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Numerical modelling of thermal phenomena in laser beam and hybrid welding processes using Abaqus FEA

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Abstract

This paper concerns numerical analysis of thermal phenomena accompanying laser beam and laser-arc hybrid welding processes. Temperature field was obtained on the basis of the solution into energy conservation equation with Fourier law using finite element method. ABAQUS/Standard solver was used for calculations. Electric arc and laser beam heat sources were described respectively by "double ellipsoidal" heat source and Gaussian distribution with assumption of linear decrease of heat source power intensity with material penetration deep. Heat source movement along welded plate was obtained using DFLUX subroutine. Thermo-physical parameters dependant on temperature as well as latent heat of fusion were taken into account in FE analysis. The results of calculations include temperature field in rectangular elements butt welded by a single laser beam and hybrid laser-arc technique.

Keywords: Laser Beam Welding, Hybrid Welding, Temperature Field, Finite Element Analysis

1. Introduction

Thermal load of welded elements depends on the type of welding method and a kind of welding source and is an important phenomenon, since it determines the shape of the weld, structure composition and properties of welded joint.

Physical phenomena accompanying welding processes are the scope of foundry, metallurgy and mechanics. The welding pool is created due to heating and melting the material by the welding source. Heat transfer in welded joint significantly affects size, shape and depth of the fusion zone, thus after solidification geometry of the weld [1, 2]. Modelling of welding processes is very complex since it includes coupled thermal phenomena such as conduction, convection, radiation in phase transformation system (solid-liquid state, liquid-gas state, phase transformations in solid state) [3, 4].

In recent years, due to significant progress in computer science, numerical modelling becomes an alternative to experimental studies. Abaqus is commercial software which allows for simulation of thermal phenomena in wide range of industrial processes. However, this tool used in simulations of welding processes requires an appropriate modelling of movable welding source, which can be implemented into DFLUX subroutine [5, 6].

This paper contains results of numerical simulations of temperature field in plates butt-welded by two different processes: laser beam welding and laser-arc hybrid welding, which are among the most modern and developing techniques for joining metals.

In laser welding, the beam is a heat source with a high concentration of energy and high power. This heat source penetration in material results from the analysis of the process [7] and is closely related to the density and level of energy concentration as well as physical properties of the material. A highly concentrated beam causes rapid melting of the material, which allows using very high welding speed with a small amount of molten material and a small heat affected zone. During welding the material is intensively heated to high temperatures, reaching up to the boiling point. Local increase of temperature leads not only to melting the workpiece, but also to the local evaporation of metal and the creation of the "keyhole", which is also a heat source penetrating the material [7, 8].

Laser-arc hybrid welding process combines laser beam welding with electric arc welding interacting in a single process. The combination of laser beam and electric arc allows for creation of joints that have many advantages in comparison to welds made in a single laser beam welding [9, 10]. However, weld shape and quality of the joint depends on the proper selection of the large number of process parameters such as laser beam power, arc current and voltage, welding speed, laser beam spot diameter, angle of the electrode, relative arrangement of heat sources, etc. Selection of some process parameters can be estimated by numerical simulation of this welding process.

In this study numerical analysis of heat transfer was carried out in ABAQUS/Standard module. Numerical model takes into account thermo-physical properties of steel changing with temperature [1] and latent heat of fusion [8, 11]. The implementation of a movable heat source in ABAQUS\Standard was established in DFLUX subroutine which allowed for modelling of movable welding source used in simulation of discussed welding processes.

2. Mathematical and numerical model

Numerical analysis of temperature field was performed for laser beam and hybrid laser-arc butt welded plate. „Uncoupled heat transfer" [5] analysis in Abaqus/Standard solver was performed to calculate temperature field in welded element. The model takes into account thermo-physical parameters, such as thermal conductivity, density and specific heat dependent on temperature. ABAQUS thermal analysis is based on the energy conservation equation and Fourier's law [6]. Temperature field in variational formulation is expressed as follows

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

where $\lambda=\lambda(T)$ is a thermal conductivity [W/mK], U is a internal energy, Q is a volumetric source power [W/m^3] with laser beam and electric arc volumetric heat sources taken into account, q_S is a heat flux toward element surface [W/m^2], δT is a variational function and $T = T(x_\alpha, t)$ is a temperature [K].

Equation (1) is completed by initial condition $t = 0 : T = T_0$ and boundary conditions of Dirichlet, Neumann and Newton type, with heat loss due to convection and radiation taken into account.

