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MODELLING OF THERMAL PROCESSES IN A DISSYMMETRICAL WELDED CAST ALUMINIUM DESIGNS

N. Višniakov, D. Ščekaturovienė, O. Černašėjus
Welding and Material Science Institute, Vilnius Gediminas Technical University,
28 Basanavičiaus Str., LT-2009 Vilnius, Lithuania

Abstract: *Number of constructions, produced from eutectic silumins are continually increasing, therefore problem of their welding became very actual. Eutectic aluminium - silicon alloys are sensitive to changes of a welding thermal cycle. These cast aluminium alloys constructions after welding have large residual stresses, and mechanical properties of welded joint deteriorate. It is difficult to define welding regime in case of complex construction shape, especially near the component edges and other components with different wall thickness, using classical calculation methods. Most useful way to define heat input, optimal welding current and speed is simulating of welding process using finite elements method (FEM). The mentioned method enables to achieve lower size of the heat affected zone and better quality of welded joint.*

Keywords: *cast aluminium alloy, eutectic silumin, TIG welding, thermal deformation, finite elements method.*

1. INTRODUCTION

Cast aluminium alloys constructions are used very widely. Complex constructions usually are joined using welding process. Sometimes the large components are mechanically damaged during exploitation. The change to new one is expensive, and sometimes it is cheaper to use repair welding or surfacing. During welding, local metal overheating takes place. Metal heating and cooling initiate different physical and chemical processes, structural transformations, volume changes, stresses, plastic deformation appearance. This variables influence on welding constructions quality. For more responsible constructions and elements affected by the hard load it is intolerable. All supplemental methods (bending, heat treatment) used to reduce the residual stresses and deformations just increase production costs sometimes without expected outcome. Therefore usually it is necessary to improve welding technology, to optimise the welding regimes, depending on welding arc thermal influence on the metal near the seam, and reduce these negative effects.

The computational simulation methods can help to solve the problem of optimal metal welding regime establishment. The simulation by finite elements method (FEM) is applicable especially for welding of complicated shape structures, when classical selection methods of welding regime are not suitable. Many works (Brown & Song, 1992; Karlsson & Josefson, 1990; Khromov, 1999; Kiselev, 1998; Lho, 1995; Pasthatskij, 2000; Zhang et al., 1996) are devoted to the problems of the modeling of temperature fields and stressed state of welded designs. It is a lot of samples, made as 2-D (Luo et al., 1999; Sluzalec, 1986) or simplified 3-D solutions (Jang et al., 2001; Medvedev 2001; Ueda et al., 1993), implemented for different welding methods. Therefore some aspects of such problems solution in case of known heat input models, demand further study, particularly carrying out of welding processes with concentrated heat sources. Because in practice for welding with concentrated heat sources it is difficult to achieve convergence of the solution or authentic results.

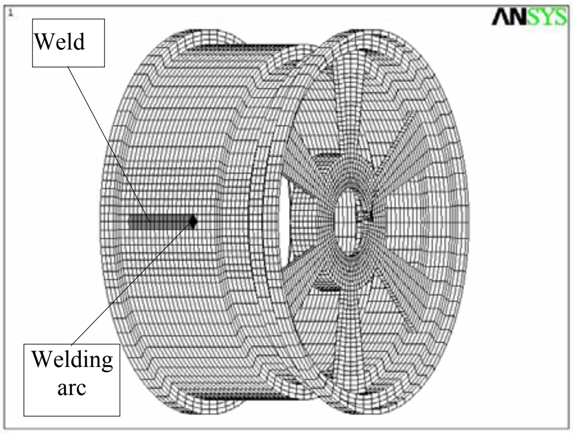

Fig. 1. General view of cast rims finite elements model

2. OBJECT OF STUDY

Object of modeling and experiments is eutectic cast aluminium - silicon alloy complicated shape construction. The cast aluminium - silicon alloys have good casting properties: fluidity, which ensures production of fine wall and complicated form castings, small linear shrinkage till 1 %, low melting temperature 863 °K, small cracking liability, good mechanical properties (Hatch, 1989). Strength and corrosion resistance of aluminium - silicon alloys are increased using alloying, modification and heat treatment.

For heavily loaded components the most suitable aluminium alloys are with improved mechanical properties. Designs from the given alloys after welding cannot be subjected to the subsequent post heat treatment or bending. Eutectic aluminium - silicon alloy chemical composition is presented in the Table 1. Cast aluminium rims have complicated shape, different wall thickness in various places. During welding different heat transferring conditions in the rims relatively the weld axis can be found. This complicates the optimal welding regimes selection and residual deformations prediction, using classical calculation methods.

