COMPUTER ANALYSIS OF STRESS AND DEFORMATIONS IN LASER WELDED T-JOINT AT DIFFERENT INCLINATIONS OF THE WELDING SOURCE

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Abstract

This paper concerns computer analysis of stress states and numerical prediction of the formation of deformations in T-joint welded by a laser beam technique. Numerical analysis of thermomechanical phenomena are carried out in Abaqus / FEA commercial engineering software, which is based on finite element method (FEM). Three dimensional discrete model is created in the design module of Abaqus / CAE. Different inclinations of welding source are assumed with respect to the edges of joined elements. Numerical analysis takes into account changing with temperature thermomechanical properties of welded plate made of austenitic steel. Simulations of complex thermomechanical phenomena in welding process required the implementation of additional numerical subroutine written in Fortran programming language.

Mathematical modells of the power distribution of a moving welding source and the position of the source relative to the edges are implemented into numerical subroutine DFLUX. Temperature distribution, stress state and welding deformations are analysed on the basis of numerical simulations of thermomechanical phenomena.

Keywords: Numerical modelling, laser welding, temperature field, welding deformations, T-joint

1. INTRODUCTION

Increasing demands for the quality of produced welded joints are encourage engineers and technoligists to improve welding technology. Technological innovations have contributed to the intensive development of welding technology. Increasigly, modern techniques of metal joining are used in many automated production lines [1-3]. Laser beam welding is a one of methods that contribute to the rapid development of the industry. In laser welding process coupled thermo-mechanical phenomena are present in a wide temperature range [3]. A very high density of laser beam power provide very narrow melded zone, heat affected zone and low joint deformations [3, 4]. Welding of machine parts can be done without additional post treatment [1, 5, 6]. One of popular laser welded joints are T- joints. In the case of these welded joints the use of laser beam allowed to obtain much higher welding speeds and no need for use of additional filler material [2, 3]. This significantly reduced the amount of heat input to the welded joint which reduced welding deformation [3, 5, 6]. An important factor determining the quality of the weld is the thermal load which has a significant influence on resultant weld shape and its mechanical properties [2, 4].

The paper presents the analysis of the influence of laser beam beam inclination on the formation of stress state and deformation in butt-welded T-joint. Numerical simulations of laser welding technique are performed for three different inclinations of laser beam relative to joined edges of T-joint. Assumed beam inclinations are α=30º, α=45º and α=60º. Numerical simulations are conducted in ABAQUS FEA software based on finite element method. Butt welded T-joints assumed in the analysis are made of X5CRNI18-10 austenitic steel [3]. Material properties changing with temperature are considered in calculations. The implementation of additional author's numerical procedure DFLUX was necessary to perform numerical simulations of welding process in ABAQUS FEA. Modeling of inclined welding heat source motion at predetermined angle to the assumed welding line is performed in additional DFLUX procedure included into the solver. Temperature distribution in welded joint, shape of melting zone, stress state and created welding deformations are determined.

2. FINITE ELENETS MODEL

In numerical analysis of thermomechanical phenomena Abaqus FEA commercial engineering software is used. The design module of Abaqus/CAE allowed to design three-dimensional discrete model of T-joint with dimensions L = 60 mm, b = 20 mm, s = 20 mm, g = 2.5 mm. Prepared discrete model is presented in **Figure 1.** The largest concentration of fiite element mesh is assumed near the welding source movement line due to the large temperature gradient occurring in the heat source activity zone. Simulations are performed for three different inclinations of welding source α = 30º, α = 45º and α = 60º. The analysis is divided into two stages - calculations of thermal phenomena and mechanical phenomena separately. Calculations of thermal phenomena are performed in the first stage. In the second stage calculations of mechanical phenomena are executed with initial conditions based on results from first stage for every time period. In the mechanical analysis boundary conditions are chosen to provide a static determination of considered system. The total number of elements used in the numerical model is 74400. Changing with temperature thermos physical properties of welded T-joint are assumed in numerical simulations for austenitic steel X5CrNi18-10, which are presented in **Figure 2** [3].

