Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE

Informatyka w Technologii Materiałów

Vol. 13, 2013, No. 1

MODELING OF INCONEL 625 TIG WELDING PROCESS

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Abstract

Inconel 625 alloy is widely used in the aerospace industry because of its high strength, especially at high temperatures, corrosion resistance and excellent weldability. The study presents modeling of the TIG welding process using a Gaussian heat source. The calculations were performed using our in-house software Mod_FEM_met, designed for modeling, among others, welding processes using finite element method and employed as a service of PL-Grid+ infrastructure. The program has a modular structure, with the modules for solving the Navier-Stokes and heat transport equations together with a coupling super-module used in welding simulations. To increase computing speed and accuracy in areas with large error of approximation, adaptive meshes were used. Calculations were performed for plate made of Inconel 625. In the calculations the temperature dependent properties of Inconel 625 alloy, as well as thermal phenomena at the edges and inside the weld pool were taken into consideration. The results of the calculations include the dimensions and shape of the weld pool, as well the velocity and temperature fields. The results indicate how the efficiency of heat source can be used as a parameter to optimize the fitting of calculations to the experimental data.

Key words: TIG welding, finite element method, SUPG stabilization, mesh adaptation, computational fluid dynamics (CFD)

1. INTRODUCTION

At present one of the most popular method of joining metals is welding by electrical arc. This process provides excellent connection quality with relatively small number of defects. In the last twenty years, based on experiments and computer modelling, there has been considerable progress in understanding the processes in the weld pool. Many models were created to calculate heat and mass flow in the welding area, which make it possible to predict the size of weld pool and area of the so called heat-affected zone (Rońda et al., 1996; Rońda & Oliver, 2000). Mass and energy flow in the welding area is driven by the interaction of the electromagnetic force, Marangoni forces, the forces of buoyancy and vapour friction on the surface of the weld pool. The coefficient of surface tension has strong influence on the direction of rotation of the molten metal in the weld pool. It is assumed that it depends on the temperature and concentration of surface active elements.

This paper presents the results of simulations of processes occurring in weld pool during welding by electric arc. To this end in-house software for numerical simulations of metallurgical processes Mod_FEM_met was used. The program allows one to solve metallurgical problems in the following stages: defining the study area, creation of a mesh, specification of the physical phenomena, solution of the problem and visualization of results. In the case of welding the software was used for modelling heat transfer between the electric arc, weld pool and the rest of welded material as well as the flow of liquid steel. The accuracy of the calculations was increased by the built-in software module for finite element

 ISSN 1641-8581

adaptivity. It allows one to control the accuracy of calculations based on approximation error estimation.

2. MATHEMATICAL FORMULATION

The mathematical model adopted in the numerical implementation includes some basic equations of physical phenomena occurring in the weld pool. The software used in our work applies some simplifications to the welding model. The weld pool surface is flat. The calculations do not include electromagnetic force generated by the electrical arc. Also the adopted analytical Gaussian distribution of the energy flux supplied to the material is only the rough approximation to the real interaction of the arc and the metal. Below we present the full mathematical model without the simplifications. We plan to implement numerical approximations of all the described processes in future releases of the software.

The first equation in the model is the classical equation of continuity, equivalent to the law of conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{1}$$

where: ρ – density of alloy in the solid state and liquid state, v – velocity vector, t – time.

In the case of incompressible fluids, equation (1) reduces to the condition of vanishing divergence of velocity vector field:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{2}$$

The second fundamental equation is the law of momentum conservation. The equation includes specific interactions for the welding process:

$$\rho_0 \left(\frac{\partial v}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}\right) = -\nabla P + \nabla \cdot \{\mu\, [(\nabla \boldsymbol{v}) + (\nabla \boldsymbol{v})^T]\} + \boldsymbol{J} \times \boldsymbol{B} - K\boldsymbol{v} + \rho_0 \boldsymbol{g}[1 - \beta(T - T_0)] \tag{3}$$