3. SIMULATION METHODOLOGY

3.1 Finite elements modelling and mesh generation

Welding specimen geometry (see Figure 1) and loading conditions are modelled, using the software "ANSYS". To create a welded constructions volumetric model the "Solid70" 8-node brick finite elements was used.

Table 1. Cast aluminium - silicon alloy chemical composition, % (rest aluminium)

Chemical composition, %					
Si	Mg	Ti	Fe	Cr	M
11.3	0.14	0.16	0.16	0.004	0.006

The process of welding was simulated with incremental steps, when welding arc movement process was divided into the suitable time intervals. In any cases of heat transfer process during welding, 3 models were used: heat source model, welded construction model and heat exchange conditions model.

3.2 Heat input model

For arc welding imitation model of a heat source, moving along the surface was used. The basic characteristic of a heat source at the fusion welding is the quantity of transmitted energy into the welded metal (Frolov, 1988).

$$q=Q\eta=0.24kIU\eta, \quad (1)$$

where q is effective welding arc power, Q is complete welding arc thermal capacity, η is welding arc thermal efficiency, k is factor which incorporates the influence of current strength, type of electric current and arc voltage.

Heat input into welded joint is simulated by enter a thermal energy of a heat source. However putting into practice the given model for welding with concentrated heat sources usually it is difficult to achieve convergence of the solution. Therefore in the present paper the surface model of heat source was used, taking into account the sizes of welding arc spot. The thermal efficiency of welding process depending on welding method and method of edges preparation are taken into account when calculation of the general capacity of heat source is carried out.

3.3 Transient thermal analysis

Temperature distribution of in a body, temperature changes during welding and sizes of heat-affected zone were established, using calculations based on the finite elements method. The simulation of heat exchange processes in a welding pool and welded constructions slightly differs from the classical tasks of heat conduction. It is required to establish distribution of temperature in welded constructions, taking into account the dependence of material properties on temperature. The changes of material modular condition and phase transformations influence on the accuracy of results. In the case of simulation processes of heat exchange the greatest problems are related with heat transfer to the welding pool. Heat energy transfer can take place in 3 ways: conduction, convection and radiation. In the solid heat is transferred due to conduction. From the metal surface heat is rejected due to convection and radiation. Heat transfer processes are important during welding: heat input during welding, dissipates in the atmosphere and solid due to cooling. Enthalpy of the material as a function of temperature (see Figure 2) was used in the thermal analysis with phase change problem. Using the software system TC-4A for thermochemical equilibrium calculation, melting point, phase changes and solidification temperatures of the aluminium - silicon alloy were established. The accepted conditional characters and definitions:

- aluminium alloy is the isotropic material with properties being varied depending on temperature (thermal conductivity, effective emissivity, enthalpy)
- the thermal energy is transferred to in 3 ways: heat conduction, convection and radiation.

Table 2. Properties of aluminium-silicon alloy for transient thermal analysis

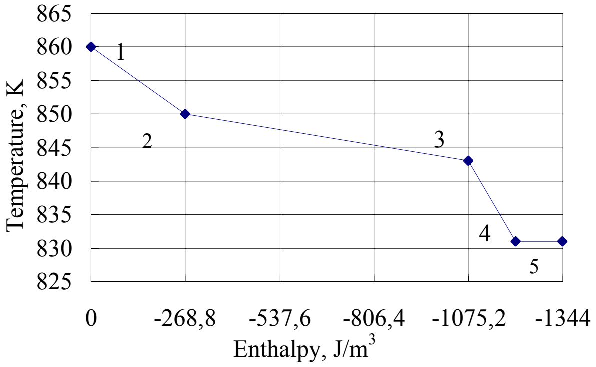

Fig. 2. Aluminium - silicon alloy enthalpy curve: 1 – liquid; 2 – liquid + aluminium phase; 3 – liquid + + aluminium + silicon phases; 4 – liquid + aluminium + + silicon + Mg_2Si phases; 5 – solid

When the energy source (welding arc) is movable source, the thermal influence of consecutive moving source on the separate points should be summarized. As the first law of thermodynamics states that thermal energy is conserved then the general differential equation is (Barauskas, 1988):

$$\rho c\left(\frac{\partial T}{\partial t}+v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}+v_z\frac{\partial T}{\partial z}\right)=Q+\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right), \quad (2)$$

where ρ is density of material, c is specific heat, T is temperature, t is time, Q is heat flow rate, K_x, K_y, K_z are thermal conductivities