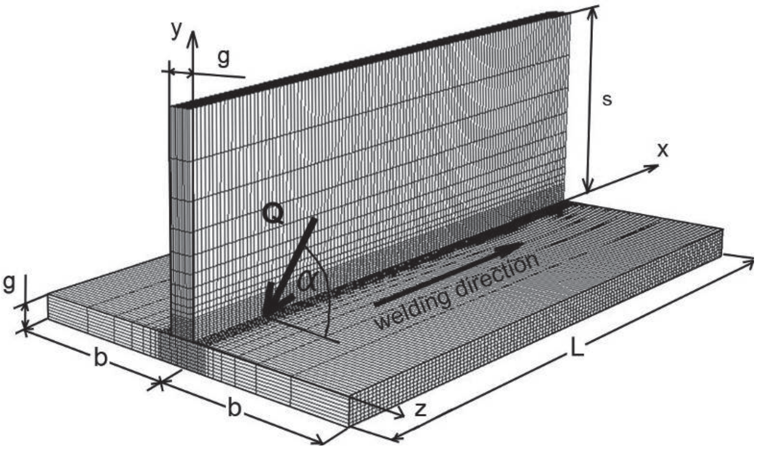

Figure 1 Scheme of analyzed domain with the finite element mesh

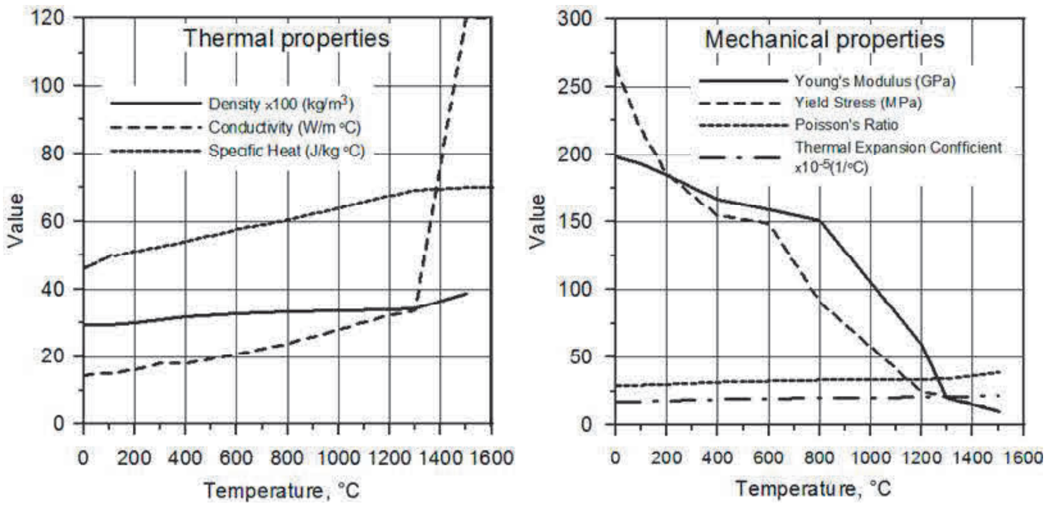

Figure 2 Thermomechanical properties assumed in calculations [3]

3. MATHEMATICAL MODEL

In order to perform a numerical analysis of thermomechanical phenomena it is necessary to consider appropriate mathematical and numerical model. Numerical analysis in Abaqus is conducted in Lagrange coordinates. Position of the heat source is determined during the analysis in each time step in correspondence with welding speed. Temperature field is determined on the basis of solution of energy conservation equation expressed in the criterion of weighted residuals [7]:

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

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.

Presented equation of heat transfer is completed by the initial condition $t = 0$: $T = T_o$ and boundary conditions of Dirichlet, Neumann and Newton type [2, 8].

$$T\big|_\Gamma = \tilde{T} \qquad q_{Sym} = -\lambda \frac{\partial T}{\partial n} = 0 \qquad q_S = -\lambda \frac{\partial T}{\partial n} = \alpha_k (T\big|_\Gamma - T_0) + \varepsilon\sigma (T\big|_\Gamma{}^4 - T_0^4) \tag{2}$$

where α_k is convective coefficient (assumed as α_k = 100 W / m^2 °C, ε is radiation (ε = 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 mathematical Gaussian volumetric heat source model (3) is used to describe the power distribution of the welding source. The model assumes linear changes in energy distribution along welded material penetration depth [9].

