Application of Abaqus to analysis of the temperature field in elements heated by moving heat sources

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Abstract

Numerical analysis of thermal phenomena occurring during laser beam heating is presented in this paper. Numerical models of surface and volumetric heat sources were presented and the influence of different laser beam heat source power distribution on temperature field was analyzed. Temperature field was obtained by a numerical solution the transient heat transfer equation with activity of inner heat sources using finite element method. Temperature distribution analysis in welded joint was performed in the ABAQUS/Standard solver. The DFLUX subroutine was used for implementation of the movable welding heat source model. Temperature-depended thermophysical properties for steel were assumed in computer simulations. Temperature distribution in laser beam surface heated and butt welded plates was numerically estimated.

Keywords: Numerical simulations, Temperature field, Heat source, Laser beam heating, Laser beam welding

1. Introduction

The laser beam is a concentrated heat source, which has a wide application in industry, furthermore its wide spectrum of application still increasing. Laser material processing is most popular nowadays and laser welding is one of the most modern and developing techniques of metal joining. This welding method allows joining materials previously regarded as a nonweldable or difficultly weldable. Because of technological advantages of laser welding and laser surface treatment these technologies are competing with previously used conventional methods. One of the important features of laser heating is forming of the surface layer without changing the volume of the workpiece. Rapid laser melting in the welding process, allows obtaining very high welding speed with a small melted zone and heat affected zone [1-8].

However, the laser beam heating creates new, untypical requirements and is a cause of occurring physical phenomena untypical at conventional heating methods. Heat distribution proceeds in different conditions in comparison with heating by traditional heat sources of low and medium power. During laser processing the material is heated to very high temperatures, even reaching the boiling point and thermal phenomena occurring in the laser welding process are also considered on the basis of metallurgy and foundry [9-15].

The movable high power density heat source, which is the laser beam, differs from classical welding and heating sources. Very important, in terms of formal modeling, is a proper selection of heat source shape and its energy distribution, used in numerical calculations. The new mathematical models describing the distribution of the energy flux taking into account the real conditions are being constantly looked for [1, 4, 13, 16].

The paper presents surface and volumetric heat sources distribution models and the results of the numerical simulation of temperature field in the laser beam surface heated and butt welded plates, performed using different heat source models. Numerical analysis was performed in ABAQUS/Standard module [17, 18]. Temperature-dependent thermophysical properties and latent heat of fusion were taken into account in the numerical model [10-12].

Numerical analysis of the temperature field in elements heated by a movable heat source made in ABAQUS\Standard requires the implementation of subroutines written in FORTRAN programming language, where the heat source power distribution used in the calculation can be modeled. For the implementation of movable heating sources, a DFLUX subroutine is used in this study.

2. Heat sources

In the number of papers published in recent years attention is paid to the numerical models of heat sources in the laser heating process. The papers mostly apply to a surface heat source models, but there are much less studies focused on the numerical models of welding heat sources (taking into consideration the laser beam penetration depth) [1, 4].

Essentially the Gaussian distribution model is used to describe the laser beam heat source power distribution, in the following form

$$q(r) = \frac{fQ}{\pi r_0^2} \exp\left(-f \frac{r^2}{r_0^2}\right) \tag{1}$$

where Q is the laser beam power [W], r_o is the beam radius [m], r is the current radius [m] and coefficient f (usually assumed as $f=3$) characterizes the beam distribution.

The shape of laser beam power distribution may be different then given by equation (1). Changes in heat source power distribution shape can be obtained by accepting different (even) exponents $n1$ and $n2$ [8, 15]

$$q(r) = \frac{3Q}{\pi r_0^2} \exp\left(-3\left(\frac{x}{r_0}\right)^{n1} - 3\left(\frac{y}{r_0}\right)^{n2}\right) \tag{2}$$

where x and y are the current coordinates, for $n1=n2=2$ this model is a typical Gaussian distribution.

