INFLUENCE HEAT SOURCE SLOPE ON THE SHAPE AND SIZE OF FUSION ZONE IN LASER WELDED T-JOINT

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Abstract

The work concerns the modeling and numerical analysis of thermal phenomena in laser welded T-joints. The effect of laser beam slope relative to welded elements on the temperature distribution is analyzed. The shape and size of fusion zone is predicted on the basis of obtained results. Temperature field in welded T-joint is modelled in Abaqus/FEA engineering software as three dimensional task. Numerical analysis takes into account thermomechanical properties changing with temperature for welded plates made of austenitic steel. Additional author's numerical subroutine DFLUX is implemented into Abaqus/FEA in order to solve issues concerning mathematical description of movable laser welding heat source. Formulas for coordinate system transformations in terms of the rotation of coordinate system about selected angle are used for the proper positioning of the heat source regard to joined edge of T-joint.

Keywords: Laser welding, numerical modelling, temperature field, T-joint, Abaqus FEA

1. INTRODUCTION

Previously applied methods of T-joints welding were based on classical arc welding technology. Fillet welds were performed by applying additional material to the joint. This produces huge thermal loads, in consequence has a significant influence on the global deformations of the entire welded construction [1-4].

Rapid development of modern production techniques allowed using more advanced welding technologies. Welding technology using a laser beam is intensively studied and implemented in various industries [3, 5]. Laser welding technology allows for a much higher welding speed with a small amount of molten material and narrow heat affected zone in comparison to conventional methods used to perform T-joints [3, 5, 6]. Laser beam welding is a complex process, accompanied by coupled thermomechanical phenomena occurring in a wide range of temperatures. These phenomena have a direct impact on the quality of the welded joint [2, 7, 8]. Important stage in numerical modeling of thermal processes is the proper selection of technological parameters of the process which have a significant impact on the obtained weld shape as well as its mechanical properties [3, 4, 9]. Numerical prediction of thermal loads in laser welded joints is important at the stage of construction design [3, 8, 10]. Appropriate positioning of the heat source to joined elements is important during execution of T-joints using a laser beam.

The paper presents the numerical prediction of the shape and size of melted zone in welded T-joint. The influence of changes of beam angle on the quality of joints is analyzed. Based on the finite element method numerical simulations of laser welded T-joint are performed using Abaqus FEA software. The implementation of additional subroutine DFLUX written in FORTRAN allowed the simulation of the trajectory of motion and positioning of the beam relative to the connected parts in Abaqus FEA solver. Material model used in the analysis takes into account thermophysical properties of welded T-joint changing with the temperature [10]. Shape and size of the melted zone for three different slopes of the laser beam are estimated on the basis of performed numerical simulations. Obtained results are compared together to illustrate the influence of the slope of heat source on the geometry of the weld.

2. NUMERICAL MODELING

Numerical analysis of thermal phenomena in laser welding process is performed using Abaqus FEA software. Temperature field is obtained for the solution of energy conservation equation together with Fourier law [11], expressed in the criterion of weighted residuals method as follows:

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

where $\lambda = \lambda(T)$ is a thermal conductivity, W/(m K), $U = U(T)$ is a internal energy, J/kg, q_v is laser beam heat source, W/m^3, q_S is a heat flux toward elements surface, W/m^2, δT is a variational function, ρ is a density, kg/m^3.

Equation (1) is completed by the initial condition $t = 0 : T = T_o$ and boundary conditions of Dirichlet and Neumann type:

$$T\big|_\Gamma = \tilde{T} \qquad q_{Sym} = -\lambda \frac{\partial T}{\partial n} = 0 \tag{2}$$

as well as Newton type condition with the heat loss due to convection and radiation:

$$q_S = -\lambda \frac{\partial T}{\partial n} = \alpha_k (T\big|_\Gamma - T_0) + \varepsilon \sigma (T\big|_\Gamma{}^4 - T_0^4) \tag{3}$$

where α_k is convective coefficient (assumed as $\alpha_k = 150$ W/m^2 °C, ε is radiation ($\varepsilon = 0.5$), σ is Stefan-Boltzman constant and $q(r, 0)$ is the heat flux towards the top surface of welded workpiece ($z = 0$) in the source activity zone of radius r, $T_0 = 20$ °C is an ambient temperature.

The numerical analysis of thermal phenomena is performed in Lagrange coordinates. Coordinates of the centre of welding heat source is determined for each time step, depending on the assumed welding speed. Solid - liquid phase transformation is taken into in account in internal energy U, between solidus and liquidus temperatures, assuming $T_S = 1400$ °C, $T_L = 1455$ °C and latent heat of fusion $H_L = 260 \times 10^3$ J/kg.