The following initial and boundary conditions are accepted:

1. Temperature acting over surface of element

$$T=T_0, \quad (3)$$

2. Thermal flow acting over surface of element

$$\{q\}^T\{\eta\}=-q_0, \quad (4)$$

where $\{\eta\}$ is unit normal vector

3. Convection acting over surface of element

$$\{q\}^T\{\eta\}=-h_p\left(T_{ap}-T\right), \quad (5)$$

where h_p is convective film coefficient, T_{ap} is ambient temperature, T is temperature at the surface of the analysed object.

4. Phase changes of material during melting and solidifying, which determined the changes of internal energy are defined as:

$$Q'=H_2-H_1=\Delta H, \quad (6)$$

where H_2 is enthalpy of system corresponded to the temperature at the end of process, H_1 is enthalpy of system corresponded to the temperature in the beginning of the process.

Properties of aluminium alloy, which are used for transient thermal analysis, are shown in the Table 2 and Figures 2–4 (Višniakov &Valiulis, 2000).

Thermal efficiency	Convective film coefficient	Stefan-Boltzmann constant	Ambient temperature	Density	Specific heat
η	h, W/m^2*K	σ, W/m^2*K^4	T_a, K	ρ, kg/m^3	C_P, J/kg*K
0.52	14.7	5.67e^{-8}	20	2685	900

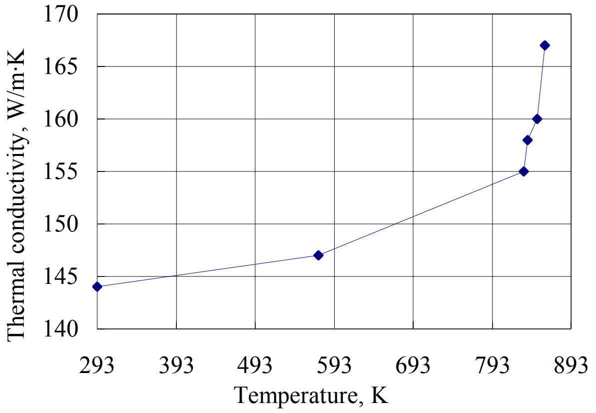

Fig. 3. Aluminium-silicon alloy thermal conductivity as a function of temperature

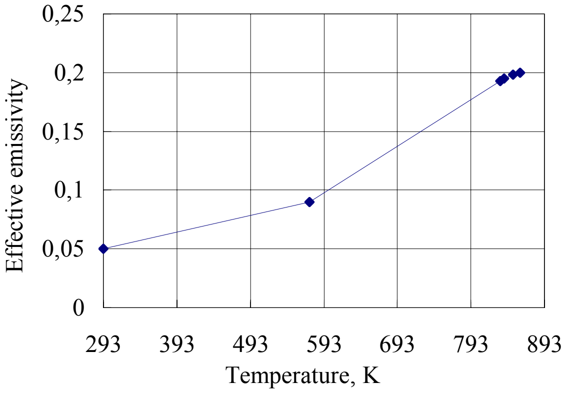

Fig. 4. Aluminium-silicon alloy effective emissivity as a function of temperature

4. METHODOLOGY OF THE EXPERIMENTS

The test bench for assembling, welding and for temperature measurements of aluminium rims was created. Cast rims were welded, using automatic tungsten inert-gas arc welding (TIG). For cast rims welding the OK Tigrod 18.05 filler electrode ∅ 4.0 mm was used (See Table 3). Welding regime parameters were changed in ranges: welding current from 160 A to 230 A, and welding speed from 8,5 m/h to 13 m/h. Temperature was measured at 3 points close to the edge of rims. Thermocouples fixed on the welded component surface and computer recording device DAD 1011c were used for the experiments.

5. ANALYSIS OF THE RESULTS

5.1 Results of temperature distribution simulation

Heat affected zone is very large (where temperature is above 573 °K) when the longitudinal welds are welded close to the edge of rim by using recommended welding regimes according to the metal thickness. In this zone recrystallisation takes place, and deterioration of the metal properties was found. Temperature distributions in the cast aluminium rims during welding with different regimes are shown in Figures 5 and 6. Heat input in the weld area depends on welding current and welding rate. These parameters were changed during the experimental welding and in the heat transferring calculations.