In numerical modeling of the laser beam welding, as well as during laser beam heating, Gaussian model describing the laser beam heat source is often accepted [1, 4, 5, 7, 13, 14]. In modeling of the of laser beam heat source intensity distribution it's difficult to determine the size and shape of the heat source along the thickness of the welded element with specified accuracy, ensuring the similarity to real conditions. In heat source models, especially in analytical and analytical-numerical considerations, shape of the source is adopted in the form of equivalent volume of a cylinder of given radius r_o and height d, assuming a constant beam power over the entire laser beam penetration depth d.

$$q_v(r, z) = \frac{Q}{\pi r_o^2 d} \exp\left(-\frac{r^2}{r_o^2}\right) u(z) \tag{3}$$

where $u(z) = 1$ for $0 \le z \le d$ and $u(z) = 0$ for other positions of z, z is a current depth.

However, analysis of the welding process shows that the power of the beam decreases with increasing depth of the penetration, which should be taken into account in numerical modeling. Often it is assumed a linear decrease of energy, assuming a heat source in the shape of a cone or truncated cone [5].

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

where d is a penetration depth, and $r = \sqrt{x^2 + y^2}$.

Other heat source model, which takes into consideration changes in power density with penetration depth, is the cylindrical-involution-normal (C-I-N) [16] heat source power distribution, described by the following equation

$$q_v(r, z) = \frac{kK_z Q}{\pi\left(1 - e^{(K_z s)}\right)} e^{-\left(kr^2 + K_z z\right)} \left[1 - u(z - s)\right] \tag{5}$$

where $K_z = 3/s$ is the heat source power exponent [m^{-1}], $k = 3/r_0^2$ is the beam focus coefficient [m^{-2}] and s is heat source beam penetration depth [m], $u(z - s)$ is the Heaviside'a function.

The laser beam heat source energy intensity exponential change along penetration depth of welded element is taken into account in the Goldak's volumetric heat source model [3], usually used for numerical modeling of the electric arc heat source power distribution. The shape of this source is a combination of two half-ellipses connected to each other with one semi-axis. . Power distribution of this 'double ellipsoidal' heat source is described as follows

$$q_1(x, y, z) = \frac{6\sqrt{3} f_1 Q}{abc_1 \pi \sqrt{\pi}} \exp(-3\frac{x^2}{a^2}) \exp(-3\frac{y^2}{b^2}) \times$$

$$\times \exp(-3\frac{z^2}{c_1^2})$$

$$\tag{6}$$

$$q_2(x, y, z) = \frac{6\sqrt{3} f_2 Q}{abc_2 \pi \sqrt{\pi}} \exp(-3\frac{x^2}{a^2}) \exp(-3\frac{y^2}{b^2}) \times$$

$$\times \exp(-3\frac{z^2}{c_2^2})$$

where a, b, c_1 and c_2 are set of axes that define front ellipsoid and rear ellipsoid, f_1 and f_2 ($f_1 + f_2 = 2$) represent distribution of the heat

source energy at the front and the rear section, thus resultant distribution of the source energy is total sum described as $q_v(x,y,z)=q_1(x,y,z)+q_2(x,y,z)$, Q is the heat source power [W].

3. Temperature field. Mathematical and numerical model

Temperature field of the plate heated by the laser beam was determined using „Uncoupled heat transfer" finite element analysis in ABAQUS/Standard [17]. Temperature-depended thermophysical properties, such as thermal conductivity, density and specific heat were taken into account in calculations. ABAQUS thermal analysis is based on the law of energy conservation and Fourier's law [18]. Temperature field $T = T(x_\alpha, t)$ is expressed as

$$\int_V \rho \dot{U} \delta T \, dV + \int_V \frac{\partial \delta T}{\partial x_\alpha} \cdot \left(\lambda \frac{\partial T}{\partial x_\alpha} \right) dV = \int_V \delta T \, q_v \, dV + \int_S \delta T \, q_s \, dS \quad (7)$$

where λ is a thermal conductivity [W/mK], U is a internal energy, q_V is a laser beam heat source power [W/m³], q_s is a heat flux toward element surface [W/m²], δT is a variational function.
Initial condition $t = 0 : T = T_0$, boundary conditions of Dirichlet and Newton type, which takes into account the convection heat loss and radiation emission heat loss complete the equation (7)

$$T\big|_\Gamma = \tilde{T} \quad (8)$$

$$q_S = -\lambda \frac{\partial T}{\partial n} = \alpha_k (T\big|_\Gamma - T_0) + \varepsilon \sigma (T\big|_\Gamma^4 - T_0^4) \quad (9)$$

where α is convective coefficient, assumed as α_k=50 W/m²K, ε is radiation coefficient (ε=0.5), and σ is Stefan-Boltzmann constant.