Boundary conditions are defined as follows

$$T\big|_\Gamma = \tilde{T} \qquad (2)$$

$$q_S = -\lambda \frac{\partial T}{\partial n} = \alpha_k (T\big|_\Gamma - T_0) + \varepsilon\sigma(T\big|_\Gamma^{\;4} - T_0^4) - q(r,0) \qquad (3)$$

where α_k is a convective coefficient, assumed as α_k=50 W/m^{2}K, ε is radiation coefficient (ε=0.5), and σ is Stefan-Boltzmann constant and $q(r,0)$ is the heat flux towards the top surface of welded workpiece ($z=0$) in the source activity zone.

Melting and solidification phenomena was considered assuming fuzzy solidification front with linear approximation of solid fraction (f_S) between solidus (T_S=1750K) and liquidus (T_S=1800K) temperatures [11], defined as follows

$$f_s = \begin{cases} 1 & \text{for} \quad T < T_S \\ \dfrac{T_L - T}{T_L - T_S} & \text{for} \quad T_S \le T \le T_L \\ 0 & \text{for} \quad T > T_L \end{cases} \qquad (4)$$

Density was calculated from the ratio of density in solid and liquid state: $\rho = \rho_S f_S + \rho_L (1 - f_S)$, where density of solid and liquid state was set respectively ρ_S=7800 kg/m^3 and ρ_L=6800 kg/m^3.

In equation (1) internal energy U takes into account the latent heat of fusion, thus specific heat $c(T) = dU/dT$ is defined as follows

$$c(T) = \begin{cases} c_S & \text{for} \quad T < T_S \\ \dfrac{c_S + c_L}{2} + \dfrac{H_L}{(T_L - T_S)} & \text{for} \quad T_S \le T \le T_L \\ c_L & \text{for} \quad T > T_L \end{cases} \qquad (5)$$

where c_S and c_L is specific heat of solid and liquid phase respectively (assumed as c_S=650 and c_L=840 J/kgK), H_L is a latent heat of fusion which was set to 270×10^3 J/kg.

Thermal conductivity varies with temperature in the solid state $\lambda=\lambda(T)$ was assumed in calculations, according to data form the literature. Much higher value of $\lambda(T)$ was assumed in high temperatures, which corresponds to the motion of liquid material in the welding pool [1, 8]. In temperatures $T<T_1$=1000^{o}C thermal conductivity was empirically determined according to the relationship

$$\lambda(T) = 59.92 - 0{,}0221T - 5.4 \cdot 10^{-5} T^2 + 4.3 \cdot 10^{-8} T^3 \qquad T \in [0, 1000\,^oC] \qquad (6)$$

where $\lambda(T)$ was assumed to be constant: $\lambda_{const}=\lambda(T_1)=\lambda(1000)$ in temperature range $1000<T<T_S$ [^{o}C].

In the mushy zone $\lambda(T)$ was linearly approximated, according to the following formula

$$\lambda(T) = \lambda(T_1) + (\lambda(T_L) - \lambda(T_1)) \frac{T - T_s}{T_L - T_s} \qquad (7)$$

where $\lambda(T_L)=\lambda_{const}=117$ [W/m°C] is liquid phase thermal conductivity In temperatures exceeding liquidus temperature.

A very important issue, taking into account the formal rules of numerical modelling, is the selection of an appropriate heat source model used in calculations. The new mathematical models of the distribution of energy flux delivered to the material and further transport of the energy into the material are constantly looked for in order to represent the real welding conditions as much as possible. In modelling of laser beam welding process laser beam interaction on the material is usually considered as a volumetric heat source with a Gaussian distribution in radial direction and assumed changes of energy intensity with materials penetration deep [2-4, 7, 8]. A major problem in the modelling of the laser beam energy distribution is determination of the size and shape of the heat source along the thickness of the workpiece with specified accuracy and conditions for similarity. From analysis of this welding process it is observed that power decreases with increasing the depth of penetration, which should be taken into account in numerical modelling.

In this study linear decrease of heat source with penetration deep is assumed. Laser beam heat source model is expressed by the following formula [7]

$$Q_1(r,z)=\frac{Q_L}{\pi r_o^2 d}\exp\left[\left(1-\frac{r^2}{r_o^2}\right)\left(1-\frac{z}{d}\right)\right] \tag{8}$$

where Q_L is laser beam power [W], r_0 is a radius of laser beam, $r=\sqrt{x^2+y^2}$ is a current radius, d is maximum penetration deep of a heat source [m] and z is a current penetration [m].

