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MODELLING OF LASER WELDING FOR MATERIALS WITH DIFFERENT PROPERTIES

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Abstract

Joining metals and alloys with different properties gives greater flexibility in design and production as compared to manufacturing with one type of material only. Due to this, expensive materials can be applied only at places where their use is indispensable. However, joining different combinations of metals become a challenge, due to the differences in physical and chemical properties. Laser welding, due to such advantages as good weldability and high quality of joints with narrow heat affected zone, allows for solving many problems appearing in traditional joining methods.

The current paper concerns modelling of laser welding processes for materials with different physical and chemical properties. The model consists of a coupled set of incompressible fluid flow equations, heat equation and convection-diffusion equations for different material types. The formulation takes into account the dependence of material properties on temperature and chemical composition. Discontinuity of density and viscosity, together with the chemical composition of fluid in weld pool influences the velocity and temperature distribution in the weld pool and in consequence determines the shape and properties of a joint.

Key words: laser welding, fluid flow, dissimilar welding, CLSVOF method, Marangoni convection

1. INTRODUCTION

Laser welding used for several years method of fusion joining, is now widely used in industry. This technique became common due to possibility of welding metals with high precision, deep penetration welding with high speed and low heat input, small deformations. Due to these advantages, this method has become one of the most popular technique for joining materials. One of the possibilities to study processes occurring during welding is computer modeling. Being improved over the years numerical methods for solving differential equations give more accurate results verified by experiments. The article concerns the modeling of laser welding materials with different properties. During welding occurs convection and mutual diffusion of elements of welded materials (Bahrami et al., 2015). The dominant factor forcing fluid motion in such systems is gradient of surface tension (Sahoo et al., 1988) and the recoil force acting on the surface of the weld (Semak & Matsunawa, 1997). Tracking the position of the liquid-gas interface has significant effect on the accuracy of the physical processes model. In the literature there are two approaches based on fixed or moving grid. First method rely on binding grid with interface and the movement of the grid nodes together with interface. Position of interface in this approach is exactly determined by the associated grid nodes. In the second method, the boundary is moved through stationary Eulerian grid. This approach requires the calculation of the interface position in each time step. The advantage of this method compared with the previous is ability to track the interface which merge or divide in time. The disad-

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vantage is low accuracy in determining of interface position and its curvature.

In the literature there is lot of publications describing the various methods of the interface tracking based on fixed grids e.g. Level Set (LS) method, Volume of Fluid (VOF) method (VOF) or Coupled Level Set and Volume of Fluid (CLSVOF) method (Chakraborty et al., 2013). There are many publications where the VOF method is used (Yokoi, 2007). This method is more efficient because it does not require solving additional equations and satisfies the principle of conservation of mass. Unfortunately, this method does not permit to determine the exact position of the interface. The interface at each time step is reconstructed using volume fraction function calculated on stationary Eulerian grid. The value of this function indicates which phase is located inside the grid cells. The same grid is used to solve multiphase flow problems. The volume fraction field is advected by the velocity field and algorithm reconstructs interface in the next time step. The cause of the difficulty may be the necessity to obtain a sharp interface at each iteration. This in turn gives a discontinuity of properties such as density and viscosity at the interface which may cause instability of the numerical solution. Although the VOF method satisfies the principle of conservation of mass, derivatives of phase fraction functions are discontinuous in the vicinity of the interface. Therefore, the calculated interface curvature and the normal vector are inaccurate. This results in the formation of the artificial velocity field, so called "parasitic currents", by unbalanced surface tension forces (Sun & Tao, 2010).

This article concerns the use of these methods for modeling of laser welding of materials with different physical properties. Welding of such materials is difficult due to the asymmetry of heat and mass flow and segregation of surface active elements. The microstructure of the welded parts is also asymmetrical with respect to the plane of welding. Modeling of such system of different materials, will enable the flow tracking during welding and allows to understand the heat and mass transport in the weld pool.