Considering volumetric heat source distribution at the top surface of the element $q(r,0)$, boundary condition of Newton type (9) has the following form

$$q_S = -\lambda \frac{\partial T}{\partial n} = -q(r,0) + \alpha_k (T\big|_\Gamma - T_0) + \varepsilon \sigma (T\big|_\Gamma^4 - T_0^4) \quad (10)$$

The numerical analysis of the temperature field takes into account temperature dependent thermal conductivity presented in figure 1. It was assumed much higher value of effective thermal conductivity in the liquid zone than in the solid zone, because of the motion of liquid material in the melted zone [4, 9,14].

Internal energy U in equation (7) takes into account the latent heat of fusion (H_L) in the mushy zone with assumption of linear approximation of solid fraction. Specific heat $c(T) = dU/dT$ is described as follows

$$c(T) = \begin{cases} c_S & for \quad T < T_S \\ \dfrac{c_S + c_L}{2} + \dfrac{H_L}{(T_L - T_S)} & for \quad T_S \le T \le T_L \\ c_L & for \quad T > T_L \end{cases} \quad (11)$$

In the computations, thermo-physical properties were assumed as: solidus temperature T_S=1750K and liquidus temperature T_L=1800K, specific heat in solid state c_S=650 and in liquid state c_L=840 J/kgK, H_L=270×10³ J/kg (latent heat of fusion). Density in the mushy zone was calculated with linear approximation of solid fraction between T_S and T_L temperatures: $c_{LS}\rho_{LS} = c_S\rho_S f_s + c_L\rho_L(1-f_s)$, where ρ_S=7800 kg/m³ and ρ_L=6800 kg/m³. Solid fraction f_S in the mushy zone [10-12] is described by the following equation

$$f_s = \begin{cases} 1 & for \quad T < T_S \\ \dfrac{T_L - T}{T_L - T_S} & for \quad T_S \le T \le T_L \\ 0 & for \quad T > T_L \end{cases} \quad (12)$$
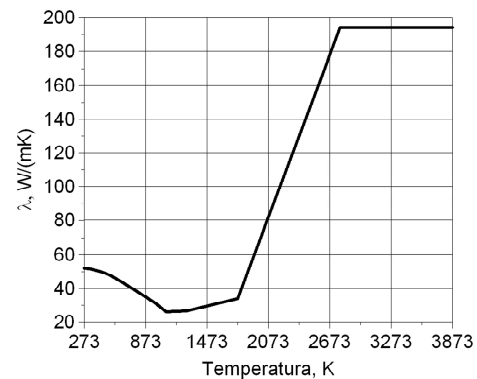

Fig. 1. Thermal conductivity assumed in calculations [4]

4. Results

Numerical simulations of temperature field in laser beam surface heating and welding processes were performed for the rectangular elements of dimensions 150x30x5mm. Movable heat source speed, the same for every simulation, was assumed as v=0.7m/min. Using the symmetry of the analyzed element (flat) for numerical calculations of surface heating as well as welding processes, half of the element was considered with assumption of thermal isolation in the plane of symmetry (fig. 2). In figure 2 finite element mesh used in simulations of laser surface heating as well as laser welding processes is also presented.

In numerical calculations of laser beam surface heating of the flat, heat source model (1) was used with coefficient f=3 as well as (2) model with n_1=2 and n_2=8, thus assuming a different (circular and rectangular) cross-section of the laser beam. In both cases heat source parameters were assumed as: $Q=3\,kW$ and r_0=1mm.

Temperature distribution in cross-section of element heated by the laser beam heat source with power distribution described by equations (1) and (2) is presented in figures 3 and 4 respectively. In these figures, characteristic temperature isolines (T=1000K) were pointed out, which determine the heat affected zone (HAZ), that is zones of structural transformations. From comparison of temperature distribution it can be observed that different cross-sections of the laser beam (circular and rectangular) contribute to the formation of different heating zones (fig. 3 and 4)