In numerical analysis of hybrid welding process two different heat sources melts the workpiece. Except laser beam heat source model described in (8) an additional, proposed by Goldak [12], "double ellipsoidal" model is used to describe electric arc heat source power distribution. This heat source model can simulate different types of arc welding and various process parameters, and also has very good features of power density distribution control in the weld and heat affected zone (HAZ), therefore is widely accepted by the researchers.

In Goldak's heat source model power distribution is realized in two half-ellipsoids connected each other with one semi-axis, thus heat source is defined as a sum of front and rear energy distribution, described as follows

$$Q_2=\begin{cases} q_1(x,y,z)=\dfrac{6\sqrt{3}f_1Q_A}{abc_1\pi\sqrt{\pi}}\times\exp(-3\dfrac{x^2}{c_1^2})\times \\ \quad\times\exp(-3\dfrac{y^2}{a^2})\times\exp(-3\dfrac{z^2}{b^2}) & \text{for } x<x_o \\ q_2(x,y,z)=\dfrac{6\sqrt{3}f_2Q_A}{abc_2\pi\sqrt{\pi}}\times\exp(-3\dfrac{x^2}{c_2^2})\times \\ \quad\times\exp(-3\dfrac{y^2}{a^2})\times\exp(-3\dfrac{z^2}{b^2}) & \text{for } x\geq x_o \end{cases} \tag{9}$$

where a, b, c_1 and c_2 [m] are set of axes defining front ellipsoid and rear ellipsoid, Q_A is the heat input [W], f_1 and f_2 ($f_1+f_2=2$) represents energy distribution at the front and the rear section of the heat source.

3. Results of calculations

Simulations of laser beam welding as well as laser-arc hybrid welding were performed for plate made of steel with length L=250mm, width w=30mm and thickness g=5mm. It was assumed that welding is realized without the additional material. The schematic sketch with assumed the same spatial discretization for simulations of both laser beam and hybrid welding processes is illustrated in figures 1-2. Finite element mesh is dense in the range of heat sources activity zone with linear increase of spatial step in x-y plane. In order to reduce computational time, symmetry of the joint was used assuming only a half of the mesh with thermal isolation constraint in the plane of symmetry. Used in computational model finite element mesh consist of 16200 cubic elements. Laser beam welding and hybrid welding process parameters assumed in calculations are illustrated in table 1.

Table 1.
Technological parameters of laser beam welding and hybrid welding used in calculations

Welding method	Parameters		
Laser beam welding	Q=3800W, r_o=1mm, d=7 mm, v=0.7m/min		
Laser-arc hybrid welding	Laser-to-arc distance	Arc	Laser beam
	d=5 mm	Q_1=7000 W, c_1=4 mm, c_2=12 mm, a=4 mm, b=4 mm	Q_2=3600 W, r_0=1 mm, s=7 mm
		v= 1.6 m/min	

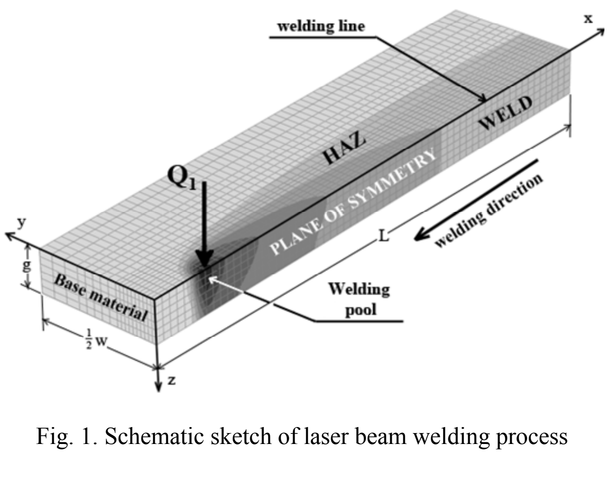

Fig. 1. Schematic sketch of laser beam welding process

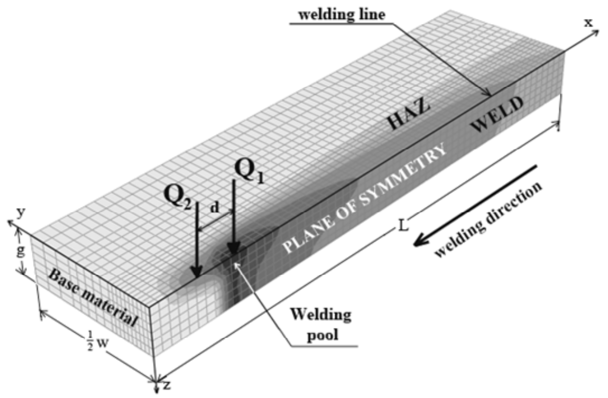

Fig. 2. Schematic sketch of laser-arc hybrid welding process with leading electric arc in the tandem