Table 3. Filler electrode chemical composition, % (rest aluminium)

Chemical composition, %			
Si	Mn	Fe	Zn
12.0	0.1	0.2	0.05

After the calculations the optimum welding current and welding speed for 2 - 3 mm metal thickness were determined. Components with wall thickness 2-3 mm can be welded using the following regime: welding current 160 A, arc voltage 15 V, welding speed 13 m/h. The heat affected zone area decreased 1.5 times.

5.2 Measurements results of temperature changes

Temperature measurements with thermocouples in particular points of the aluminium rim during welding experiments confirm accuracy of the computational thermal analysis results. The difference between experimental and simulation results does not exceed 5% (See Figures 7 and 8).

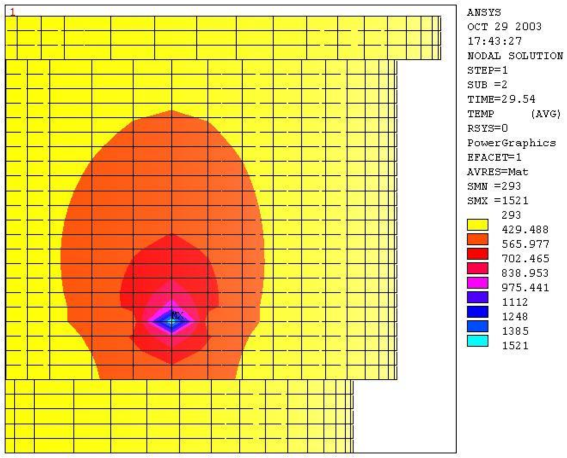

Fig. 5. Temperature distribution during welding. Welding regime parameters: welding current 230 A, arc voltage 15 V, welding speed 8.5 m/h

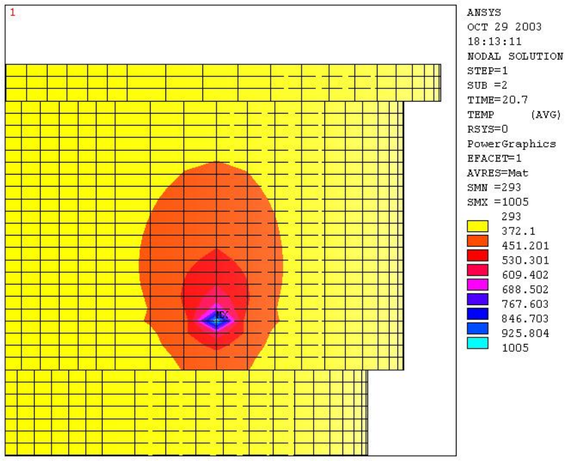

Fig. 6. Temperature distribution during welding. Welding regime parameters: welding current 160 A, arc voltage 15 V, welding speed 13 m/h

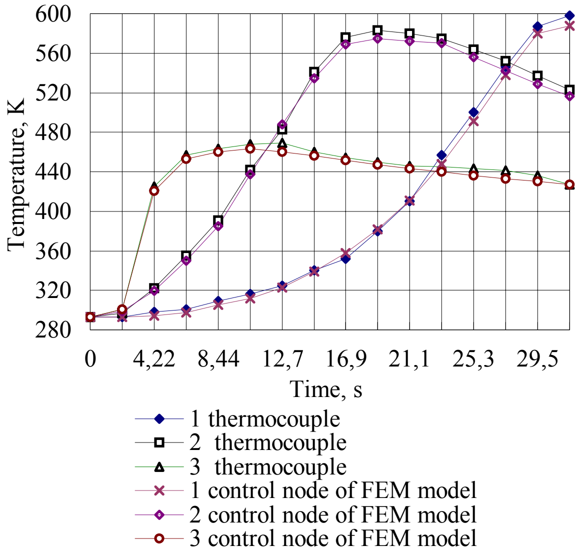

Fig. 7. Experimental and theoretical temperature distribution in the body during welding. Welding regime parameters: 240 A, 8,5 m/h

