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NUMERICAL MODEL OF A TIG WELDING PROCESS FOR THE AVIATION INDUSTRY, INCLUDING ANALYSIS OF THE HEAT TRANSFER

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Abstract

TIG welding is an important process, which is commonly used in the aircraft industry. A number of elements of airplane bodies or shields of engines are made using this technique. Numerical models of this process are needed to understand better phenomena involved in the TIG welding and to design the optimal process parameters. In the present paper numerical simulations were performed and the possibilities of modeling heat transfer in the investigated process were evaluated. Comparison of results of numerical simulations with the experimental data confirmed good predictive capabilities of the model, as far as realistic description of the phenomena involved in this process are considered. Correctness of the Goldak model, which describes density of the energy in the heat source, was confirmed as well.

Key words: friction stir welding, aluminum, scandium, mechanical properties

1. INTRODUCTION

Welding processes are used for very simple elements with groove and fillet joint, and for very complicated assemblies with both types of welding combinations. Welding process create numerous internal stresses in welded materials. All this stresses are connected with heating/cooling process (melting, solidification, and heat affected zone) and specific volume changes. As a result, a large deformation of welded assemblies can occur or develop the cracks during part operation.

Very complicated fixtures, which require a costly and time consuming development period, are used for reduction of part deformation during welding process. An attempt to transfer such a difficult process like welding to the virtual world in order to reduce a development cost is the main objective of this work. The TIG - Tungsten Inert Gas (in North America called GTAW - Gas Tungsten Arc Welding) process is very important in a majority of industries. Engineers and technologists try to reduce high costs of manufacturing by applying numerical simulation at the stage of the process design and selection of the best manufacturing parameters. This inspired the authors of the present work to perform analysis of possibilities of numerical simulations of the TIG process, which is welding process often used in the aviation industry. Predictions of the thermal state in the welded part and in the welding table are the particular objective of the work. Application of the sensitivity analysis to evaluate importance of the variables and validation of the model by

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comparison with the experimental data are performed, as well.

2. TIG WELDING PROCESS

The TIG welding process was invented during Second World War by the American aircraft industry. This method, from the very beginning, was used to join mainly magnesium and aluminum parts. In 1930 Russell Meredith demonstrated first TIG process for welding of magnesium by using helium gas. The TIG utilizes electrodes made of pure tungsten or tungsten combined with oxides (thoriumoxide, zinconiumoxide) additionally protected by an insert gas. Mentioned material of electrodes creates a stable arc and makes it easier to strike. A schematic illustration of the TIG process is presented in figure 1.

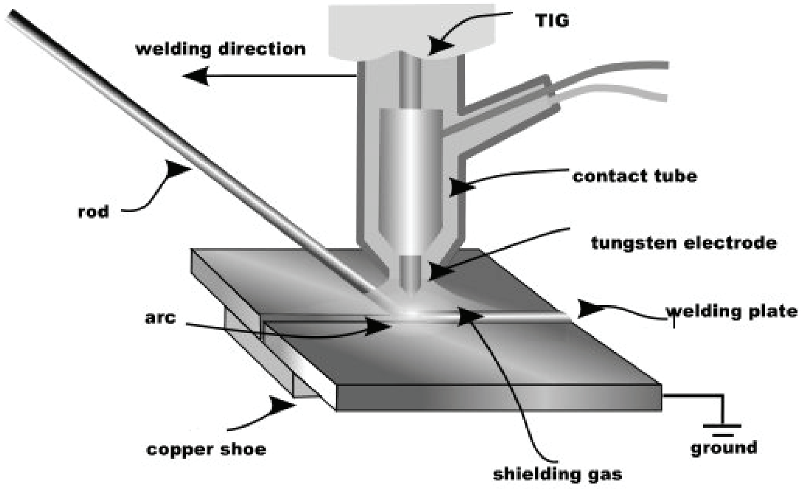


Fig. 1. Schematic illustration of the TIG (GTAW) process.

The electrical discharge generates a plasma arc between the electrode tip and the welded part. The welding path is generated by an arc initialized by a power source in the high frequency generator, up to several MHz. Resulting small sparks provide the initial conducting path through the air for the low voltage current. Frequency with the high voltage (several KV) produces strong electrical interface around the welding cell. Temperature of the arc is usually between 12000 K and 15000 K above the pool surface and about 1700 K to 2500 K on the melted surface. These values depend on material that is used during welding. Three different kinds of current can be distinguished in the TIG welding: direct current (DC) with a positive electrode, DC with negative electrode or alternative current (AC), respectively. The AC is mainly used for the welding of aluminum and magnesium. The DC process can be used for majority of materials, including thick plates of aluminum.