In numerical calculations of laser beam welding process (fig. 5) the same finite element mesh (fig. 2) was used as in the case of surface heating. Heat source models (4), (5) and (6) were used in temperature field simulations. Table 1 describes the heat sources parameters used in calculations.
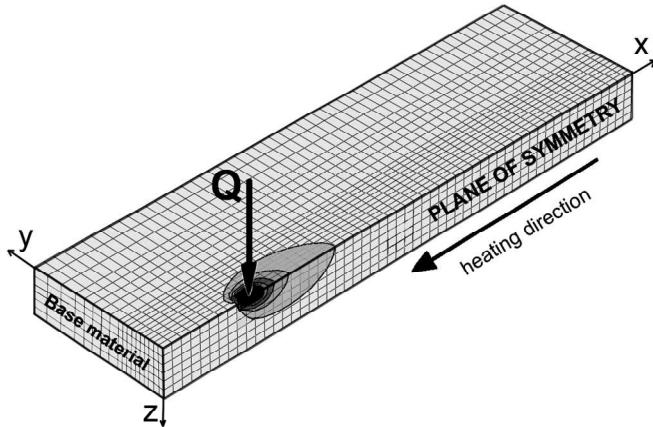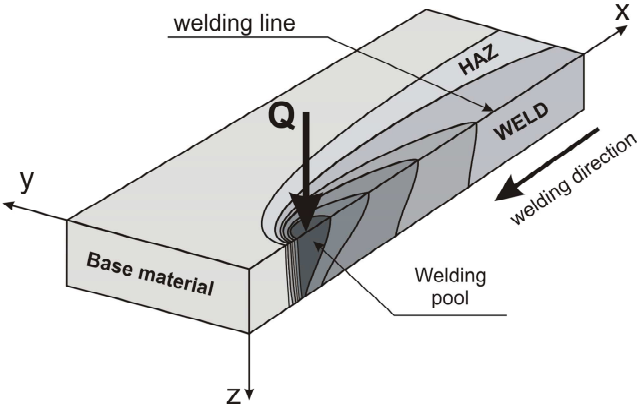

Fig. 2. Scheme of laser beam surface heating
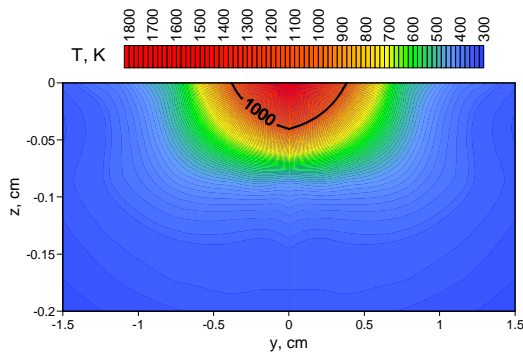
Fig. 3. Temperature distribution in cross-section of the element heated by heat source (1)

Fig. 4. Temperature distribution in cross-section of the element heated by heat source (2)

Fig. 5. Scheme of laser beam welding

Table 1.
Welding sources parameters

Heat source models	Parameters
Gauss model (4)	$Q = 3$ kW, $r_o = 1$ mm, $v = 0.7$ m/min, $d = 7$ mm
C-I-N model (5)	$Q = 3.2$ kW, $r_o = 1$ mm, $v = 0.7$ m/min, $ds = 7$ mm
Goldak's model (6)	$Q = 3.2$ kW, $c_1 = 1$ mm, $c_2 = 1$ mm, $a = 1$ mm, $b = 7$ mm, $f_1 = 0.6$, $f_2 = 1.4$, $v = 0.7$ m/min

Temperature field in welded elements calculated using three sources models is presented in figures 6, 7 and 8 respectively.
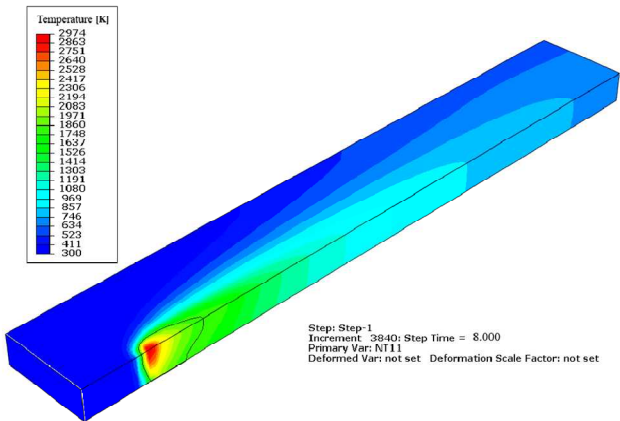

