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Aleksander Siwek*

NUMERICAL SIMULATION OF THE LASER WELDING

The model takes into consideration thermophysical and metallurgical properties of the remelting steel, laser beam parameters and boundary conditions of the process. As a result of heating the material, in the area of laser beam operation a weld pool is being created, whose shape and size depends on convection caused by the Marangoni force. The direction of the liquid stream depends on the temperature gradient on the surface and on the chemical composition as well. The model created allows to predict the weld pool shape depending on material properties, beam parameters, and boundary conditions of the sample.

Keywords: *laser treatment, computational fluid dynamics (CFD), Marangoni effect, metallurgical transformation, geometry of the melted zone*

SYMULACJA PROCESU LASEROWEGO SPAWANIA

Model uwzględnia własności termofizyczne i metalurgiczne przetapianej stali, parametry wiązki laserowej i warunki brzegowe procesu. W wyniku nagrzania materiału w obszarze działania wiązki lasera tworzy się jeziorko cieczy, którego kształt i rozmiar zależą od konwekcji wywołanej siłą Marangoniego. Kierunek strumienia cieczy zależy od gradientu temperatury na powierzchni, a także składu chemicznego. Utworzony model pozwala na przewidywanie kształtu strefy przetopionej w zależności od własności fizycznych materiału, parametrów wiązki i warunków brzegowych próbki.

Słowa kluczowe: *obróbka laserowa, komputerowa dynamika płynów, efekt Marangoniego, przemiany fazowe, kształt strefy przetopionej*

1. Introduction

Laser welding of metals and alloys is one of the most often applied welding techniques because of high joining speed, precision and low deformation in comparison with traditional welding process [1]. The process that make use of high power density laser beam is frequently used in industry. During the laser welding there occur such complicated phenomena as changes of material properties with temperature, phase transformations, creation of liquid phase and convection caused by, among other things, Marangoni flow effect [2].

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* Faculty of Metals Engineering and Industrial Computer Science, AGH University of Science and Technology, Kraków, Poland, `asiwek@agh.edu.pl`

Traditional optimization of the process based on experiment needs expenditures and is time-consuming. Making use of computer simulation allows to replace a part of experimental research with physical process modeling. In the present work there have been used computer programs of Gambit to shape modeling and building of finite elements mesh and the program Fluent by which calculations were carried out [3]. The numerical approach used in discretization is based on the finite element method to solve a two dimensional Navier-Stokes equation assuming incompressible flow. A laminar model and implicit formulation are suitable for solution convergence.

Calculations were executed on the IBM Blade Center HS21 computational cluster equipped with 112 Intel Xeon Dual Core 2.66 GHz with Linux RedHat OS in the Academic Computer Centre CYFRONET AGH. The simulation took about 1 h of one dual core CPU time to simulate about 0.1 s of real-time welding in 1000 iterations.

The model takes into consideration the thermophysical properties and metallurgical transformation of steel, laser beam parameters and boundary condition of the process. As a result of heating the material a weld pool is being created in the area of laser beam operation. The shape and size of the weld pool depend on convection caused by Marangoni force. The direction of fluid stream depends on the temperature gradient on the surface as well as on the chemical composition [4, 5, 6]. The created model allows to predict weld pool shapes depending on the physical properties of material, laser beam parameters and boundary conditions of specimen. The model takes into consideration the stages of heating and cooling. On the basis of continuous-cooling-transformation (CCT) diagram for welding material, it is possible to calculate the shape of areas of individual phase transformations appearance during the cooling of material [7, 8].

2. Mathematical description of the weld pool

The laser welding process is schematically shown on Figure 1. The laser beam of Gaussian distribution [9] moves over steel specimen supplying the surface with energy. It results in the creation and expanding of a metal weld pool until the axis of laser beam crosses a given intersection. The energy supplied by the laser beam is partially lost through radiation and natural convection. The circulation of liquid in the weld pool is forced by surface tension and buoyant force (Fig. 2). The section for which computations were carried out is marked in Figure 1.

A mathematical model of the problem includes the following physical phenomenon controlling behavior of weld pool: welding and solidification, movement of liquid in the pool, heat exchange in the pool, heat penetration to the treated material and heat exchange with the environment through free surface.