In the above formula, the left hand side shows the classic balance of momentum in the Euler description, containing time derivative of velocity and convection term, assuming constant fluid density ρ_0. The right hand side of the equation is responsible for dynamic interactions. In the first term, the gradient of pressure P represents the isotropic part of stress tensor. The second term represents the effects of viscous forces, where μ is the dynamic viscosity of the fluid. The third term is related to electromagnetic interactions. It is assumed that the moving particles with electric charges, represented by the vector of electric current ***J***, are influenced by the magnetic field of induction ***B***. The next part of the momentum balance is related to the existence of a two-phase region (mushy zone). This two-phase region occurs between the liquid metal within the weld pool and the solid phase of welded material. In this area flow is slowed down as a result of dendrites crystallization. Accurate modelling of the above process requires multiscale analysis. In the numerical model adopted in the software, mushy zone influence is represented by the term $K\boldsymbol{v}$ (Voller & Prakash, 1987), where:

$$K = \frac{C(1-f_L)^2}{f_L^3 + q} \tag{4}$$

In the above formula, the variable C is constant and it depends on the dendrite size. In the model we assume that $C = 1.6\times10^3$. f_L is the participation of liquid phase. For $f_L = 1$, K is equal to 0, and for $f_L = 0$, K is equal to C/q. In the code, the normalizing constant q is equal to 0.001. The last part of equation (3) corresponds to the gravity force and the buoyancy force. The model assumes Boussinesq approximation for which the buoyancy force is proportional to the difference of densities and is calculated as the product of reference fluid density ρ_0, the coefficient of thermal expansion β and the difference between the fluid temperature T and the reference temperature T_0. In the Boussinesq approximation small density variations are assumed so that the density gradient can be eliminated from the momentum balance equation, assuming the constant medium density ρ_0.

The last equation, describing the process of heat transfer in weld pool, is the energy conservation equation. The equation written for temperature T as the independent variable has the from:

$$\rho_0 c\left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + \sigma^{-1}(\boldsymbol{J} \cdot \boldsymbol{J}) + \rho_0 L_f \frac{\partial f_L}{\partial t} \tag{5}$$

The expression on the left hand side corresponds to the convection in the velocity field. The constant c represents specific heat. The first term on the right hand side shows the diffusion with the coefficient of thermal conductivity k. The next term refers to the heat generated by the current ***J***. The current is created by moving charged particles, σ denotes the electrical conductivity. This part is not yet included in the calculations. Instead, the influence of the electrical current is included in the model of a surface heat source. The last term describes the impact of the phase change on the energy balance. L_f means the latent heat of fusion.

Two independent groups of boundary conditions, one for the flow variables and the second for temperature, complement the mathematical model of the weld pool. Conditions for the flow include:

1. the inflow boundary, where velocity vector v_b is given at each boundary point,
2. the outflow boundary, where the pressure p_b is given
3. the condition for the liquid-solid contact, treated as a non-slip surface where the velocity vector is set to zero,
4. free surface of the liquid.

The last of the boundary conditions consists of two part. The kinematic part which sets to zero the velocity component normal to free surface and the dynamic part. The dynamic part determines the surface forces and takes into account the Marangoni effect - the movement of fluid due to the changing surface tension, being a function of temperature and the concentration of surface active element f^α (Siwek & Didenko, 2004). As a result the tangential force is given by the formula:

$$\tau_{\boldsymbol{s}} = \mu_L \frac{\partial(v\cdot s)}{\partial \boldsymbol{n}} = \frac{\partial \gamma}{\partial T}\frac{\partial T}{\partial s} + \frac{\partial \gamma}{\partial f^\alpha}\frac{\partial f^\alpha}{\partial s} \tag{6}$$

where vectors $\boldsymbol{n}$ and $\boldsymbol{s}$ are unit vectors: normal and tangential to the boundary of the domain.

The thermal boundary conditions determine temperature on the surface or the heat flux across the surface. The simplest method of applying the boundary condition for heat flux, defined using normal derivative of temperature, is the direct substitution of flux q:

$$-k\frac{\partial T}{\partial \boldsymbol{n}} = q \tag{7}$$

The second heat flux condition takes into account convection and radiation that occur on the molten metal surface:

$$-k\frac{\partial T}{\partial \boldsymbol{n}} = -h_c(T - T_a) - \sigma\varepsilon(T^4 - T_a^4) \tag{8}$$

Here, h_c – is the heat transfer coefficient, T_a – ambient temperature, ε – emissivity of the surface, σ – Stefan-Boltzmann constant.