Additional DFLUX subroutine is implemented into Abaqus FEA simulations movable welding heat source. Classical movable volumetric heat source model, described by Gaussian power distribution is assumed in analysis for the intensity distribution of laser beam heat source power [12].

$$Q_v(r,z) = \frac{Q \cdot \eta}{\pi r_o^2 h} \exp\left[1 - \frac{r^2}{r_o^2}\right]\left(1 - \frac{z}{h}\right) \tag{4}$$

where Q is a laser beam power, W; η is efficiency of the process; h is the heat source penetration depth, m; z is actual depth, m; r_0 is a beam radius, m; while r is actual radius, m; where $r = \sqrt{x^2 + y^2}$.

The adopted computational model assumes linear changes in energy distribution along welded material penetration depth. In addition, beam radius r_0 is modified in equation (4). The radius changes with depth in relation to equation (5), having a shape of truncated cone (**Figure 1**):

$$r_o = r_t - (r_t - r_b) \cdot \frac{z}{h} \tag{5}$$

where r_t is a beam radius, for z = 0, r_b is a beam radius, for z = h

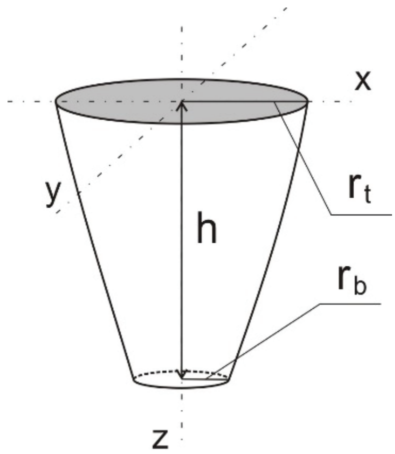

Figure 1 Shape of modified radius beam r_o

Correct positioning of the axis of the source relative to the edges of connected elements (**Figure 3**) is required in the case of numerical simulation of thermal phenomena in welded T-joints using volumetric heat source. Coordinates system should be transformed in DFLUX subroutine by the angle between the line of slope of a beam and the stringer in T-joint (**Figure 2**).

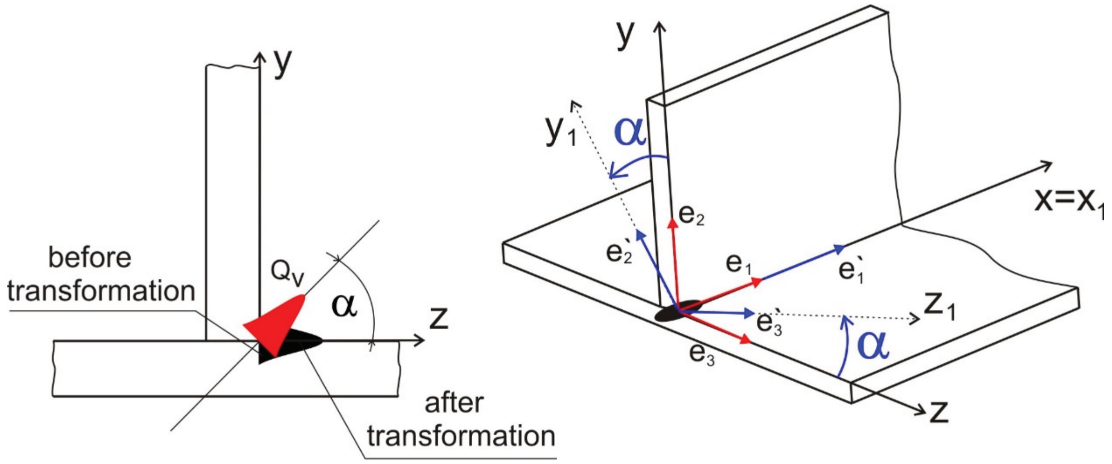

Figure 2 Transformation of heat source power distribution

The transformation of welding source power distribution is carried out using transformation model:

$$A_{i'} = \gamma_{i'j} A_j \tag{6}$$

where

$$\gamma_{i'j} = \mathbf{e}_{i'} \cdot \mathbf{e}_j \tag{7}$$

After rotation of the considered system with respect to selected axis the transformation matrix is obtained

$$\gamma_{i'j} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \tag{8}$$

Equations of coordinates transformations are obtained after the solution of presented transformation matrix from the basic system (x, y, z) to the rotated system (x_1, y_1, z_1):

$$\begin{cases} x = x_o \\ y = \cos\alpha \cdot y_1 + \sin\alpha \cdot z_1 \\ z = -\sin\alpha \cdot y_1 + \cos\alpha \cdot z_1 \end{cases} \quad (9)$$

The Gaussian heat source power distribution in the base coordinate system and in rotated coordinate system is shown in **Figure 3**.