The model assumes that the layout is axially symmetrical (Fig. 1). Material properties such as density, specific heat, thermal conductivity and viscosity depend on temperature. At the velocity of laser beam assumed in the model, the thermocapillary movement of liquid plays a significant role in the vicinity of weld top surface (Fig. 2). It leads to an expansion of the weld pool.

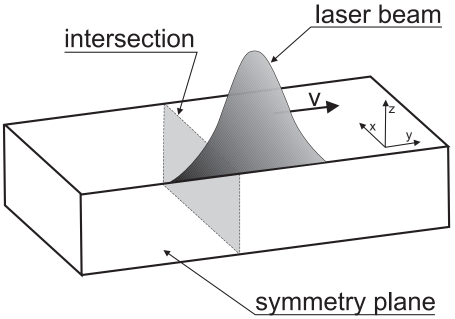

Fig. 1. Schematic illustration of the numerical model for laser surface welding process

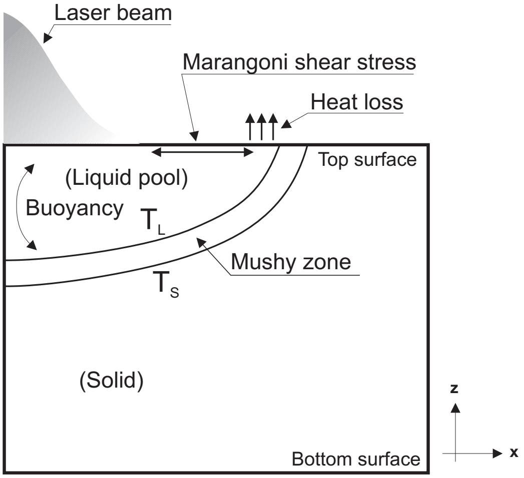

Fig. 2. Schematic illustration of the weld pool cross section

The influence of Marangoni effect on the top part broadening of the pool decreases along with increase of laser beam velocity movement over the material. It follows from decrease in the mixing time of weld. The calculation of thermo-capillary force influence in the finite volume method was carried out by user defined function (UDF), which, after compilation, was put into the calculations of liquids fluid dynamic as a code of the program Fluent.

3. Dynamic in the weld pool

Physical phenomena which are responsible for the circulation of liquid in weld pool are surface tension and buoyant force. Surface tension increases along with decrease on temperature, minimal value is achieved at the axis of laser beam and maximum value at the circumference of the beam. The presence of surface active elements in alloys radically changes properties of surface layer [10]. The equation derived on the basis of Gibbs and Langmuir theory describes the dependence of surface tension on temperature and activity [11]:

$$\gamma^o - \gamma = R\ T\ \Gamma_s\ \ln[\ 1 + K a_i\ ] \tag{1}$$

where:

γ^o, γ – surface tension of pure metal and solution,

R – gas constant,

T – temperature,

Γ_s – surface excess of element in state of saturation,

K – adsorption coefficient,

a_i – chemical activity of substance i in solution.

The adsorption coefficient is the function of temperature and can be expressed by the equation [10]:

$$K = e^{(\Delta S^o/RT)} e^{-(\Delta H^o/RT)} = k_1\ e^{-(\Delta H^o/RT)} \tag{2}$$

where:

k_1 – constant dependent on entropy of segregation ΔS^o,

ΔH^o – standard enthalpy of adsorption.

Therefore the equation describing the dependence of surface tension of solution on the temperature and chemical activity of substance is as follows [10]:

$$\gamma = {\gamma_m}^o - A(T - T_m) - R\ T\ \Gamma_s \ln[1 + k_1 a_1 e^{-(\Delta H^o/RT)}] \tag{3}$$

where:

${\gamma_m}^o$ – surface tension of pure metal at the melting point,

$A = -\partial\gamma^o/\partial T$ – temperature coefficient of buoyant force of pure metal.

On the surface of weld pool there appears a liquid flow as a result of the temperature gradient of surface tension. The quantity of the flow is described by Marangoni number:

$$Ma = \frac{\partial\gamma}{\partial T}\frac{\partial T}{\partial x}\frac{L^2}{\mu a} \tag{4}$$

where:

L – characteristic dimension of the sample,

μ – viscosity,

a – thermal diffusivity.

The value of Marangoni number can be calculated by differentiating the equation (3) with respect to the temperature and calculating temperature distribution on the surface of weld pool using e.g. the finite volume method (Fig. 3).