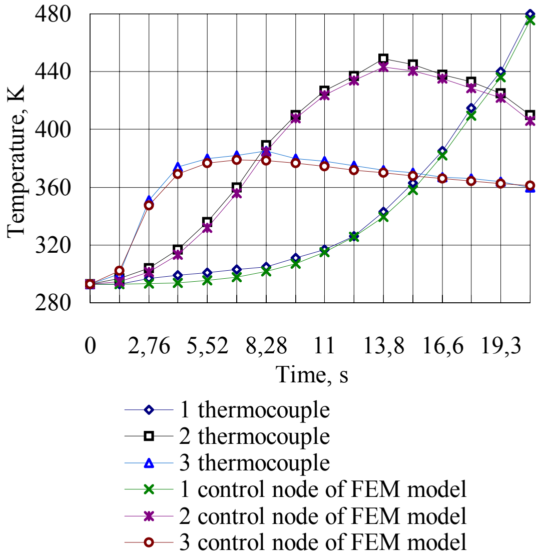

Fig. 8. Experimental and theoretical temperature distribution in the body during welding. Welding regime parameters: 160 A, 13 m/h

6. CONCLUSIONS

1. Using of the given heat source model and three–dimensional transient thermal analysis method for thermal cycles simulation gives a possibility to determine values of those parameters with high accuracy, especially for very complicated shape cast aluminium alloy welded components.
2. Comparisons of experimental and simulations results show that used calculation methodology gives the high correspondence of the results with the experimental. Values of temperatures received by finite elements method are very close to the real temperature distribution in the welded construction. Difference between experimental and simulation results do not exceed 5%.
3. Three–dimensional numerical simulation of TIG welding process by FEM is suitable for calculation of heat affected zone area in the welded joint. The calculated sizes of welded seam precisely reflect real geometry of welded seam. By changing the heat flow input estimated by calculations, it is possible to optimise welding regime and to reduce the size of heat affected zone. In this case the heat affected zone area decreased 1.5 times.

7. REFERENCES

R. Barauskas. Basis of finite elements method. - Kaunas: Technology, 1998. – p. 333 (in Lithuanian).

Brown S., Song H. Implications of tree-dimensional numerical simulations of welding of large structures // Welding Journal, 1992, Vol. 71, № 2, 55–62p.

V. V. Frolov. Welding theory. - Moscow: Higher education, 1988. - p. 560 (in Russian).

J. E. Hatch. Aluminium properties and physical metallurgy - Moscow: Metallurgy, 1989. – p. 420 (in Russian).

Jang G.B., Kim H.K., Kang S.S. The Effects of Root Opening on Mechanical Properties, Deformation and Residual Stress of Weldments // Welding Research Supplement, 2001, 80–89p.

Karlsson R., Josefson B. Three–dimensional finite element analysis of temperatures and stresses in a single-pass butt-welded pipe // Trans. ASME, Journal of Pressure Vessel Technology, 1990, Vol. 71, № 9, 76–84p.

Khromov V.N. Simulation of thermoelastic plastic deformation in the calculation of distribution of residual stresses and strains // Metallovedenie i Termicheskaja Obrabotka Metallov, № 5, 1999, 24–28p. (in Russian)

Kiselev S.N. Current aspects of computer modeling thermal and deformations stresses and structure formation in welding and related technologies // Svarochnoe proizvodstvo, № 10, 1998, 17–24p. (in Russian)

Lho T. J. A study on mathematical modeling parameter optimization in gas tungsten arc welding of thin pipes // Journal of Engineering for Industry, Vol. 117, 1995, 78–83p.

Luo Y., Ishiyama M., Murakawa H. Welding Deformation of Plates with Longitudinal Curvature // Trans. of JWRI, 1999, Vol. 28, № 2, 97–106p.

Medvedev S.V. Computer modeling of residual welding deformations at technological design of welding construction // Svarochnoe proizvodstvo, № 8, 2001, 10–17p. (in Russian)

Pashatskij H.B. Thermal processes at welding of flat components // Svarochnoe proizvodstvo, № 7, 2000, 3–5p. (in Russian)

Sluzalec A. Moving Heat Source Analysed by Finite Elements and Its Application in Welding // Indian journal of Technology, Vol. 24, 1986, 303–308p.

Ueda Y., Wang J., Murakawa H., Yuan M. Three–dimensional numerical simulation of various thermo-mechanical processes by FEM (Report I) // Trans. Of JWRI. 1993. Vol. 21, № 2, 111-117p.

Višniakov N., Valiulis A.V. Welding deformations in cast aluminium alloys // Material Science, Vol. 6, № 2, Kaunas, 2000, 88–91p.

Zhang Y.M., Cao Z.N, Kovacevic R. Numerical analysis of fully penetrated weld pools in gas tungsten arc welding // Proc. Instn Mech. Engrs, Vol. 210, 1996, 187–195p.