SIMULATIONS AND EXPERIMENTAL RESEARCH ON LASER BUTT-WELDED T-JOINTS

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Abstract

This work concerns numerical modelling of laser butt-welding of T-joints, made of S355 steel. Numerical analysis of thermomechanical phenomena is performed in ABAQUS FEA engineering software. Additional, author's subroutines are implemented in designed three dimensional model using Fortran programming language. Developed subroutines describe the distribution of volumetric laser beam heat source power, the kinetics of phase transformations in solid state as well as isotropic strain generated by the temperature field and structural strain during heating and cooling of welded steel. Performed computational analysis takes into account thermomechanical properties changing with temperature. Butt-welded T-joints are performed on Yb:YAG laser in order to verify the results of numerical simulations. Characteristic zones of the cross section of the joint are compared to numerically predicted geometry of fusion zone and heat affected zone. Numerically predicted displacement in chosen sections of the joint is compared to real displacement, measured using profilographometer New Form Talysurf 2D/3D 120.

Keywords: Laser welding, T-joint, numerical modeling, phase transformations, welding deformations

1. INTRODUCTION

In recent years there has been rapid development of modern manufacturing techniques including materials joining methods. Laser welding technology (**Fig. 1**) due to its numerous advantages in comparison to conventional welding methods has been applied in many industries. Implementation of laser welding technology has contributed to the search for new, innovative design solutions, reducing the manufacturing time and costs of production with unchanged mechanical properties of the joint. Obtained in laser butt-welding process, one of the modern welded constructions are sandwich panels [1] of different types, depending on the shape of the stiffening element.

The use of sandwich panels continues to grow and effectively displaces classically fillet welded T-joints. In the laser butt-welding process of sandwich panels the beam penetrates the outer surface of the faceplate joining it with a stiffening core [2]. The main issues in these joints are welding deformations affecting the final deformation of the entire large-scale construction. The execution of appropriate joints with required quality and mechanical properties requires the analysis of thermomechanical phenomena occurring during welding and the prediction of appropriate process parameters ensuring significant reduction of welding deformations [3-9]. Experimental research on thermomechanical phenomena in welding processes are expensive and time consuming therefore mathematical and numerical modelling is becoming a cheaper alternative.

Numerical analysis of the distortion of welded joints is very important at the initial stage of the design, in terms of the quality and the durability of welded constructions. Mathematical and numerical model of coupled thermal, structural and mechanical phenomena should allow the execution of a comprehensive analysis taking into account phase transformations during material's state changes, phase transformations in solid state and the influence of structural strain on the deformation of welded joints [3].

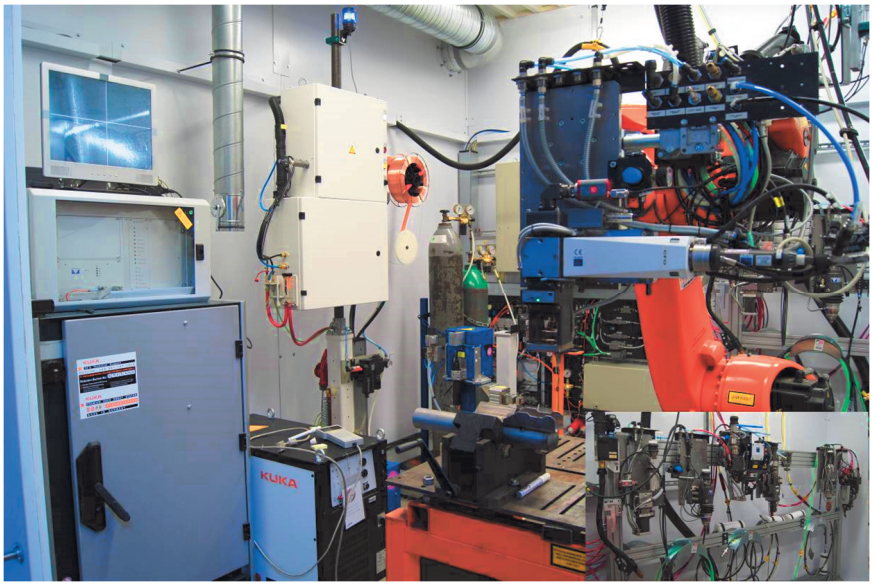

Fig. 1 Research station at Welding Institute in Gliwice, equipped with Trumpf TruDisk 12002

This work concerns numerical modelling of thermomechanical phenomena in laser welding process, performed to predict distortion of butt-welded T-joints made of S355 steel. Numerical simulations are executed in ABAQUS FEA engineering software, based on finite element method. Additional subroutines are developed in order to implement movable heat source power distribution as well as phase transformations in solid state into the analysis. Presented results include calculated temperature distribution and welding deformations generated by temperature field and structural transformations. Numerically obtained displacement is compared to experimental results in order to assess the suitability of developed numerical models for practical applications.