The heat source in TIG welding method is electrical arc. The solutions to the classical time-dependent electromagnetic equations for the electrical arc can give values of the current, that heat the welded material according to formula (5). The solution of this equation in 3D case is very time consuming. For this reason, in the software, the surface heat source proposed in (Goldak et al., 1984) was used. At places where heat source is applied, the condition (8) is enriched by the term, with values corresponding to the graph area of the two-dimensional Gaussian function.

$$-k\frac{\partial T}{\partial \boldsymbol{n}} = \frac{6\sqrt{3}Q}{abc\pi\sqrt{\pi}} e^{-3\left[\left(\frac{x-x_G}{a}\right)^2+\left(\frac{y-y_G}{b}\right)^2+\left(\frac{z-z_G}{c}\right)^2\right]} - h_c(T - T_a) - \sigma\varepsilon(T^4 - T_a^4) \tag{9}$$

In the above formula Q is the power of the heat source, a, b, c half-axes of the heat source ellipsoid, x_G, y_G, z_G position of the ellipsoid center.

3. SPACE DISCRETIZATION

Space discretization is done by the finite element method, using an appropriate weak formulation. For the fluid flow problem a well known stabilized formulation presented in (Franca et al., 1992) is used (our weak formulation is exactly the same as proposed in the paper). For energy balance we used weak formulation based on the formula:

$$\int_{\Omega_e}\left[\psi T_{,t} + \frac{k}{\rho c}\psi_{,i}T_{,i} + \psi v_i T_{,i}\right]dx_i + \oint_{\Gamma_e}\frac{1}{\rho c}h_c\psi T\,ds = \int_{\Omega_e}\left[\frac{L_f}{c}\psi f_{l,t}\right]dx_i - \oint_{\Gamma_e}\frac{1}{\rho c}\psi[q_G + h_c T_a - \sigma\varepsilon(T^4 - T_a^4)]ds \tag{10}$$

where domain and boundary integrals are written using test functions ψ, and summation convention is applied for derivatives (differentiation is denoted by “,”). The formulation additionally applies stabilization, to take into account the case of dominating convection. Similarly to the case of the Navier-Stokes equations, SUPG type stabilization (Franca & Frey, 1992) is utilized. Neumann boundary conditions are included in weak formulations, Dirichlet boundary conditions are enforced using the penalty method.

4. TIME DISCRETIZATION

Time discretization scheme used in the modelling of the weld pool takes into account on one hand the time discretization for each of the partial (fluid flow, heat transfer) problems and on the other hand the interaction of variables for both problems. Time discretization for each problem is performed in the implicit manner by the nonlinear Euler scheme and Picard iterations to solve non-linear problems. This solution offers greater stability than explicit methods, the fact that is important when adaptive meshes are used. It is also important for adaptivity that one step time integration is used.

5. GEOMETRIC MODELLING AND MESH GENERATION FOR THE PROBLEM OF HEAT TRANSFER IN WELD POOL

In testing the software for modelling of the weld pool we always used simple linear and multi-linear approximation with vertex shape functions and constrained approximation in the case of hanging nodes, appearing in adapted meshes. We used meshes with tetrahedral and prismatic elements (Banaś & Michalik, 2010). The pre-processing phase (geometrical modelling and mesh generation) is done by software external to the main simulation code. Similarly, visualization of results is performed by external codes. The simulation program allows for importing and exporting meshes and fields in several popular formats, it is designed to make extensions to other formats easy.

6. SOFTWARE ARCHITECTURE

The finite element formulation presented in previous sections is implemented in special problem dependent modules of the Mod_FEM framework (Mod_FEM, 2013). The framework allows one to produce finite element codes having a special modular structure (Banaś., 2004a; Banaś, 2004b; Banaś, 2004c). The main idea consist in creating many small modules for basic finite element tasks. Mod_FEM framework provides tools for producing codes by combining special problem dependent modules and modules for mesh manipulation, approximation, interfacing with linear solvers. The characteristic feature of the framework is that it enables the creation of parallel, distributed memory codes without changing basic modules, by adding suitable overlay modules (Michalik et al., 2013).

Another feature of the framework is that it enables creation of codes for coupled problems by utilizing separate modules for different physical phenomena and special super-modules that perform the suitable coupling. The code created for welding simulations used two separate problem modules – one for fluid flow and the second for heat transfer. The role of the modules was to provide element stiffness matrices and load vectors resulting from appropriate weak formulations. The special coupling super-module performed control tasks: reading and writing input and output data, time integration, mesh adaptation.

As a basis for mesh adaptations error estimates given by the Zienkiewicz-Zhu method (Zienkiewicz & Zhu, 1992) were used. Estimates were computed separately for velocity and temperature fields and combined by the super-module in order to control mesh adaptations for the coupled problem (the same mesh is used for velocity, pressure and temperature fields).