$$Q_v(r,z) = \frac{Q \cdot \eta}{\pi r_o^2 h} \exp\left[1 - \frac{r^2}{r_o^2}\right]\left(1 - \frac{z}{h}\right) \tag{3}$$

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 cylindrical shape of heat source is assumed as the shape of a truncated cone. Parameters of the heat source used in calculatiuons are set to: r_t = 0.3 mm, while r_b = 0.1 mm.

$$r_o = r_t - (r_t - r_b) \cdot \frac{z}{h} \tag{4}$$

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

The proper positioning of the source relative to welded edges is necessary to perform numerical simulations of T-joint welding process. The implementation of heat source is possible through transformation equations concluded in additional DFLUX procedure [7]. The scheme of the transformed system is presented in **Figure 3**.

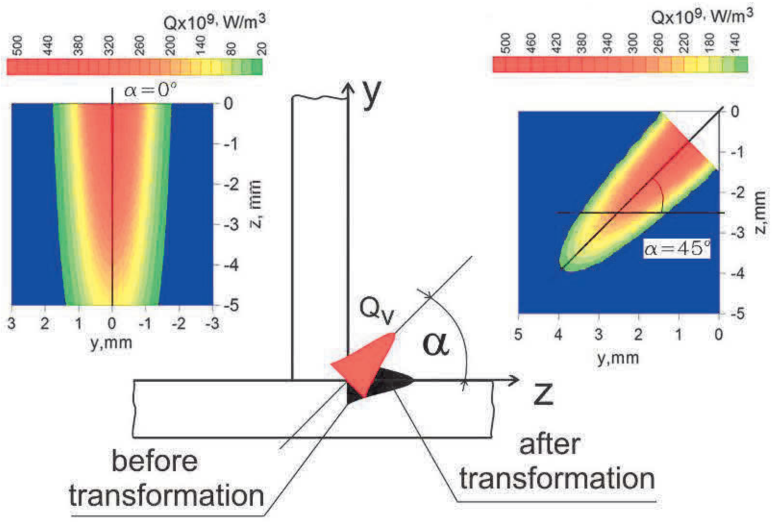

Figure 3 Transformation of heat source power distribution

The numerical analysis of mechanical phenomena in the Abaqus program is described in elastic-plastic range and is based on classic equilibrium equations [3, 5, 6]:

$$\nabla \circ \dot{\boldsymbol{\sigma}}(x_\alpha, t) = 0, \qquad \dot{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}}^T \tag{5}$$

where $\boldsymbol{\sigma} = \boldsymbol{\sigma}(\sigma_{ij})$ is stress tensor, x_α describes location of considered point (material particle), ($\circ$) is inner exhaustive product

Equilibrium equations (5) are complemented by constitutive relations, initial conditions and boundary conditions are prescribed for preventing rigid body motion.

$$\dot{\boldsymbol{\sigma}} = \mathbf{D} \circ \dot{\boldsymbol{\varepsilon}}^e + \dot{\mathbf{D}} \circ \boldsymbol{\varepsilon}^e \tag{6}$$

$$\boldsymbol{\sigma}(x_\alpha, t_0) = \boldsymbol{\sigma}(x_\alpha, T_S) = 0, \qquad \boldsymbol{\varepsilon}^e(x_\alpha, t_0) = \boldsymbol{\varepsilon}^e(x_\alpha, T_S) = 0 \tag{7}$$

D = **D**(T) is a tensor of temperature dependent material properties, $\boldsymbol{\varepsilon}$ is total strain, $\boldsymbol{\varepsilon}^e$ is elastic strain, $\boldsymbol{\varepsilon}^p$ is plastic strain and $\boldsymbol{\varepsilon}^{Th}$ is thermal strain.

$$\varepsilon^{total} = \varepsilon^e + \varepsilon^p + \varepsilon^{Th} \tag{8}$$

Elastic strain is modeled for isotropic material using Hooke's law, while plastic flow model is used to determine plastic strain based on Huber-Mises yield criterion and isotropic strengthening [6].