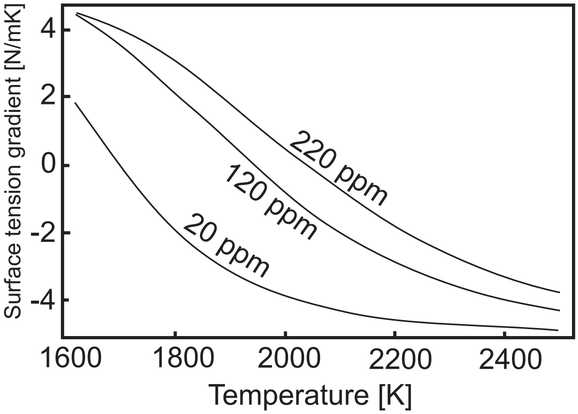

Fig. 3. Calculated temperature coefficient of surface tension as a function of temperature and sulphur content

For pure metals and steel of low concentration of oxygen and sulphur, the surface tension diminishes along with temperature increase. In case of a gaussian power distribution of the laser beam, the tension reaches maximum on a boundary of weld pool, therefore a liquid motion will be directed from an axis of the laser beam to the boundary of weld pool. In alloys containing a greater amount of sulphur and oxygen, the liquid movement will be directed in the opposite direction for the sake of a positive value of $\partial\gamma/\partial T$ coefficient. On the axis of beam there appears a flux directed downward the pool, transporting the hot metal towards bottom, causing the creation of a narrow but deep weld pool.

The dependence of density of the molten metal on temperature, causes an upward movement ofthe hot part of molten metal and the dropping of colder part downward the weld pool. The density temperature relation is described by the equation:

$$\rho(T) = \rho_m(1 - \beta(T - T_m)) \tag{5}$$

where:

ρ_m – liquid metal density at the melting point T_m,

β – thermal expansion coefficient.

4. Heat transfer in the weld pool

The liquid flow and mass transport is modeled by solving equations of conservation of mass, momentum an energy at the weld pool area. It is assumed that the liquid is incompressible and Newtonian and the flow is laminar.

For the process of melting and solidification the energy transport in the weld pool is described by the equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho \vec{v} h) = \nabla \cdot (\frac{k}{c_p} + \nabla h) + S_h \tag{6}$$

where:

k – thermal conductivity,

h – sensible heat calculated as $h = \int c_p dT$,

c_p – specific heat,

ρ – material density,

S_h – volume source of enthalpy, equal to energy absorbed from laser beam.

In order to determine the liquid-solid interphase boundary, the enthalpy of material H is calculated as a sum of the sensible heat h and the latent heat ΔH i.e. $H = h + \Delta H$.

A liquid volume fraction V_L is defined as:

$$V_L = \begin{cases} 0 & T < T_s \\ 1 & T > T_l \\ (T - T_s)/(T_l - T_s) & T_s < T < T_l \end{cases} \tag{7}$$

where: T_l, T_s – liquidus and solidus temperatures

The latent heat quantity can be given by the formula:

$$\Delta H = V_L L \tag{8}$$

where: L – liquid latent heat

Therefore the temperature calculation consists of iterations of energy conservation law (6) and liquid fraction equation (7). Due to the low convergence of that pattern of calculations there applies the method proposed by Voller and Swaminathan [12].

5. Results and discussion

The Figure 4 presents a comparison between microsections of laser melted specimens made of rapid tool steel SW18, and the calculated shape of the pool in the plane perpendicular to the specimen movement direction. The liquid pool boundary shown in figures is determined by a solidus temperature isotherm (1580 K) calculated for the moment when the axis of beam crosses the intersection. The dashed line denotes a fusion line measured on microsection. The isotherm described by the value of 1050 K denotes the phase transition beginning in solid state. The area between isotherms 1050 K and 1580 K determines a heat affected zone (HAZ). The steel structure this area depends on local thermal cycles and kinematics of the phase transition [13].