2. NUMERICAL MODELING

Abaqus/Standard solver is used in thermal analysis. Temperature field is described by energy conservation equation with Fourier law expressed in the variational formulation [10], as follows:

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

where $\lambda=\lambda(T)$ is a thermal conductivity [W/(m K)], U is a internal energy, 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 initial condition $t = 0 : T = T_o$ and boundary conditions of Dirichlet, Neumann and Newton type taking into account heat loss due to convection and radiation as well as welding heat flux towards heated surface. Effective convection-radiation coefficient is assumed in calculations [3, 8, 9] and constant ambient temperature T_0 = 20 °C. On the surface of laser beam impact, heat dissipation is forced due to the liquid material flow in the fusion zone and blow of shielding gas. Therefore, model proposed by Mundra and DebRoy [8] is used in the analysis. On remaining boundaries of the T-joint Vinokurov model [9] is assumed for constant radiation coefficient (ε=0.5).

Fuzzy solidification front is assumed in the model [3, 5, 11]. Internal energy U in equation (1) takes into account the latent heat of fusion H_L=270×10^3 J/kg in the mushy zone (between solidus temperature T_S=1477 °C and liquidus temperature T_L=1527 °C). In the solidification model changes in density and specific heat are assumed

with linear approximation of solid fraction between solidus and liquidus temperatures, where ρ_S = 7800 kg/m^3, ρ_L = 6800 kg/m^3, c_S = 650 J/kg°C, c_L = 840 J/kg°C.

The power distribution of movable laser beam heat source is implemented into DFLUX subroutine where the motion of welding source is defined for every time increment as $x = v \cdot t$, where v is welding speed [m/min] and t is actual time [s]. Welding heat source is described by Gaussian distribution along radial direction with linear decrease of energy density along material penetration depth [8], expressed as follows:

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

where Q is laser beam power [W], r_0 is beam radius [m], $r = \sqrt{x^2 + y^2}$ is actual radius [m], s is penetration depth [m], z is actual penetration [m].

Numerical analysis of phase transformations in solid state performed in ABAQUS FEA requires two additional subroutines HETVAL and UEXPAN. Implementation of HETVAL in thermal analysis allow the determination of maximum temperature (T_{max}) of thermal cycle as well as heating and cooling times (t_h and $t_{8\text{-}5}$) for every finite element in the weld and heat affected zone. Estimated data are further exported to UEXPAN subroutine used in mechanical analysis to calculate kinetics of phase transformations during heating and cooling of steel as well as isotropic strain (thermal and structural strain). Kinetics of phase transformations in solid state analyzed in UEXPAN subroutine is determined on the basis of modified kinetics of phase transformations models [12] as well as interpolated CHT and CCT diagrams for S355 steel.

Mechanical analysis is executed taking into account previously calculated temperature history. Total strain is defined as a sum of elastic (ε^e), plastic (ε^p), thermal and structural strain (ε^{TPh}):

$$\varepsilon^{total} = \varepsilon^e + \varepsilon^p + \varepsilon^{TPh} \tag{3}$$

Elastic strain is modelled for isotropic material using Hooke's law with temperature depended Young's modulus and Poisson's ratio. Plastic flow model is used to determine plastic strain based on Huber-Mises yield criterion and isotropic strengthening. Thermal and structural strain is expressed in the increase form [13]:

$$d\varepsilon^{TPh} = \sum_i \alpha_i \eta_i dT - sign(dT) \sum_i \varepsilon_i^{Ph} d\eta_i \tag{4}$$

where $\alpha_i = \alpha_i(T)$ are thermal expansion coefficients of austenite, bainite, ferrite, martensite and pearlite, $\varepsilon_i^{Ph} = \varepsilon_i^{Ph}(T)$ is an isotropic structural strain resulting from the transformation of the base structure into austenite during heating and each phase (ferrite, pearlite, bainite or martensite) arising from austenite during cooling, $d\eta_i$ is a volumetric fractions of phases, sgn (.) is a sign function. Thermal expansion coefficients and structural strains are determined on the basis of dilatometric research [3].