4. RESULTS AND DISCUSSION

The same parameters of welding source, such as beam power Q = 1250 W, depth of penetration - h = 3 mm, welding speed - v = 0.5 m / min are assumed in calculations for all three cases of laser beam inclination. In reference to the literature the value of efficiency of laser beam welding source is assumed at 75 %.

Temperature distributions for three adopted inclinations of welding source are determined on the basis of performed numerical simulations of thermal phenomena. Temperature fields in the cross section of analyzed joint are presented in **Figure 4**. In this figure solid line points out the boundary of melted zone (isoline $T_L \approx$ 1455 °C).

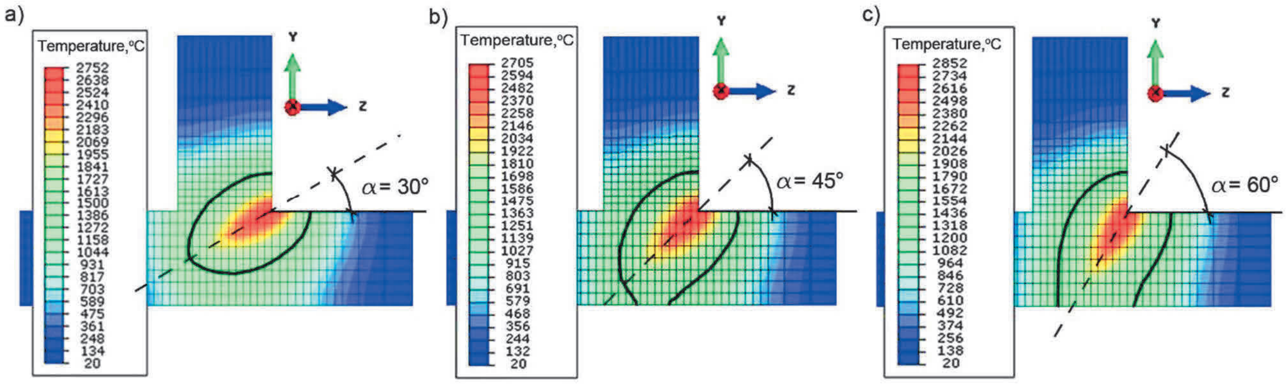

Figure 4 Temperature distribution in cross section of welded T-joints

The analysis of presented temperature distributions for the three inclinations of the heat source shows that in all three cases melting of joined edges is obtained. In the case of inclination of source at level α = 45° and α = 60° material flow through T-joint stringer is obtained. The next stage of numerical calculations included the simulation of mechanical phenomena. **Figure 5** shows the distribution of reduced temporary stress (**Figure 5a**) and (**Figure 5b**) residual stress at the heat source slope α = 30°. For the analyzed case the maximum value of the temporary stress does not exceed 255 MPa, while in the case of residual stress 210 MPa. In the other two cases similar values of stresses were obtained.