2. MATHEMATICAL MODEL

The model is based on the following assumptions:

1. welded materials behave in a liquid state as a Newtonian fluid,
2. alloys exhibit unlimited mutual solubility in the solid and liquid state,
3. flow in the weld pool is laminar and incompressible,
4. weld pool surface deforms, the extent of deformation depends on a source of force acting on it as will be further described,
5. motion of the liquid in the weld pool is induced i.e. by the gradient of surface tension,
6. during welding mutual mixing of two materials changes their physical properties along with the composition and temperature.

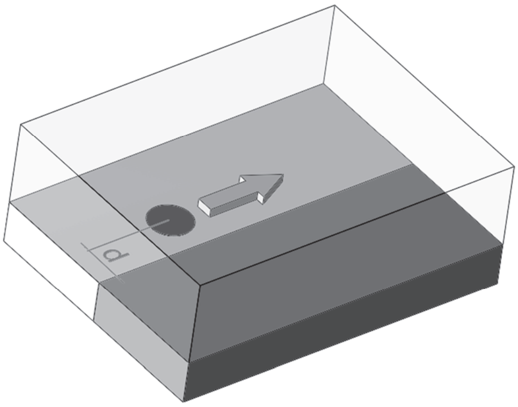

Fig. 1. *Schematic of the laser beam welding model*

Described in this article model consists of two different chemical composition plates (figure 1). Each plate is the same sizes and tightly adhere each other. In a direction parallel to the contact plane the laser beam moves at a constant velocity. Due to the difference in melting temperature and different physical properties, the model assumes a variable distance d of the laser beam axis from the contact plane. During laser welding, the shape of the weld pool strongly depends on the laser beam mode. Therefore, the model assumes the use of different modes e.g. TEM_{00}, TEM^*_{01}, TEM_{10} and TEM_{01} (Han & Liou, 2004).

The welding model is based on several differential equations. During welding the plates heats up and melts within the area of the laser beam impact. The weld pool is formed where fluid flows. The fluid flow and heat transfer in this area satisfy a number of equations described below.

The governing equation for the fluid is conservation of mass:

$$\frac{\partial \rho(\tilde{\alpha})}{\partial t} + \nabla \cdot (\rho(\tilde{\alpha})\mathbf{v}) = 0 \qquad (1)$$

where ρ is the density, $\tilde{\alpha}$ is the averaged value of volume fraction field, $\mathbf{v}$ is the velocity vector

The momentum conservation equation can be written as:

$$\frac{\partial(\rho(\tilde{\alpha})\mathbf{v})}{\partial t} + \nabla \cdot (\rho(\tilde{\alpha})\mathbf{v}\mathbf{v})) =$$

$$-\nabla p + \nabla \cdot [\mu(\tilde{\alpha})(\nabla \mathbf{v} + \nabla^T \mathbf{v})] +$$

$$+\mathbf{F}_p + \mathbf{F}_g + \mathbf{F}_\kappa + \mathbf{F}_\gamma + \mathbf{F}_r \qquad (2)$$

where μ is the viscosity, p is the total pressure

In equation (2) the last five components are body force sources. The source term $\mathbf{F}_p$ is zero in liquid phase, while in the mushy zone slows down the fluid flow by friction between the liquid and dendrites, to finally null velocity in the solid phase. To calculate $\mathbf{F}_p$ applies the classical Carman-Kozeny equation for flow through a porous media:

$$\mathbf{F}_p = -K\frac{(1-f_l)^2}{f_l^3+\xi}\mathbf{v} \qquad (3)$$

where f_l is the volume of fluid fraction, K and ξ denote the constants respectively equal to 10^6 and 10^{-4}.

Volume of fluid fraction is calculated as follow:

$$f_l = \begin{cases} 1 & T \geqslant T_l \\ \frac{T-T_l}{T_s-T_l} & T_s < T < T_l \\ 0 & T \leqslant T_s \end{cases} \qquad (4)$$

where T_s and T_l are the alloy solidus and liquidus temperature.

Next source in the momentum equation is gravity driven buoyancy force $\mathbf{F}_g$, which are caused by the change of volume depending on the temperature and composition:

$$\mathbf{F}_g = \rho_o \mathbf{g}[\beta_T(T - T_{ref}) + \beta_c(c - c_{ref})] \qquad (5)$$

In this equation β_T and β_c are the temperature and composition expansion factors, c and c_{ref} are the local and reference concentrations.