In order to analyze welding processes in Abaqus FEA, movable heat sources must be implemented in DFLUX subroutine. Movement of a heat source along welding direction (x-direction) is defined using constant welding speed in the analysis and simulation time passed into the subroutine from Abaqus solver.

Temperature distribution at various depth of welded joint (in the middle of heat sources activity plane) as well as temperature distribution at the top surface of welded workpiece (*z*=0), at various distances from the centre of welding source are presented in figures 3-4 for simulation of laser beam welding (fig. 3) and laser-arc hybrid welding (fig. 4) respectively. The general view on temperature field in welded element and temperature distribution in the cross section of laser beam and hybrid welded joints are presented in figures 5-7.

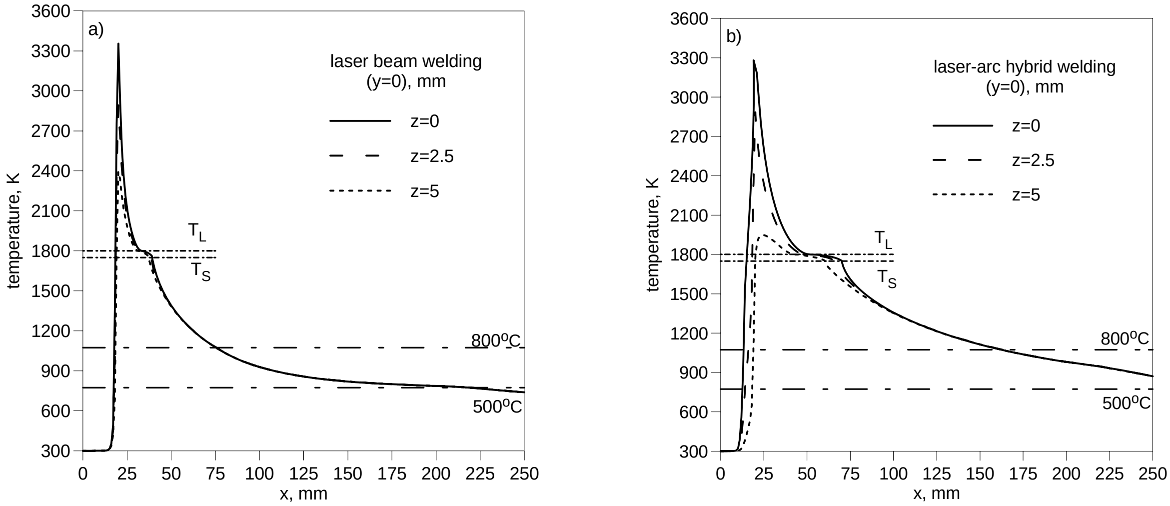

Fig. 3. Temperature distribution at various depth of welded joints in a) laser welding and b) hybrid welding processes