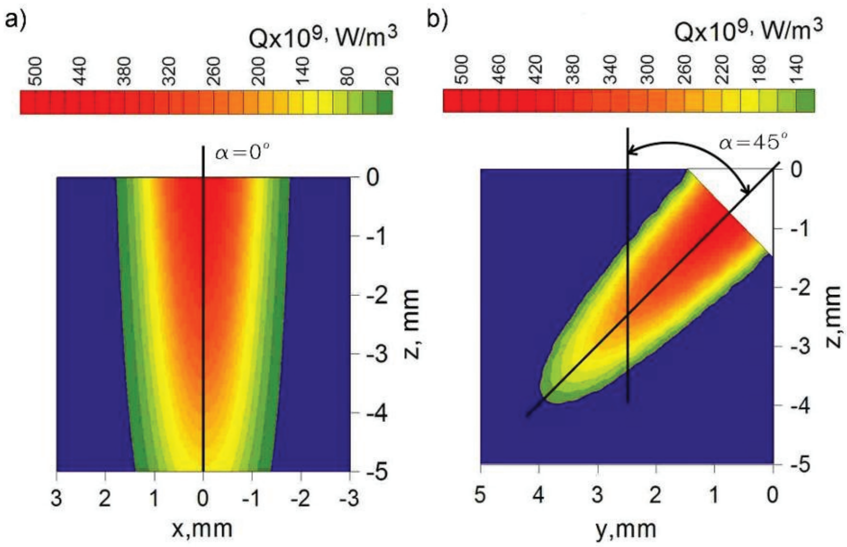

Figure 3 Heat source of power distribution in a) Cartesian and b) rotated coordinate system

3. RESULTS AND DISCUSSION

Numerical calculations of laser welding process are performed for T-joint at different beam angle α. Three-dimensional discrete model of analyzed system is developed in Abaqus CAE system. Dimensions of welded joint are set to: L = 60 mm, b = 20 mm, p = 20 mm, g = 2.5 mm. Scheme of analyzed domain with the finite element mesh used in calculations is shown in **Figure 4**. Changing with temperature thermophysical properties of welded flat are assumed in numerical simulations for austenitic steel X5CrNi18-10 [8, 10].

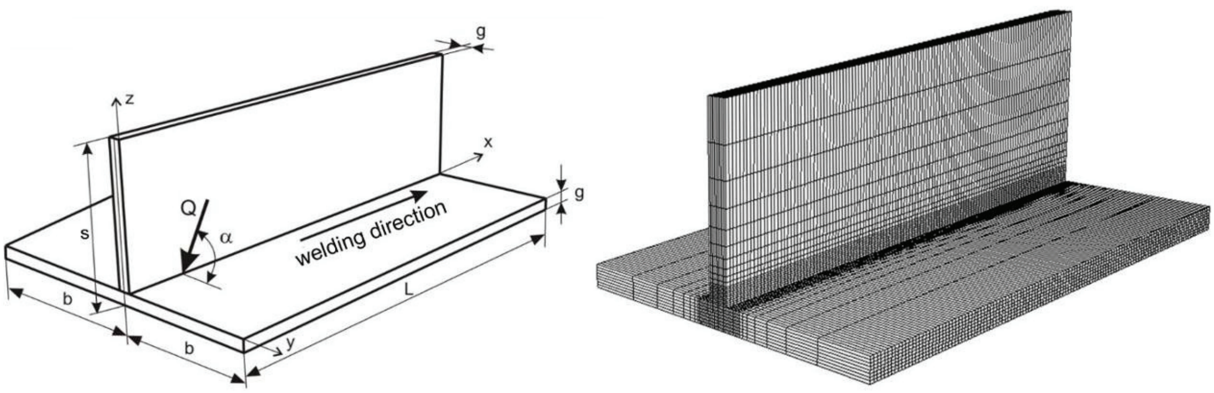

Figure 4 Scheme of analyzed domain with finite element mesh

Welding source parameters, like: power and radius of the laser beam and welding speed are adopted with respect to experimental research described in the literature [12], whereas the penetration depth of the beam is assumed by the experimental verification of the model [5]. Assumed technological parameters are presented in **Table 1.**

Table 1 Process parameters

T-joint	Heat source	Welding speed	Beam angle
I	Q = 1250 W, η = 75 %, h = 3 mm, r_t = 0.3 mm, r_b = 0.1 mm	0.5 m/min	α = 30°
II			α = 45°
III			α = 60°

Temperature distributions in welded joints are obtained on the basis of performed numerical simulations. **Figure 5** shows temperature distribution at the top surface of chosen welded T-joint (at slope angle α = 30°), where solid line points out the boundary of melted zone (isoline $T_L \approx$ 1455 °C). **Figure 6** shows the temperature distribution in the cross-sectional area of each analyzed welded T-joint, wherein the solid line indicates the numerically estimated shape of fusion zone.