The third term $\mathbf{F}_\kappa$ in momentum conservation equation (2) acts only on the surface of the weld pool. It takes into account surface tension resulting in a step change in pressure on the liquid/gas interface.

$$\mathbf{F}_\kappa = \gamma\kappa\hat{\mathbf{n}} \qquad (6)$$

where γ is the surface tension, κ is the interface curvature, $\hat{\mathbf{n}}$ is the versor perpendicular to the weld pool surface and directed towards the liquid. The force direction depends on sign of surface curvature. This force acts only on the surface of the weld pool with non-zero curvature. To determine the location of the liquid/gas interface VOF method may be used. Despite the fact that this method meets the mass conservation principle, it does not allow the accurate determination of the surface versor and its curvature. Using only VOF method results in parasitic velocities induced by the numerical algorithm (Sun & Tao, 2010). The use of the combined Level Set (Osher & Sethian, 1988) and Volume of Fluid method (CLSVOF) gives a more accurate approximation to the shape of the interface (Sussman & Puckett, 2000; Gerlach et al., 2006). This method consists of the following steps:

1. volume fraction field α is advected by the velocity field $\mathbf{v}$ according to the formula:

$$\frac{\partial\alpha}{\partial t} + \nabla \cdot (\mathbf{v}\alpha) = 0 \qquad (7)$$

2. interface is approximated as a piecewise linear segments based on volume fraction field α and next level set field ϕ is calculated, sign of this field indicates the side of the interface

3. smoothed volume fraction field $\tilde{\alpha}$ is defined as the Heaviside function according to the formula:

$$\tilde{\alpha} = H_\varepsilon(\phi) = \begin{cases} 0 & \phi < -\varepsilon \\ \frac{1}{2}\left[1 + \frac{\phi}{\varepsilon} + \frac{1}{\pi}\sin(\frac{\pi\phi}{\varepsilon})\right] & |\phi| \leqslant \varepsilon \\ 1 & \phi > \varepsilon \end{cases} \qquad (8)$$

where ε is a half of interface width

The surface tension force is nonzero only on the finite interface thickness 2ε. Versor normal to the interface is calculated for the smoothed fraction volume function field $\tilde{\alpha}$ as follow:

$$\hat{\mathbf{n}} = \nabla\tilde{\alpha} \qquad (9)$$

while the interface curvature for the distance field:

$$\kappa = \nabla \cdot \frac{\nabla\phi}{|\nabla\phi|} \qquad (10)$$

A further body force source in equation (2) is force $\mathbf{F}_\gamma$ resulting from the surface tension gradient. The presence of surface active elements and temperature gradient on the weld pool surface causes the Marangoni effect (Zhou & Tsai, 2008):

$$\mathbf{F}_\gamma = f_l\left(\frac{\partial\gamma}{\partial T}\nabla_s T + \frac{\partial\gamma}{\partial c_i}\nabla_s c_i\right) \qquad (11)$$

where ∇_s is the gradient tangential to the surface and c_i is the concentration of surface active elements.

Gradient of the surface tension on the liquid/gas interface has an important impact on the liquid circulation in the weld pool. Surface tension is a function of the temperature and the concentration of the surface active elements a_i. The relationship can be calculated according to the Gibbs and Langmuir adsorption isotherms of the surface active elements (Sahoo et al., 1988)

$$\gamma = \gamma_m^o - A(T - T_m) - \\ - R\,T\,\Gamma_s \ln\left[1 + k_1\,a_i\,\exp^{(-\Delta H^o/RT)}\right] \qquad (12)$$

where γ_m^o is the surface tension of the pure metal at the melting point, A is the negative of $\partial\gamma/\partial T$ for pure metal, k_1 is a constant related to the entropy of segregation, a_i is the activity of the element i in the solution, ΔH^o is the standard heat of adsorption.