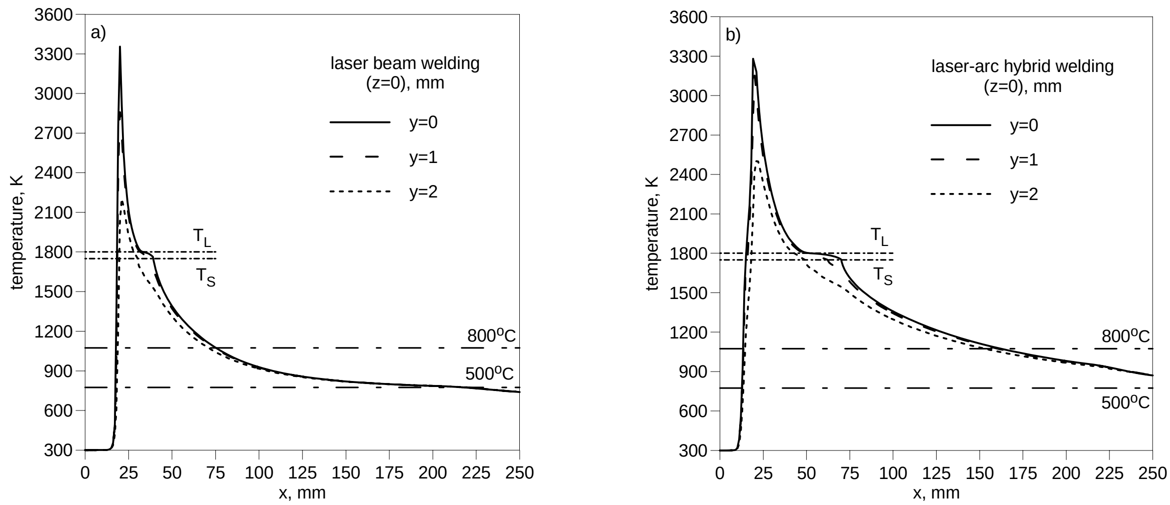

Fig. 4. Temperature distribution at the top surface of welded joint (*z*=0) in a) laser welding and b) hybrid welding processes