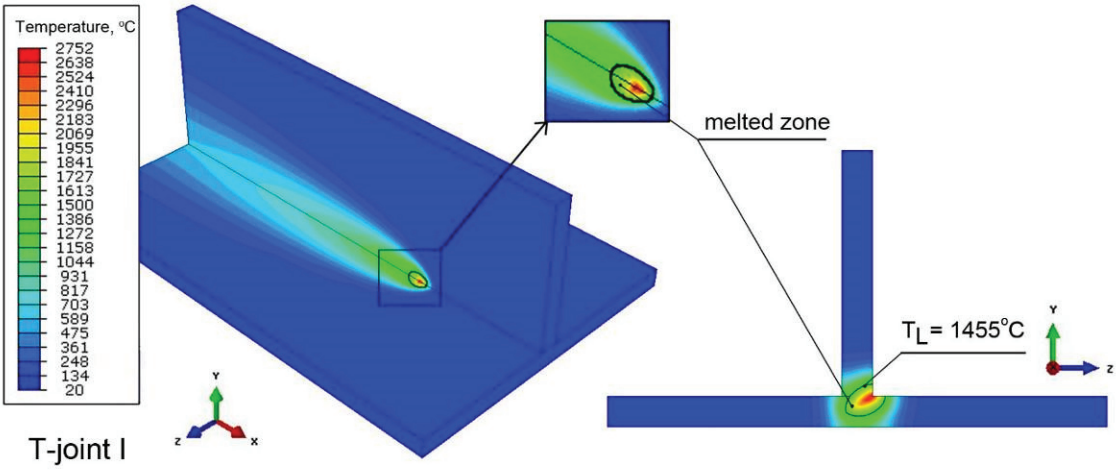

Figure 5 Temperature distribution in welded T-joint (heat source slope α = 30°)

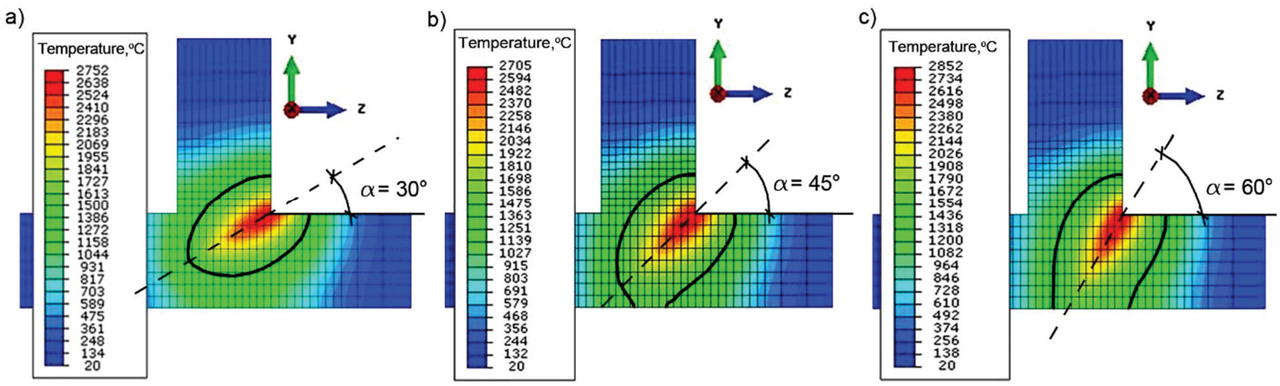

Figure 6 Temperature distribution in the cross section of welded T-joints

From the comparison of presented temperature distributions in the cross-section for three different welding heat source beam angles it can be observed that in the case of slope α = 30° the best penetration of welded joint is provided. In remaining two cases (α = 45° and α = 60°) for identical process parameters, a good melting of joined edges is observed, with simultaneous blown of T-joint stringer. This can significantly influence the quality of obtained joints.

4. CONCLUSIONS

Numerical analysis of thermal phenomena in welding process of T-joints using Abaqus FEA software is complex and requires to develop additional numerical subroutines. The numerical subroutine requires an appropriate mathematical description of heat source and in the case of performing fillet welds, the transformation of the basic coordinate system to rotated system by a given angle.

The shape of the fusion zone of welded joints for three different positions of laser beam is estimated on the basis of developed discrete model. From the comparison of obtained temperature distributions (**Figure 6**) it can be stated that for the tilt angle of the laser beam $\alpha = 30°$ the best joint is obtained in qualitative terms.

Abaqus FEA software with additional subroutines is a universal tool for the analysis of thermal phenomena in any type of joints with considered various positioning of the heat source.

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