The temperature gradient on the weld pool surface is caused by the power density distribution of the laser source and the laser motion along the sample. If the surface temperature is much higher than the melting point of the welded materials, intense evaporation causes recoil (Semak & Matsunawa, 1997; Siwek, 2010; Rońda & Siwek, 2011). The recoil force $\mathbf{F}_r$ is defined as:

$$\mathbf{F}_r = A\,B_0 T_s^{-\frac{1}{2}} \exp\left(-\frac{U}{k\,T_s}\right)\nabla\tilde{\alpha} \qquad (13)$$

Where A is a constant, B_0 is a vaporization constant, T_s is the weld pool surface temperature, U is the evaporation energy.

The energy conservation law for the model has the form:

$$\rho(\tilde{\alpha})\,C_p(\tilde{\alpha})\left(\frac{\partial T}{\partial t} + \mathbf{v}\cdot\nabla T\right) = \nabla\cdot(k\nabla T) + S_f + S_l \qquad (14)$$

where C_p is the specific heat, k is the thermal conductivity, S_f is a volumetric heat source of fusion and evaporation and S_l is the volumetric heat source from the laser beam.

In equations (1, 2, 14) a large change of physical properties such as density, viscosity, specific heat and thermal conductivity on the liquid/gas interface may result in instability of the numerical solution. Assuming a finite interface thickness 2ε of several grid sizes, successive averaged physical properties $\bar{P}$ are calculated using the smoothed value $\tilde{\alpha}$ as follows:

$$\bar{P}(\tilde{\alpha}) = P_l\tilde{\alpha} + P_g(1 - \tilde{\alpha}) \qquad (15)$$

where P_l and P_g denote liquid and gas properties respectively.

At the initial joint interface between two plates, diffusion and convection conservation equation of the species is given by:

$$\frac{\partial c_i}{\partial t} + \mathbf{v}\cdot\nabla c_i = \nabla\cdot(D_i\nabla c_i) \qquad (16)$$

where c_i and D_i are the concentration and diffusion coefficient of the ith element in the weld pool solution.

Solution of equation (16) for surface active elements enables the calculation of surface tension (equation 12), where the activity of the elements a_i could be approximated by the weight concentration in the solution c_i.

3. DISCUSSION AND CONCLUSIONS

The preliminary calculations have been carried out, using ANSYS Fluent code. The physical properties of the welded material have been described in Siwek (2010). It is assumed that the chemical composition of the two plates of dimensions $7\times3\times5\cdot10^{-3}$ m differs only in composition of sulfur. The sulfur content for each of the plates are 20 and 220 ppm. The model uses a laser beam with the power of 2 kW, diameter of 0.002 m and TEM_{01} mode. In the tests it was assumed that the laser beam moves with constant speed of 0.003 m/s in a direction parallel to the contact plane at a distance d = 0.0 m (figure 1). It was assumed that during welding the recoil force on the weld pool surface is low and does not result in deformation of the surface. Implemented in ANSYS Fluent model, solves the previously described differential equations. Therefore, the result of model calculations is multiple fields (e.g., velocity field, temperature field, species concentration field). Due to convergence of the solution for the assumed process conditions, constant time step $\Delta t = 10^{-6}$ s was adopted, whereas the size of the tetrahedral elements was reduced from the size ~$3\cdot10^{-3}$ m in the outer region of welded plates, to the size ~$8\cdot10^{-5}$ m in the vicinity of the laser beam.

The difference in sulfur concentration causes asymmetry of the weld pool (figure 2). Temperature and sulfur concentration gradients tangential to the weld pool surface affects the value and direction of the body force $\mathbf{F}_\gamma$ (11). As the process progress a sharp boundary between the two materials becomes increasingly diffuse. This effect is caused by the mixing and diffusion of the two materials.