3. EXPERIMENTAL RESEARCH

Laser butt-welding of T-joint was performed at Welding Institute in Gliwice on robotic welding station (**Fig. 1**) equipped with Trumpf TruDisk 12002 laser having maximum power 12 kW. The joint consists of two perpendicularly arranged plates made of S355 steel. The process was carried out without additional material, using the following process parameters: laser beam power Q = *4 kW*, welding speed v = 4.0 m/min, the beam radius r_0 = *0.25 mm*. General view of the resulting joint and macroscopic picture of the cross section of the joint are illustrated in **Fig. 2**.

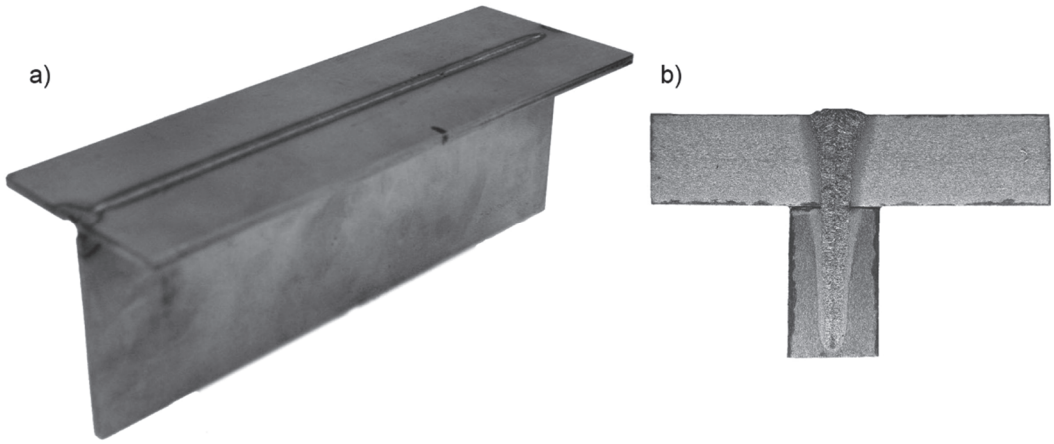

Fig. 2 Experimental research: a) a general view, b) macroscopic picture of the cross section of T-joint

The displacement in laser butt-welded T-joint was measured using laboratory New Form Talysurf profilographometer 2D/3D Taylor Hobson 120 (**Fig. 3b**). Measurement scheme of the displacement along z-axis in perpendicular direction to the weld line (the deflection) is shown in **Fig. 3a**.

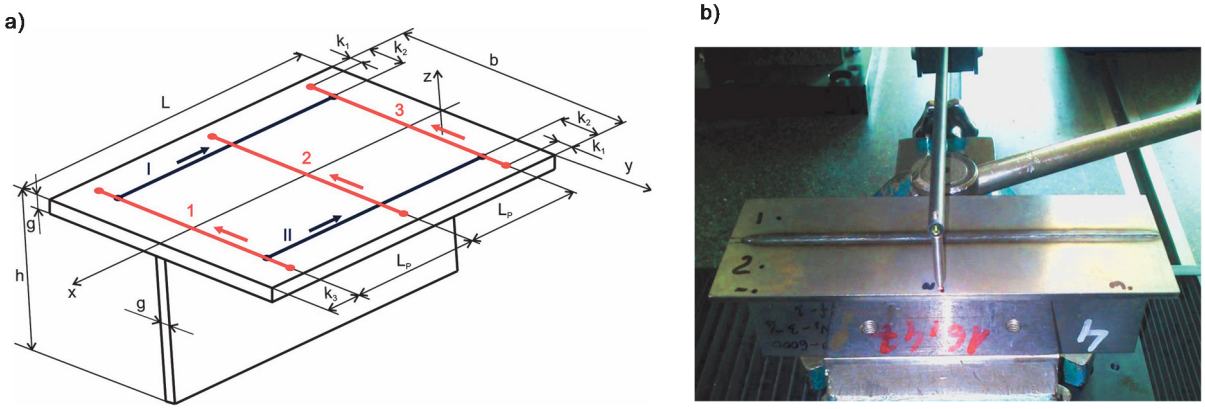

Fig. 3 Measurements of deformations*:* a) measurement scheme (L = 150 mm, L_p = 60 mm, b = 50 mm, g = 2.5 mm, h = 52.5 mm, k_1 = 2 mm, k_2 = 15 mm, k_3 = 12.5 mm), b) profilographometer used in the research