Filler materials can be also used in the TIG process. There are a lot of different kinds of fillers available. Their application is dependent on element thickness, type of joint and certain other factors. In practice, the filler material is usually the same as the base material.

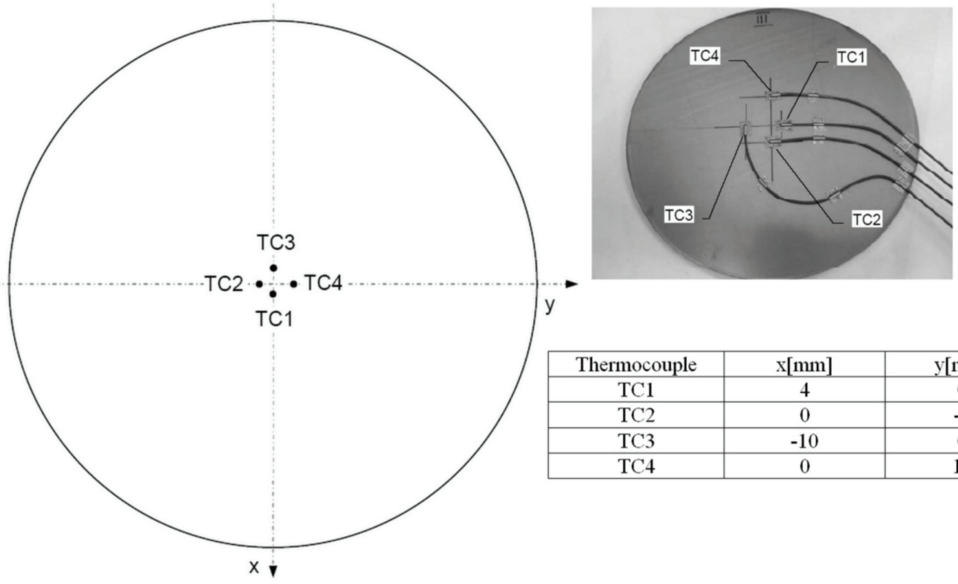
To protect the melted pool and the electrode from atmospheric environment and sustain the arc an insert gas is used. Depending on the parameters it can be argon, helium or mixture of those gases. Argon is widely used for unalloyed, low alloyed and stainless steels. It is the most commonly used shielding gas for thickness less then 3 mm, while helium is more commonly applied for thickness larger than 3 mm (Ericsson, 2003).

TIG welding process is commonly used in various types of industries. This is the reason that researchers explore possibilities of reduction of TIG production costs and beyond experimental methods numerical simulations are used.

Applications of the numerical simulations to design TIG welding technology are the main objective of the present work. All results of simulations are compared with experimental data obtained at the Rzeszów University of Technology and the predictive capability of the model is evaluated. Details of the experimental and numerical procedures are described in the following part of the paper.

3. EXPERIMENTAL ANALYSIS

Experimental research was conducted at the Laboratory of the Department of Casting and Welding at Rzeszów University of Technology. The main task of these experiments was to evaluate the temperature distribution in the part during TIG welding process of the Inconel 625 (AMS 5599) alloy. Four thermocouples situated in specific places were used to record the temperature profiles during welding. The sample with locations of the thermocouples is presented in figure 2. For selected samples thermo camera was also used to obtain the picture of temperature distribution at the welding surface.