7. NUMERICAL EXPERIMENTS

For the tests, simulations of the welding of two plates having size 0.01×0.04×0.002m made of Inconel alloy 625 were performed. The material data took into account the dependence of density, dynamic viscosity, specific heat and thermal conductivity on temperature, and the material constants such as the solidus temperature, liquidus temperature, the melting heat. The dependence on the temperature was modelled using piecewise linear data with discrete values for selected temperatures. The natural convection condition was applied to all boundaries. On the welding surface additional heat source was imposed, that moves with a constant speed, V_y = 0.04 m/s. In the model the sample is in normal atmospheric conditions p_{atm} = 101325 Pa, T = 290 K. The calculations were performed for three values of the total power of heat source P = 0.6, 1.2 and 2.4 kW. For all calculations the constant time step 10^{-4}s was used.

Adaptive meshes were employed with absolute values of element error estimates utilized in refinement criterion that controlled element divisions. To specify the values of tolerances, in such a way that computer resources are not exceeded, preliminary calculations were conducted. Moreover adaptations were limited to three generations of elements only. This adaptation strategy gave the optimum mesh density around the weld pool, in terms of accuracy and time of calculation. The geometry of the mesh with automatically adapted elements around the weld pool is shown in figure 1.

The results of calculations are presented using the graphs showing the maximum temperature and the maximum liquid alloy velocity within the computational domain, obtained at selected time instants (figure 2). As it is shown, for all three different power sources the maximum velocity values and the maximum temperature reach their approximate maximum in time after about 0.01 s. At that moment it can be assumed that steady state in the weld pool is achieved. The weld pool depth at this moment, reaches the maximum value. The shape and size of the weld pool remains constant within the error limits.

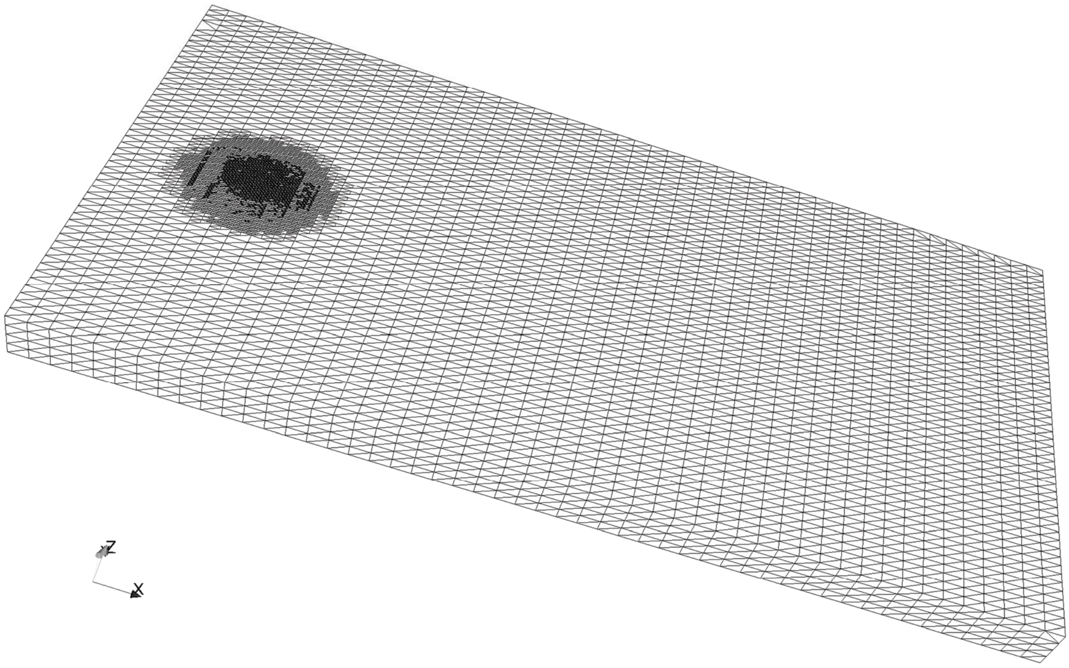

Fig. 1. *Geometry for the test problem with mesh adapted around the welding area.*