4. RESULTS AND DISCUSSION

The same process parameters are used in all numerical simulations as in experimental research. Laser beam power Q = 4 kW, beam radius r_0 = 0.25 mm, and welding speed v = 4 m/min. Heat source penetration depth is assumed as s = 8.05 mm on the basis of experimental verification. In order to reduce computational time, symmetry of the joint is assumed in calculations taking into account appropriate boundary conditions in the plane of symmetry (**Fig. 4**).

Obtained temperature distribution in the longitudinal section and cross section of welded T-joint is presented in **Fig. 5** where solid line points out the boundary of melted zone (isoline $T_L \approx 1527$ °C) and dashed lines indicated the boundary of heat affected zone (isoline $Tg \approx 727$ °C determined by average austenitization temperature Ac_1). Additionally, in this figure (**Fig. 5b**) the comparison between numerically estimated characteristic zones in the cross section of the joint and the real weld is presented.

Numerically estimated displacement u_z along x-axis in laser welded along T-joint is illustrated in **Fig. 6** for three chosen lines that correspond to experimentally measured deflection (**Fig. 3a**).

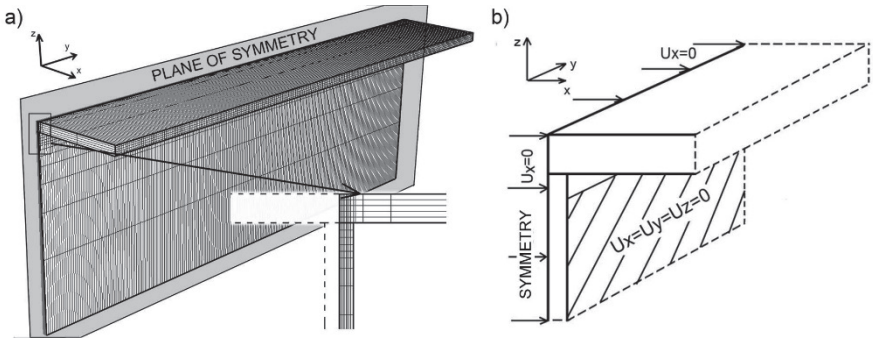

Fig. 4 Scheme of analyzed domain: a) discrete model, b) boundary conditions

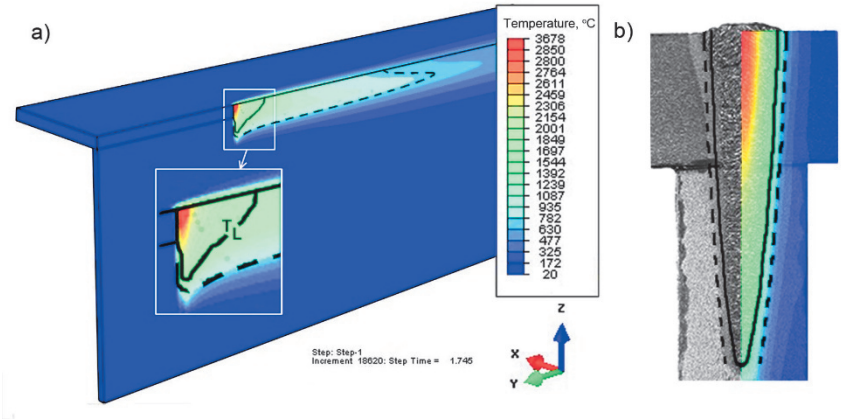

Fig. 5. Temperature distribution in welded T-joint: a) temperature profile, b) comparison of temperature distribution in the cross section of the joint with the real weld