Thermocouple	x[mm]	y[mm]
TC1	4	0
TC2	0	-7
TC3	-10	0
TC4	0	13

Fig. 2. *Location of the thermocouples in the PR1 sample.*

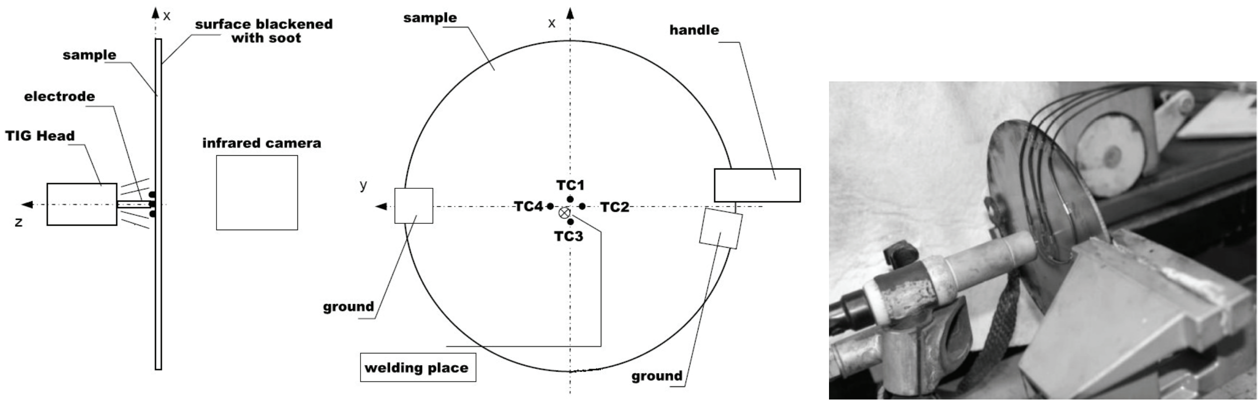


Fig. 3. *Configuration of the TIG welding experimental process.*

A simple test case involving one spot welding without argon blowing on the ridge was selected. Electrical spot was working 10 s in the first experiment and 206 s in the second experiment. The sample dimensions were 120 mm in width and 2 mm in thickness. An exact location of the spot that was working in the two cases of this experiment is shown in table 1.

Table 1. *Welding spot location at the sample during experimental welding.*

	Deviation from central point	
Number of welding	*x*, mm	*y*, mm
1	-4	3
2	-2	0.6

The parameters of the TIG welding process are as follows: direct current (DC) of 20 A with voltage 10 V and the 2.4 mm tungsten electrode was situated 3 mm away from the welded sample (figure 3).

Experimental results are shown in the next part of this article, where they are compared with the results of numerical simulations.

4. NUMERICAL ANALYSIS

4.1. Moving heat model

Thermal analysis in numerical applications is based on the works of Rosenthal (1941 & 1946) describing moving heat source in a defined geometry. In (Deng & Murakawa, 2006) authors clearly describe fundamental governing equations involving heat transport in the material. The main equation is:

$$\rho C_p \frac{\partial T}{\partial t}(x,y,z,t) = -\nabla \bullet q(x,y,z,t) + \dot{Q}(x,y,z,t) \tag{1}$$

where: ρ – density ot the material, C_p – specific heat, T – temperature, q – heat flux vector, $\dot{Q}$ – the rate of internal heat generation, x, y, z – the coordinates in the reference system, t – time, ∇ – the spatial gradient operator.

The first part of the right hand side of equation (1) is the nonlinear isotropic Fourier heat flux constituive equation:

$$q = -k\nabla T \tag{2}$$

where: k – the temperature-dependent thermal conductivity.

The specific heat, thermal conducivity and density are the three thermophysical parameters that need to be precisley defined in equations (1) and (2). For the analysed Inconel 625 (AMS5599) sample the following parameters were selected from Special Metals (2010):

- density 8440 $\frac{kg}{m^3}$,
- specific heat and thermal conductivity as functions of tempretaure shown in figure 4.

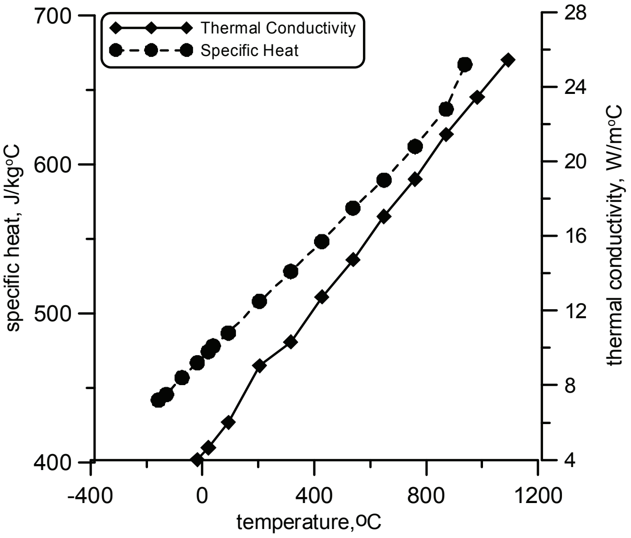


Fig. 4. Specific heat and thermal conductivity of INCONEL 625.