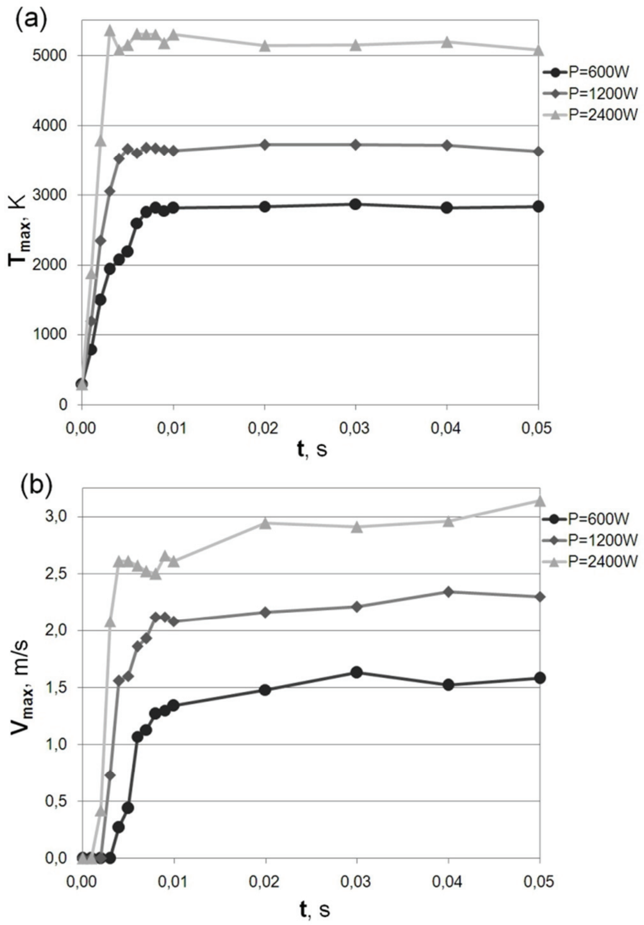

Fig. 2. *Time dependence during welding simulation: (a) of the maximum temperature T_{max} (b) the maximum liquid alloy velocity $V_{max,}$, for three values of heat source power P.*

Figure 3 shows the cross section of the welded plate at time instant $t = 0.04$ s. Three images correspond to three different values of power source. In all cases the vertical stream of liquid metal having high speed is clearly visible. Inconel 625 alloy that was used as material model in the tests have a positive coefficient of the surface tension value. Therefore on the liquid surface near the heat source centre, the surface tension value is greater than on the weld pool edges. As a consequence of the Marangoni effect, the molten alloy on the surface flows towards the centre of the heat source and then down to the bottom of the weld pool. The velocity of liquid decreases after reaching the semi-liquid zone at the bottom. The accepted model for melting and solidification takes into account the dendrites formation in the semi-liquid phase that slows the flow in that area. Additionally, in the same area the melting heat is taken from the metal.

8. CONCLUSION

We presented a code for simulating welding processes. Special modular structure was used to enable multi-physics capabilities. Preliminary results show good accuracy due to mesh adaptivity. The formulation applied allows for further extensions of the model to include more physical phenomena. The modular structure of the code allows for adapting it to new execution environments including high performance systems available for the PL-Grid+ project.