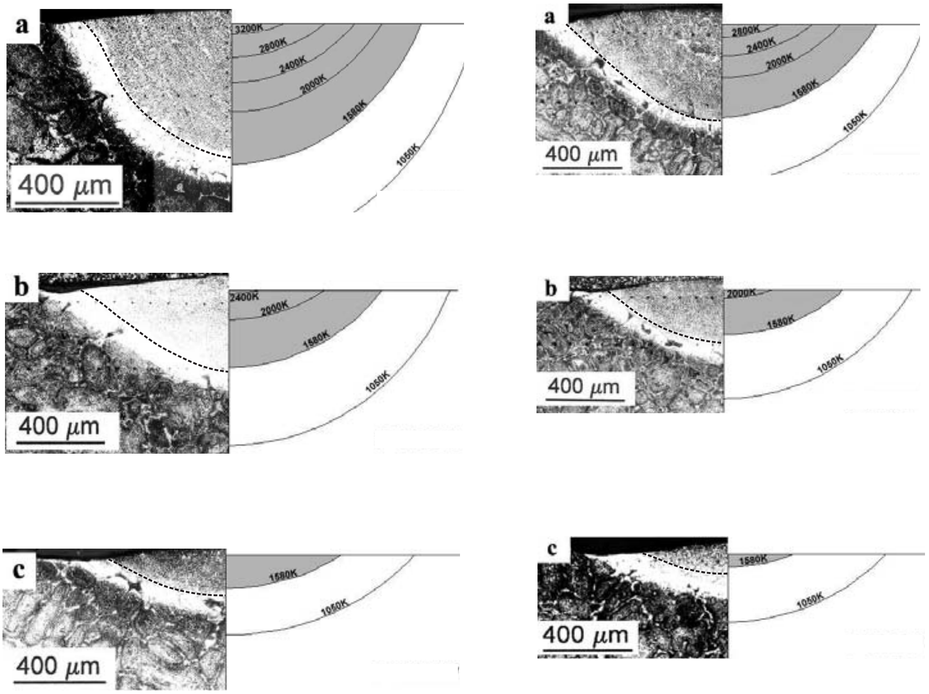

Fig. 4. Comparison between calculated and measured weld pool geometry. Welding conditions: laser beam power (P) – (a) 2410 W, (b) 1550 W, (c) 1030 W; welding velocity (v) – 8 mm/s (left column), 13 mm/s (right column). Dashed line correspond to the measured fusion line

The area nearer to the isotherm 1050 K there ensued only partially transform ferrite (α) into austenite (γ). The complete transformation $\alpha \rightarrow \gamma$ ensued at a higher temperature and the structure is fine-grained for the reason of short austenitization time. The model of the process doesnt take into consideration a volume increase visible on microphotographs of the weld pool. The volume change is caused by the solutioning of steel by carbon and alloy additions. Even though model simplification, as it is shown on drawings, the calculated weld pool agrees well with experiment results.

Figure 5 presents the thermal and velocity field development of the heat treated specimen. For the clarity only half a weld is shown. As shown in the figure, at the moment when the axis of beam crosses the intersection of specimen, there ensues rapid heating, fusion and formation of melt pool. The movement of liquid is driven mostly by surface tension and to a much less extent by buoyant force.

For the steel with content of sulphur 20 ppm, the value of $\partial\gamma/\partial T$ is negative for the temperature greater than 1700 K as it is shown on Figure 3. Therefore for the speed 8 and 18 mm/s of laser beam movement, on the pool surface there predominates a negative value of the $\partial\gamma/\partial T$. Only at the edge of weld pool there exists a small area where the $\partial\gamma/\partial T$ is positive. Except that small area, the surface tension gradient forms a liquid flux at the surface, directed outside, carrying the heat from the axis of the beam towards the weld pool (Fig. 5a). Though on the edge of weld pool the driving force of the liquid movement is directed inwards, it is to a low to surpass an opposite directed liquid flux. Consequently there appears a shallow and wide liquid area.