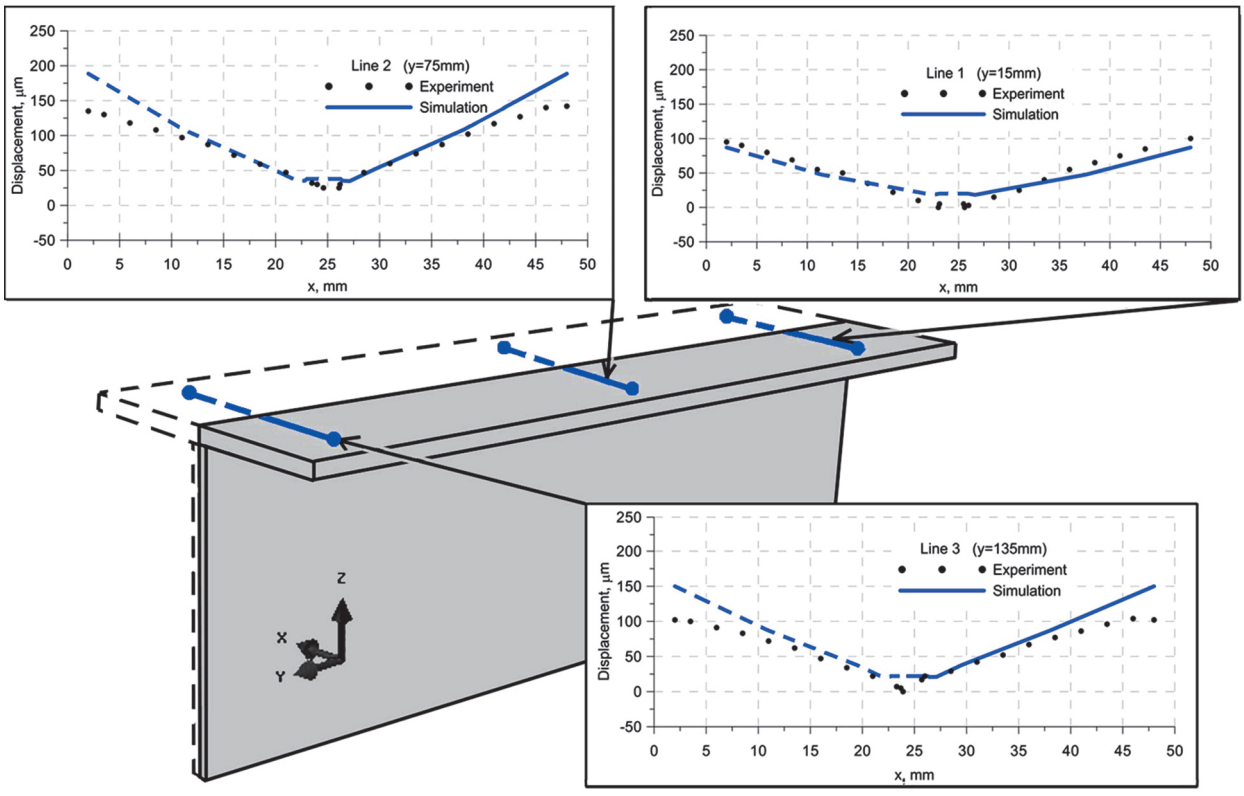

Fig. 6 Deflection along x-axis: a) line 1, b) line 2, c) line 3 (corresponding to **Fig. 3**)

CONCLUSIONS

Numerical analysis of thermal and mechanical phenomena made in Abaqus FEA requires implementation of additional procedures written in FORTRAN programming language. Elaborated subroutines allowed the analysis of movable heat source power distribution, kinetics of phase transformation in solid state as well as thermal and structural strain in Abaqus finite element simulation of laser butt welding process.

Obtained results of numerical simulations show that laser beam pass through the faceplate (**Fig. 5**) joining it with core stiffener (I-core joint) for chosen process parameters. It can be observed that deflection is symmetrical, relatively small and reaches the peak in a half of the width (*b*/2) of welded T-joint (**Fig. 6**).

Experimental research provided data describing heat source penetration depth, which was used to verify the model of laser beam power distribution. Comparison of the geometry of melted zone and heat affected zone with numerically predicted characteristic zones (**Fig. 5**b) shows a good agreement, which indicates a proper selection of proposed numerical solutions in the analysis. This is also confirmed by a comparison of the displacement in the joint obtained both numerically and by experimental research.

Elaborated numerical models can provide information about the quality and mechanical properties of laser welded joint in terms of the use of various process parameters, therefore numerical analysis may be helpful in further developing of “sandwich” panels.

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