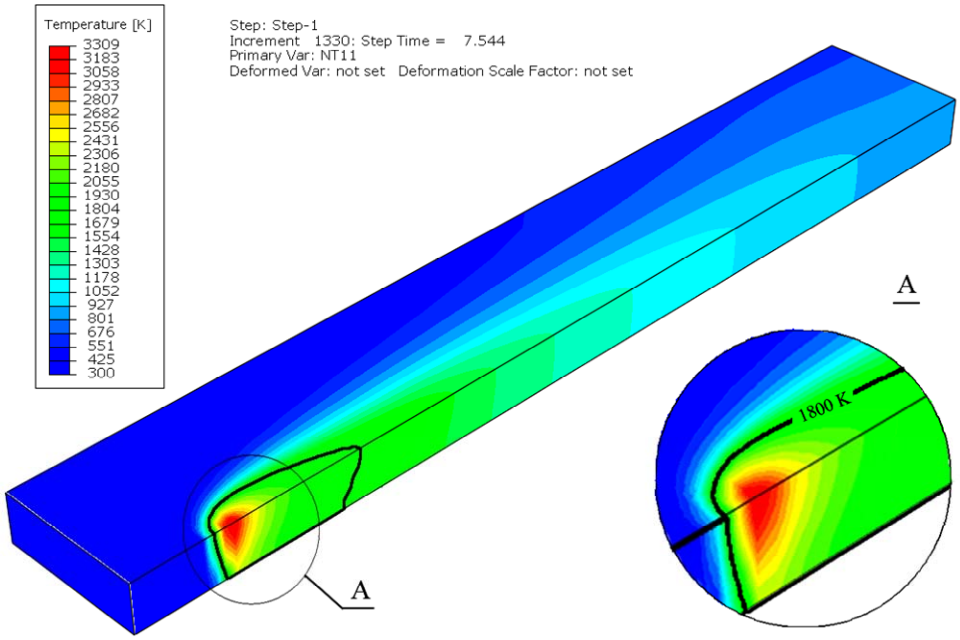

Fig. 5. Temperature field in laser beam welded joint

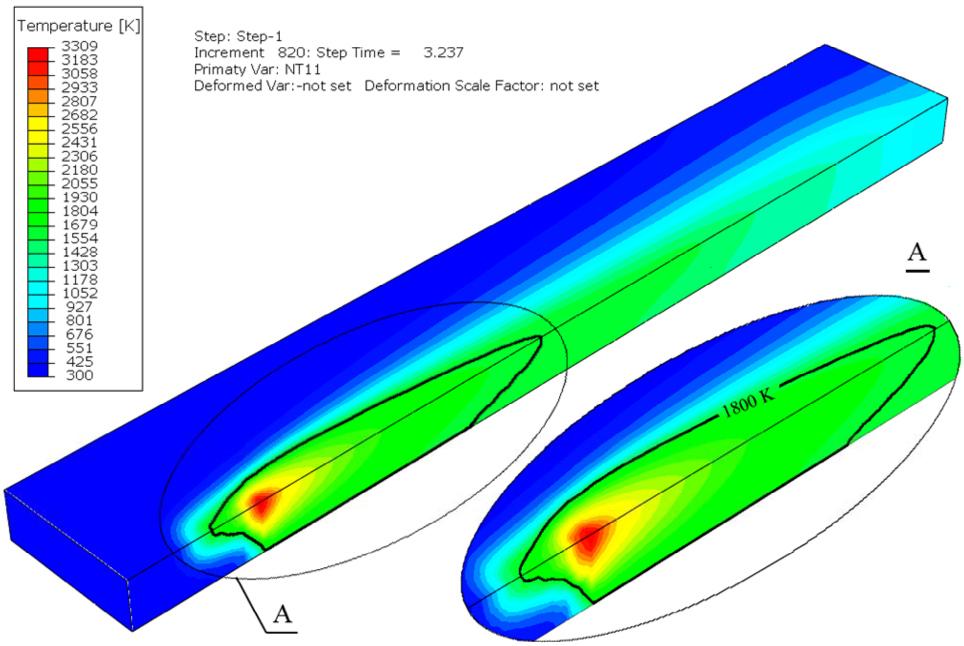

Fig. 6. Temperature field in laser-arc hybrid welded joint

In figures presenting temperature distribution (fig. 3-4), melting (solidification) temperature range is pointed out, i.e. solidus temperature (T_S=1750K) and liquidus temperature (T_L=1800K), and also temperature range 800÷500 ^{o}C used to determine cooling rates ($t_{8/5}$) as the parameters characterizing cooling intensity of welded joint at a chosen points.

Boundary of fusion zone (T_L) is marked in figures 5-6 and in figure 7 where additionally heat affected zone boundary (T=1000K) is shown.

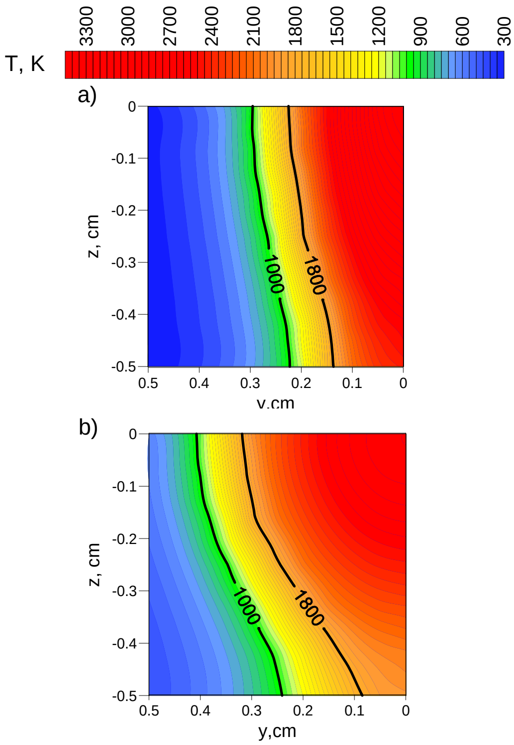

Fig. 7. Temperature field in cross section of the joint welded by a) laser beam and b) laser-arc hybrid welding techniques

4. Conclusions

Abaqus FEA allows for analysis of temperature field in welded elements by using DFLUX subroutine for definition of appropriate movable heat sources power distribution models.

From the observation of temperature distribution in various heating zones it can be seen that laser beam heating has impact nature. There are very large temperature gradients during heating and cooling. Using laser arc hybrid heat source contributes to the reduction of both heating and cooling rates which can have a significant, positive effect on the structure of welded joints and stress generated during welding

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Modelowanie numeryczne zjawisk cieplnych w procesie spawania laserowego i hybrydowego z wykorzystaniem Abaqus FEA

Streszczenie

Praca dotyczy analizy numerycznej zjawisk cieplnych towarzyszących procesom spawania wiązką laserową oraz spawania hybrydowego laser-łuk elektryczny. Rozkłady temperatury otrzymano z numerycznego rozwiązania równania zachowania energii z prawem Fouriera metodą elementów skończonych. Do obliczeń wykorzystano moduł obliczeniowy ABAQUS/Standard. Do opisu rozkładu mocy łuku elektrycznego wykorzystano model „podwójnie elipsoidalny", natomiast rozkład mocy wiązki laserowej opisano modelem gaussowskim z uwzględnieniem liniowego spadku intensywności mocy źródła z głębokością penetracji materiału. Symulację ruchu źródła spawającego uzyskano dzięki zastosowaniu procedury DFLUX. W analizie uwzględniono zmienne z temperaturą własności termofizyczne a także ciepło krzepnięcia w obszarze dwufazowym. Wyniki obliczeń numerycznych obejmują rozkłady temperatury w elementach prostopadłościennych spawanych doczołowo wiązką laserową i techniką hybrydową laser-łuk elektryczny.