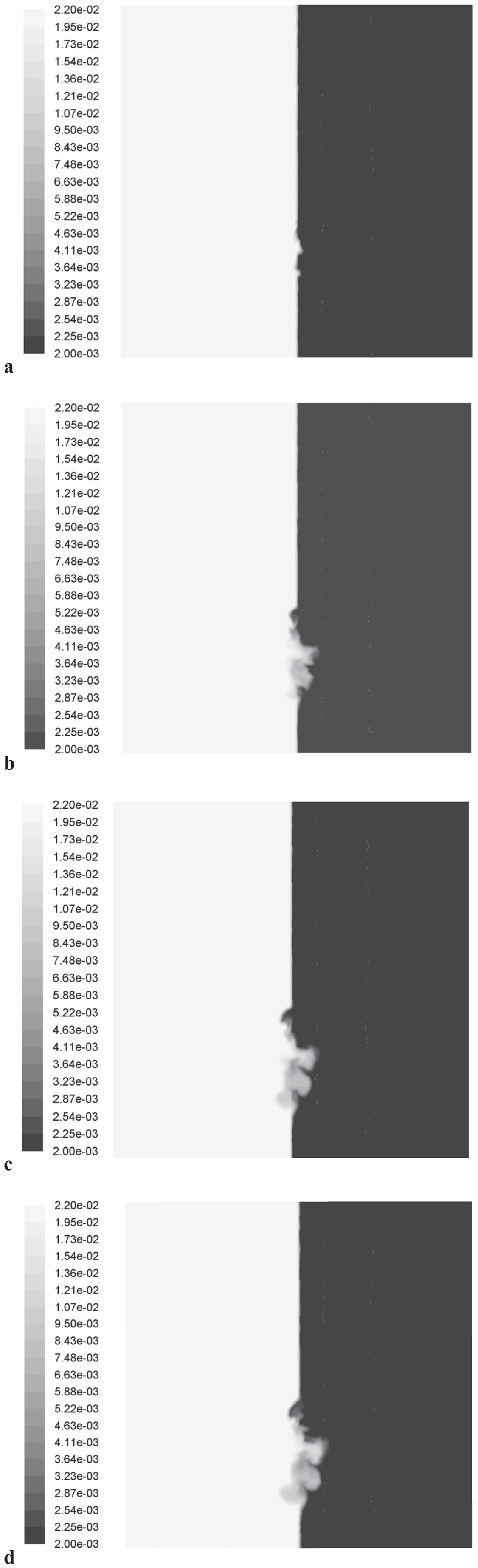

Fig. 2. Sulfur concentration field during welding after time 0.3·10^{-3} s (a), 4.2·10^{-3} s (b), 8.1·10^{-3} s (c) and 12.1·10^{-3} s (d)

Moving with constant speed laser beam, melts subsequent area of the connection forming another characteristic mixing pattern. Distance between pattern steps for the selected parameters is ~0.5·10^{-3} m.

Proposed in this article model of laser welding consists of the two plates of different composition (figure 1). It is assumed that the elements of the plates form a solid solution with unlimited solubility in the solid and liquid state. The top surface of the plates is heated by laser of different power distributions. The model assumes that distance of the laser beam axis to the contact surface, and speed of the laser beam, influence on the weld profile. The fluid flow in the weld pool is mainly forced by the Marangoni effect and recoil pressure. The difference in the physical properties of welded materials, and the change in concentration of surface active elements, is the cause of asymmetry of the velocity field of the liquid, and then the differences in the shape of the weld profile on each side of the interface. Numerical solution of the model proposed in this article can help to optimize this type of process.

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REFERENCES

Bahrami, A., Valentine, D.T., Helenbrook, B.T., Aidun, D.K., 2015, Study of mass transport in autogenous GTA welding of dissimilar metals, *International Journal of Heat and Mass Transfer*, 85, 41-53.

Chakraborty, I., Biswas, G., Ghoshdastidar, P.S., 2013, A coupled level-set and volume-of-fluid method for the buoyant rise of gas bubbles in liquids, *International Journal of Heat and Mass Transfer*, 58, 240-259.

Gerlach, D., Tomar, G., Biswas G., Durst, F., 2006, Comparison of volume-of-fluid methods for surface tension-dominant two-phase flows, *International Journal of Heat and Mass Transfer* 49, 740-754.

Han, L., Liou, L.O., 2014, Numerical investigation of the influence of laser beam mode on melt pool, *International Journal of Heat and Mass Transfer*, 47 4385-4402.

Osher, S., Sethian, J.A., 1988, Fronts Propagating with Curvature Dependent Speed: Algorithms Based on Hamilton-Jacobi Formulations, *Journal of Computational Physics*, 79, 12-49.