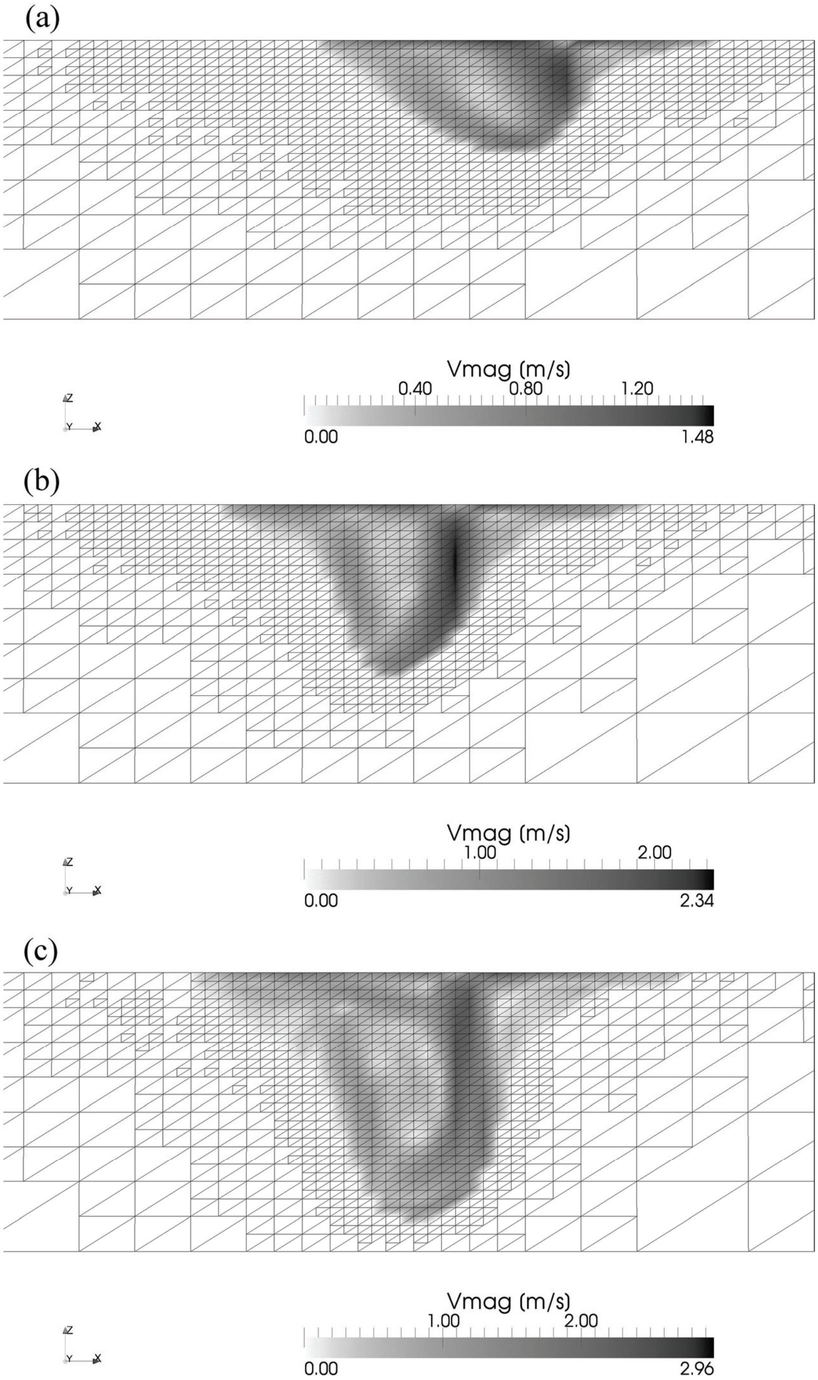

Fig. 3. *Cross section of the welded plate for time instant t = 0.04 s and power of heat source P: (a) 0.6, (b) 1.2 and (c) 2.4 kW.*

Acknowledgments. The research presented in the paper was supported in part by the PL-Grid+ project POIG.02.03.00-00-096/10.

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MODELOWANIE SPAWANIA METODĄ TIG STOPU INCONEL 625

Streszczenie

Stop typu Inconel 625 jest szeroko stosowany w przemyśle lotniczym i kosmicznym ze względu na swoją wysoką wytrzymałość szczególnie w wysokich temperaturach, odporność na korozję i doskonałą spawalność. W pracy modelowano proces spawania TIG wykorzystując gaussowskie źródło ciepła. Obliczenia przeprowadzono wykorzystując własne oprogramowanie Mod_FEM_met, będące usługą infrastruktury PL-Grid+, przeznaczone między innymi do modelowania procesu spawania za pomocą metody elementów skończonych. Program posiada strukturę modularną, w której wykorzystano moduły do rozwiązywania równań Naviera-Stokesa i transportu ciepła wraz z nadrzędnym modułem sprzęgającym użytym do modelowania spawania. Aby zwiększyć szybkość i dokładność obliczeń, w miejscach o dużym błędzie aproksymacji wykorzystano adaptacyjną siatkę. Obliczenia wykonano dla płytki wykonanej ze stopu Inconel 625. W obliczeniach uwzględniono zależność własności stopu Inconel 625 od temperatury oraz zjawiska termiczne na brzegach i wewnątrz obszaru jeziorka spawalniczego. Wynikiem obliczeń są wymiary i kształt jeziorka spawalniczego, pola prędkości i temperatury. Wyniki obliczeń wskazują, że parametrem optymalizującym dopasowanie wyników obliczeń do danych eksperymentalnych może być sprawność źródła ciepła.

Received: September 20, 2012
Received in a revised form: November 4, 2012
Accepted: November 21, 2012