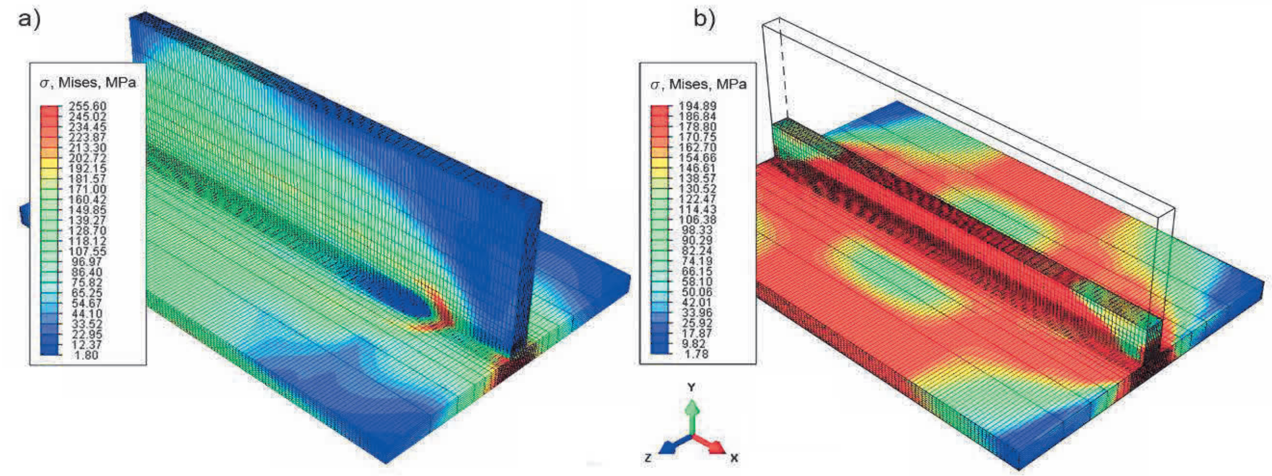

Figure 5 Residual reduced stress σ of welded T-joints: a) temporary and b) residual

Values of displacements of welded T-joint (**Figure 6**) are also estimated. Welded T-joints is deformed in both transverse and longitudinal directions. The largest displacement values occur at ends of T-joints (lines 1 and 2). For the three analyzed cases, the smallest displacement is obtained with the inclination of the source α = 30°. However, higher displacement values are obtained with a slope of α = 60°.

5. CONCLUSIONS

Comprehensive Abaqus FEA program used in simulations allows perform complex analysis of thermomechanical phenomena in laser beam welding process. The simulation program allows determining any type of joint with an arbitrarily positioned heat source. Numerical modeling of laser welding of T-joints requires the proper positioning of the source relative to the joined edges.

On the basis of developed three-dimensional discrete model of analyzed T-joint, the shape of the melted zone, stress state and welding deformation were estimated for three different positioning of welding beam source. The comparison of obtained simulation results shows that slope α = 30 ° gave the best penetration of welded joint (**Figure 4a**) and the smallest value of displacement (**Figure 6**). Values of residual stress in all cases are similar and do not exceed 210 MPa.

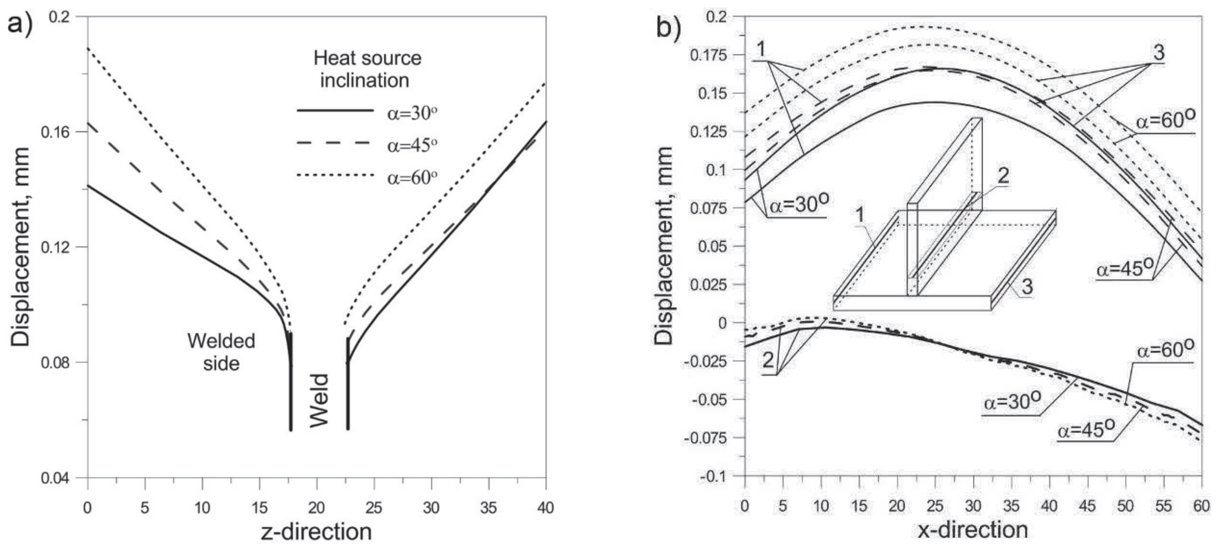

Figure 6 Numerically estimated deflection U_y: a) in cross section of welded T-joint, b) in longitudinal section of the joint

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