Rońda, J., Siwek, A., 2011, modelling of laser welding process in the phase of keyhole formation, *Archives of Civil and Mechanical Engineering*, 3, 739-752.

Siwek, A., 2010, A model of the laser beam steel welding process during vapor channel creation phase, *Mechanik*, 83(12), 930-934.

Sahoo, R., DebRoy, T., McNallan, M.J., 1988, Surface tension of binary metal surface active solute systems under conditions relevant to welding metallurgy, *Metallurgical Transactions B*, 19B, 483-491.

Semak, V., Matsunawa, A., 1997, The role of recoil pressure in energy balance during laser materials processing, *Journal of Physics D: Applied Physics* 30(18), 2541-2552.

Sun, D.L., Tao, W.Q., 2010, A coupled volume-of-fluid and level set (VOSET) method for computing incompressible two-phase flows, *International Journal of Heat and Mass Transfer*, 53, 645-655.

Sussman, M., Puckett, E.G., 2000, A Coupled Level Set and Volume-of-Fluid Method for Computing 3D and Axisymmetric Incompressible Two-Phase Flows, *Journal of Computational Physics*, 162, 301-337.

Yokoi, K., 2007, Efficient implementation of THINC scheme: A simple and practical smoothed VOF algorithm, *Journal of Computational Physics*, 226, 1985-2002.

Zhou, J., Tsai, H.L., 2008, Modeling of transport phenomena in hybrid laser-MIG keyhole welding, *International Journal of Heat and Mass Transfer*, 51, 4353-4366.

MODELOWANIE PROCESU SPAWANIA LASEROWEGO MATERIAŁÓW O RÓŻNYCH WŁASNOŚCIACH

Streszczenie

Artykuł dotyczy modelowania spawania laserowego materiałów o różnych własnościach. Dominującą siłą wymuszającą ruch cieczy w takich układach jest gradient napięcia powierzchniowego oraz siła odrzutu powstała na powierzchni jeziorka spawalniczego. W literaturze można znaleźć wiele artykułów w których wykorzystano różne metody śledzenia powierzchni międzyfazowej, np. Level Set method (LS), Volume of Fluid method (VOF), lub bardziej skomplikowanej Coupled Level Set and Volume of Fluid method (CLSVOF). W wielu publikacjach wykorzystywana jest metoda VOF. Metoda ta jest wydajna, ponieważ nie wymaga iteracyjnego rozwiązywania dodatkowych równań i spełnia zasadę zachowania masy. Niestety metoda ta nie pozwala na wyznaczenie dokładnego położenia powierzchni międzyfazowej. Granica międzyfazowa jest rekonstruowana w każdej iteracji za pomocą pola udziału fazy, dyskretyzowanego na siatce eulerowskiej. Wartość tego pola wskazuje jaka faza znajduje się w danej komórce siatki. Granica międzyfazowa przemieszcza się przez adwekcję pola fazowego. Przyczyną trudności może być wymaganie dużej dokładności wyznaczenia położenia granicy w każdej iteracji rozwiązania. To z kolei powoduje nieciągłość własności takich jak gęstość i lepkość na granicy międzyfazowej, a przez to niestabilność numeryczną rozwiązania. Metoda VOF spełnia warunek zachowania masy. Pochodne pola udziału fazy VOF nie są jednak ciągłe w okolicy granicy międzyfazowej. Dlatego obliczone z funkcji fazy VOF krzywizna granicy i wektor normalny do granicy są niedokładne. Powoduje to tworzenie się w obszarze granicznym pozornych przepływów w wyniku niezrównoważenia siły napięcia powierzchniowego.

Artykuł dotyczy wykorzystania powyższych metod do modelowania spawania laserowego materiałów o różnych własnościach fizycznych. Spawanie takich materiałów jest trudne, ze względu na tworzenie się asymetrii w przepływach ciepła i masy oraz zauważalną segregację pierwiastków powierzchniowo aktywnych. Tworząca się mikrostruktura zespawanych elementów przez to także jest asymetryczna względem płaszczyzny spawania. Modelowanie takich przepływów pozwoli na zrozumienie procesów zachodzących w jeziorku spawalniczym.

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