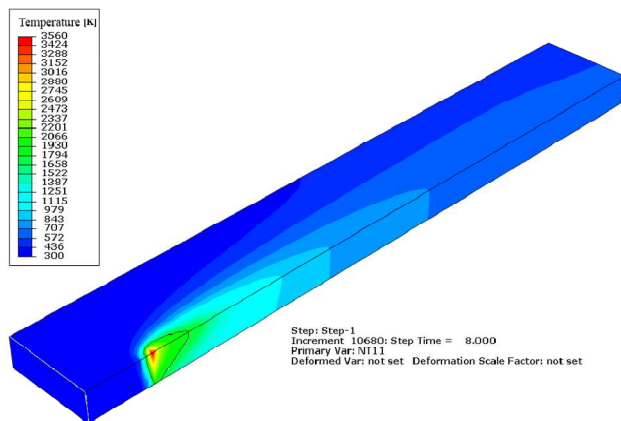Fig. 6. Temperature field in welded joint – heat source model (4)

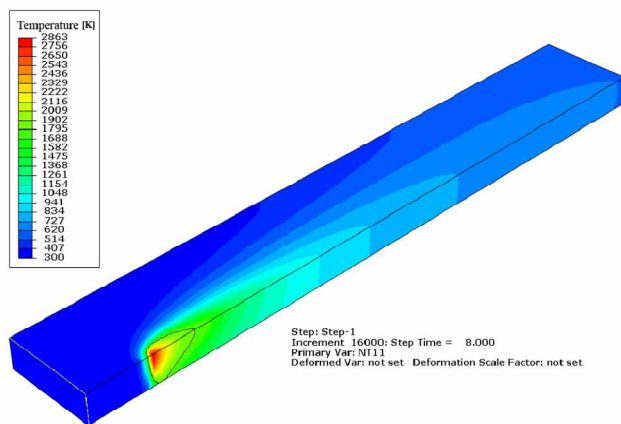Fig. 7. Temperature field in welded joint – heat source model (5)

Fig. 8. Temperature field in welded joint – heat source model (6)

In figure 9 temperature field is presented in the cross-section of welded joint obtained using (4), (5) and (6) heat source models. Marked temperatures isolines determine the fusion zone (T=1800K) and heat affected zone (T=1000K).
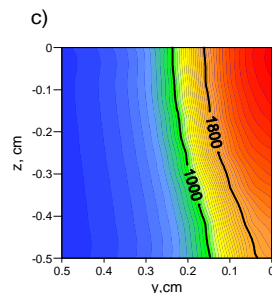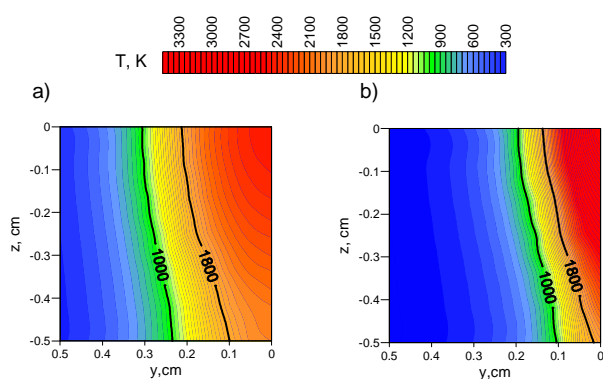

Fig. 9. Numerically estimated welded joints, a) heat source model (4); b) heat source model (5); c) heat source model (6)

A comparison of numerically estimated zones of welded joint (fig. 9) shows that using different heat source models in simulation of laser beam welding forms a very different shapes and sizes of characteristic weld zones.

5. Conclusions

Calculations of the temperature distribution are essential for the proper understanding and optimizing the laser surface heating and welding processes. On the basis of numerically obtained temperature distribution depending on used heat source model, the shape and the size of the melted zone as well as the heat affected zone can be estimated.

Using DFLUX subroutine in ABAQUS, temperature field with specification of movable heat source taken into account can be analyzed.

Numerically calculated temperature distribution is the base for determining the kinetics of phase transformations in solid state and estimating of the structure composition in elements heated by the laser beam.

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