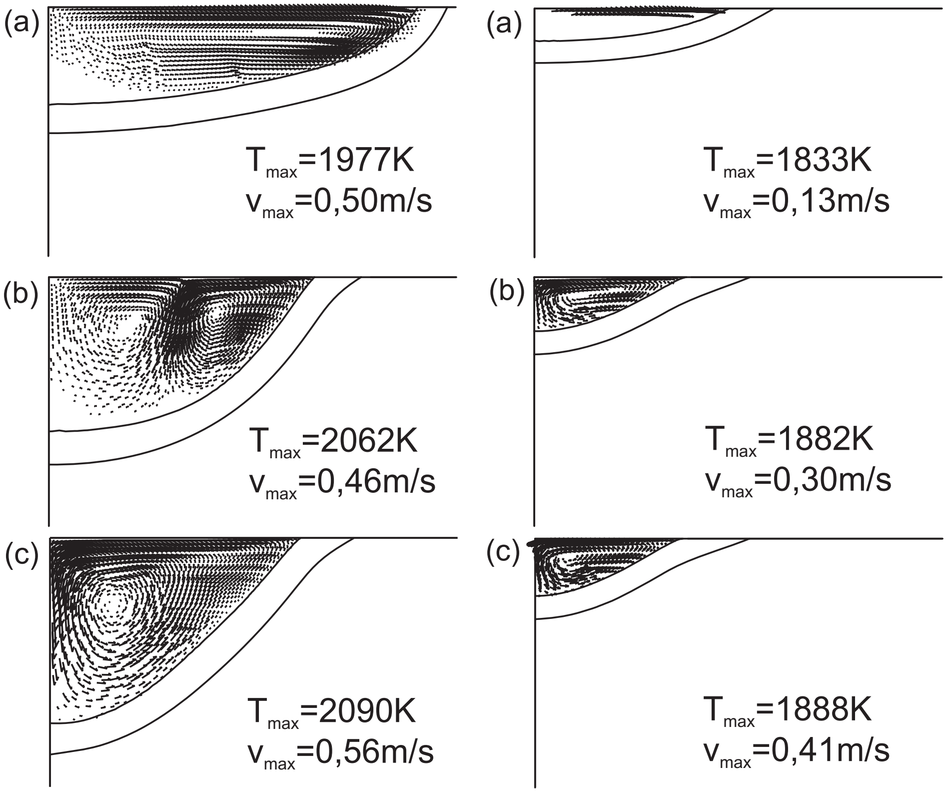

Fig. 5. Calculated weld pool flow profile. Solid line is solidus temperature, and dashed line is liquidus temperature. Welding conditions: welding velocity (v) – 8 mm/s (left column), 18 mm/s (right column); content of sulphur: (a) 20 ppm, (b) 120 ppm, (c) 220 ppm

For the content of sulphur 120 ppm, a convection heat transfer directed downwards the liquid cause the forming of a deeper weld pool for both velocities 8 and 18 mm/s (Fig. 5b). Because $\partial\gamma/\partial T$ is negative for the temperature higher than 1945 K, on the liquid surface there is formed the second flux, directed outward. Initially it is formed at the weld pool axis and then grows towards edges. The liquid flux directed downwards causes that isotherms are bent at this point and the specimen is welded deeper.

In case the sulphur content is 220 ppm, on the liquid surface there rises a part of flux directed inwards, which for the specimen welded at the velocity of 18 mm/s, covers already the whole liquid surface (Fig. 5c). Because the temperature above which $\partial\gamma/\partial T$ changes its sign to negative is 2040 K, the liquid flux directed outwards formed only at the narrow area near the laser beam axis. At the velocity of 8 mm/s the liquid at the beam axis warms up to the temperature 2090 K, therefore there are formed two liquid fluxes directed in opposite directions (Fig. 5c). The weld pool is in this case deeper than that for the velocity 18 mm/s.

The heat transfer in the weld pool depends on power distribution in the laser beam and on its movement velocity over the specimen. The increase in the laser beam movement velocity up to 18 mm/s changes the character of the weld. The specimen warms up at the weld pool axis to the temperatures lower a 150–200 K (Fig. 5) and the maximum liquid velocity is about 1.5–4 times lower. Increasing of the content of sulphur in steel from 20 to 220 ppm changes in this case the direction of liquid flux to reverse (Fig. 5a, c).

6. Summary

In the work there have been carried out a research on welding modeling of steel by numerical solving of energy, mass and momentum conservation equations. The results of calculations confirm the influence of convectional heat exchange on the shape of weld pool. The direction of liquid flux on the surface is determined by Marangoni effect. The change of sign of temperature surface tension coefficient $\partial\gamma/\partial T$ as a result of change of temperature or sulphur content favors the forming of two opposite directed liquid fluxes. The increase on sulphur content in steel and the decrease on laser beam movement velocity, increases the depth/width ratio of a weld pool [14]. The laser beam power distribution assumed in the model has a high influence on the shape of numerically obtained weld pool.

Acknowledgements

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