The heat input from the welding torch is modeled as a distributed heat flux (DFLUX in ABAQUS) focused around the weld centerline. Heat from this source is transfered throughout the rest of the plate by conduction. After the torch passes, the plate cools down to an ambient temperature and Fourier thermal boundary condition is used to simulate cooling:

$$q_{bc} = h(T - T_{bc}) \tag{3}$$

where: h – combined convection and radiative heat transfer coefficient, T – local surface temperature, T_{bc} – ambient temperature.

Heat dissipates mainly due to radiation, especially at high temperature. Radiation is defined mainly by an emissivity coefficient. The radiation is independent of temperature and the same value is used for weld and plate material. The emissivity value for Inconel 625 is taken to be about 0.7. The radiation flux is described in the model as:

$$q_i^c = \frac{\sigma\varepsilon_i}{A_i}\sum_j \varepsilon_j \sum_k F_{ij} C_{kj}^{-1}\left((T_j - T_0)^4 - (T_i - T_0)^4\right) \tag{4}$$

where:

$$C_{ij} = \delta_{ij} - \frac{(1-\varepsilon_i)}{A_i}F_{ij} \tag{5}$$

where: A_i – area of facet i, ε_i and ε_j – emissivity of facets i and j, σ – Stefan-Boltzman constant, F_{ij} – geometrical view factor matrix, T_i and T_j – temperatures of facets i and j, T_0 – absolute ambient temperature.

4.2. Goldak welding model

The Goldak model (Goldak et al., 1984) considers different kinds of shape of heat sources welding torches: triangular, conical, elliposidal or split, which can be used in the DFLUX subroutine in ABAQUS. The choice of the heat source depends upon the type of welding process. The most popular heat source model is the Gaussian Surface Flux Distribution equation:

$$q(x,y,t) = \frac{3Q}{\pi r^2}\exp\left(\frac{-3x^2}{r^2}\right)\exp\left(\frac{-3y^2}{r^2}\right) \tag{6}$$

where: Q – the energy or power input (W), r – heat flux radius, x, y – actual position on heating surface.

The geometry of the welding cone is schematically shown in figure 5.

Ewentauly the energy or power input Q is calculated from:

$$Q = \eta UI \tag{7}$$

where: η – the arc efficiency, U – the voltage, V, I – the current, A.

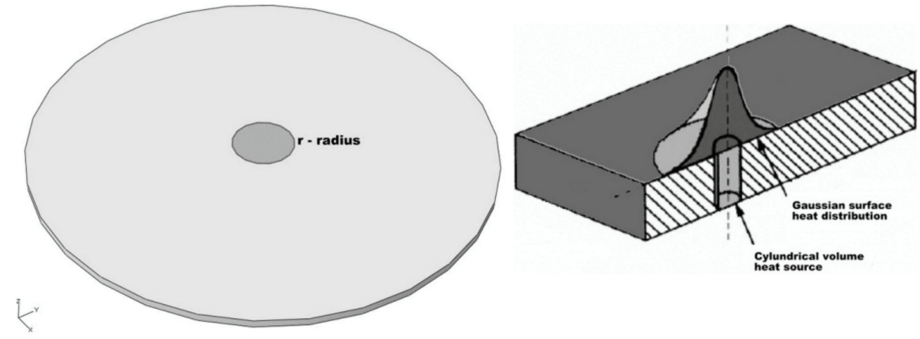


Fig. 5. *Double ellipsoidal heat source definition of the Gaussian Surface Flux Distribution.*

4.3. ABAQUS simulations

Based on the knowledge gathered during experimental part of the research, a numerical model simulating TIG welding process was established. Two different heating processes were simulated to replicate experiments presented in chapter 3. The first simulation describes welding process of a single sample with the heating source moving -4 mm along *x* direction and 3 mm along *y* direction. Following the experiment, in simulations voltage of the welding machine was set at 10 V, current at 20 A, efficiency of the welding process at 0.74. Radius of the heat surface was sat at 1.9 mm. Obtained results of simulations are compared with experimental data in figure 6.

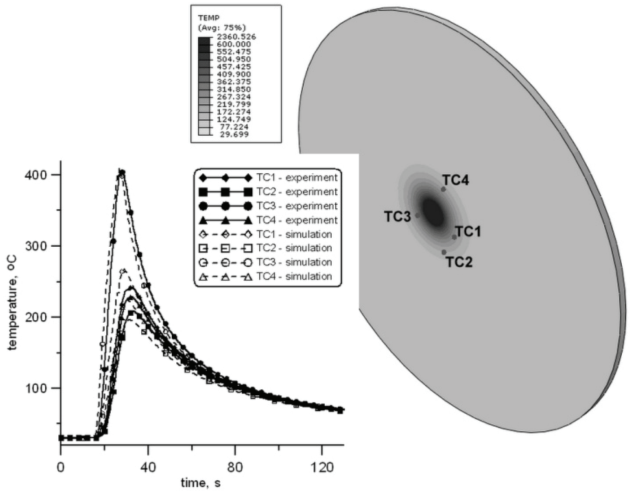


Fig. 6. *Comparison of the time-temperature profiles obtained from the experiment and predicted by numerical simulation for the first welding.*

Similar simulation was made for the second welding. Welding arc was moved to another part at the sample exactly -2 mm along *x* direction and 0.6 along *y* direction. Arc efficiency was set to 0.72, like in the first example. Comparison between experimental results and numerical simulations is shown in figure 7.

Comparison of experimental results with numerical calculations confirms good predictive capabilities of the model and perspectives of transfer of the welding process into virtual simulations. Application of the Goldak heat transfer model with Gaussian surface flux allows for realistic simulation of the TIG welding.

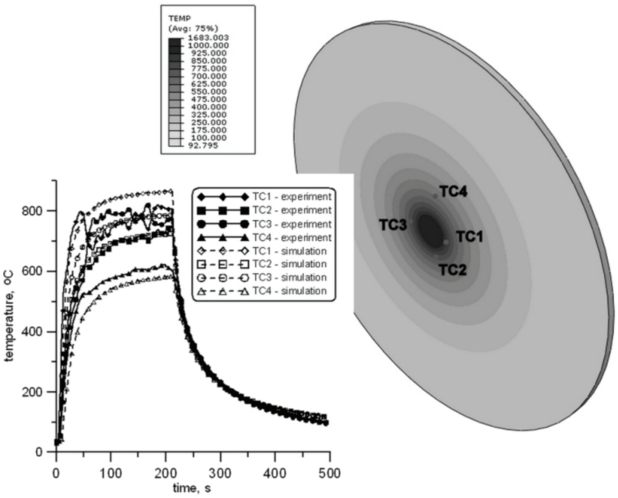


Fig. 7. *Comparison of the time-temperature profiles obtained from the experiment and predicted by numerical simulation for the second welding.*

5. CONCLUSIONS

Performed numerical simulations confirmed good predictive capabilities of the model and proved that it is possible to replicate realistically behavior of the material in experiments. Application of the Goldak model of the shape of the heat source gave good agreement between experimental data and numerical simulations. This model will be used in further works, which will focus on:

- Application of the sensitivity analysis and inverse method. The former should supply information about importance of the parameters in the model, the latter will allow to identifying these parameters.
- Performing experiment composed of calorimetric tests, which should supply information about efficiency of welding arc and maximum range of welding melted pool. That information will be

very useful for more complicated simulations of the TIG welding process.
- Final experiments in the industrial conditions and validation of the model.

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NUMERYCZNY MODEL SPAWANIA METODĄ TIG W PRZEMYŚLE LOTNICZYM, OBEJMUJĄCY ANALIZĘ TRANSPORTU CIEPŁA

Streszczenie

Spawanie TIG jest jednym z najważniejszych procesów używanych w przemyśle lotniczym. Wiele elementów zarówno dla kadłubów, awioniki jak i silników powstaje dzięki temu procesowi. Inżynierowie potrzebują coraz to nowocześniejszych modeli, które pozwolą na łatwe zrozumienie zjawisk zachodzących podczas procesu spawania. W artykule autorzy dokonali szeregu symulacji numerycznych mających na celu ocenienie możliwości modelowania rozkładu ciepła w procesie spawania metodą TIG. Wyniki symulacji porównano z pomiarami przeprowadzonymi na laboratoryjnym stanowisku spawalniczym. Porównanie wyników symulacji numerycznych i pomiarów wykazało dobrą zgodność potwierdzając możliwości modelu w zakresie realistycznego opisu procesu spawania metodą TIG. Potwierdzona została również prawidłowość działania modelu Goldaka opisującego rozkład energii źródła ciepła w procesie spawania.

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