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RESEARCHES ON THE THERMAL FIELDS ANALYSIS AT MAG-M MECHANIZED BUTT WELDING WITH SOLID WIRE

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ABSTRACT

The thermal field has a major influence during the welding process. The heat transfer resulting from welding has an influence on the metallurgical and mechanical properties of steels and welded joints. The most affected regions are: fusion zone (FZ) and heat affected zone (HAZ) due to high temperatures to structural transformations of welded joints. The research is based on the theoretical investigations on high-temperature welding areas through MAG-M mechanized butt welding with solid wire of the naval high strength steel, EH 36. For theoretical research, a model with 3D finite elements was used. For the welded joint, the filler technique was used, which means the filler material is modelled with finite elements. The finite elements are activated when the heat flow passes through them.

Keywords: fusion zone, heat affected zone, 3D finite element model, temperature field, solid wire.

1. INTRODUCTION

Due to the transformations that occur during the welding process, in the fusion zone (FZ) and heat-affected area (HAZ) where high temperatures are recorded, a numerical heat transfer investigation may predict the behavior of the material during the welding process. Most welding processes, and the MAG-M welding process, by transferring the generated heat, can cause damage. In addition to the welding joint, besides quality and productivity, the most important is that at the end of the welding process a welded joint to be obtained whose mechanical properties are optimal. Finite Element Analysis, based on numerical methods, is very useful to predict distortions and residual stresses caused by welding, even in the design phase of the product. Numerous two-dimensional and three-dimensional numerical models have been developed to simulate one of the most complex technological processes, such as the welding process.

A complex model of the thermal source - often used in the modelling and simulation of the welding process - was developed by Goldak, who reported the heat source as an ellipsoid model [1], [2]. As a particularity, Goldak modelled the heat flux in different ratios in front and in the rear of the thermal source. Other models for thermal sources were developed by Sabapathy et al. [3] and Ravichandran et al. [4]. Ueda and Yamakawa [5], Hibbitt and Marçal [6] could be considered pioneers in development of finite element method applicable in the welding process simulation field. Based on the coupled sequential analysis technique, Friedman [7], Andersson [8] developed a specific procedure applied in simulation of welding process. The analysis of the thermo-physical phenomena, conducted during butt welding of plates, was made by performing only a half numerical model and obtaining a great economy of computing and numerical analysing time. A significant contribution was introduced by McDill et al. [9], [10], [11], [12] who introduced a dynamic adaptive discretization of elements mesh. Besides, finer mesh is needed in the important regions of the welded joint, where the temperature gradients are high and metallurgical and mechanical properties are seriously affected [13], [14].

Three dimensional finite element model of butt welding joint - used for simulation of heat transfer in naval steel joint performed by MAG-M welding process - is developed and described in this paper.

2. NUMERICAL MODEL DEVELOPMENT

In the case of welding by fusion, temperature field profile depends on primary welding parameters - voltage, amperage, welding speed - thermo-physical properties of the base material - specific heat, mass density, thermal conductibility, thermal diffusivity and heat loss by convection and radiation. Two double-ellipsoidal heat sources are considered in simulation of naval plates which are welded by MAG-M welding process [15]. The model of plates with thickness of 10 mm, including the V bevel between the edges of plates (prepared according to API-5L standard) and the mesh refined in the most interesting joint's regions is illustrated in Figure 1.

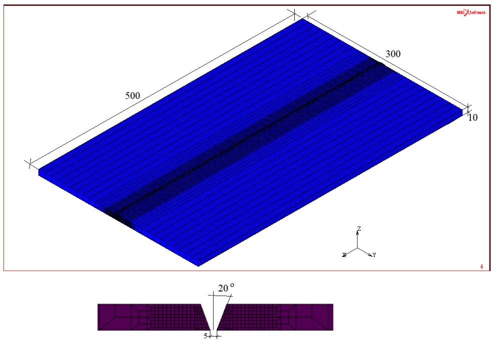


Fig. 1. Three-dimensional mesh model

SOLID7 element (eight-nodded, isoparametric, three-dimensional brick elements) is recommended for the thermal and structural analysis. A trilinear interpolation function is used to describe the temperature within each element based on the nodal temperatures. Values of temperature and flux gradients are predicted in the entire welded joint. Still, they are particularly pursued in and around the fusion zone (FZ) and heat affected zone (HAZ), where metallurgical and mechanical properties are seriously affected. A successive refinement of mesh is applied in these regions. In order to save time of computing, analysis and processing of data, the finite elements dimensions are larger far away from these areas. The heat transfer in the plates was modelled as 3D heat transfer problem using the MSC Marc Mental code.

The numerical model has been developed, taking into consideration the following assumptions:

- isotropy of base metal;

- thermo-physical properties dependent on temperature;
- convection and radiation losses;
- latent heat specific to the phase transformation.

The initial temperature of the base metal has been considered 15^{0}C. During the whole process, the welding speed of each heat source has been considered according to the below table and these values have been considered invariably. The heat input, specific to each heat source, is kept constant. In the third phase, the first source ends the heating action on the joint and the second thermal source keeps moving until it reaches the end of the plates.

The experimental programme was carried out in the *Welding Advanced Research Center (SUDAV)* of the Department of Manufacturing Engineering from Faculty of Engineering, "Dunarea de Jos" University of Galati.

The following materials were used in this experimental program: base material (high strength steel sheet EH 36, dimensions 300x150x10mm), filler material (solid wire ER70S-6 according to AWS A5.18, diameter 1.2 mm) and auxiliary materials (M21 - Corgon 18 gas mixture and flat concave channel ceramic support).

In the experimental program, the stand for thermal field analysis and stress and deformation states at MAG-M mechanized welding was used in the PA position presented in detail in Figure 2.

This stand consists of three zones: zone I - welding of samples, zone II - recording of data on the thermal field and zone III - recording of data on voltages and deformations.

The stand is equipped with universal welding equipment Phoenix 405 Progress pulse MM TDM and K-BUG 5102 welding tractor.

Figure 3 shows zone II of data acquisition for thermal fields and effective welding of the sample.

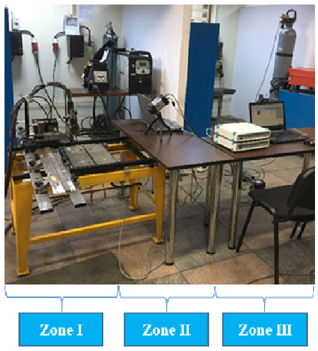


Fig. 2. Stand for thermal field analysis and stress state and deformations at MAG-M mechanized welding in horizontal position PA [16]

Fig. 3. Zone II acquisition of data on welding thermal fields [16]

The welding of the two tables has been done in two passes. The first pass is the root layer and the second is the fill layer. The welding parameters are shown in the Table 1.

Table 1. The welding parameters

Layer no.	The welding parameters			
	v_e [m/min]	I_w [A]	U_a [V]	v_t [cm/min]
	v_p [cm/min]	L_p [mm]	v_w [cm/min]	E_l [KJ/mm]
	Q_G [l/min]	$t_{preg} = t_{posg}$ [s]	h_{D-C} [mm]	t_{sm} [s]
1. root	4.5	158	21	20
	60	4	7.15	0.617
	18	5	17	0.2
2. filler	7	185	27	30
	60	8	15	1.33
	18	5	17	0.2

The welding sources are modelled according to Goldak's model in which the heat flux has different ratios in front and in the rear of heat source (Fig. 4).

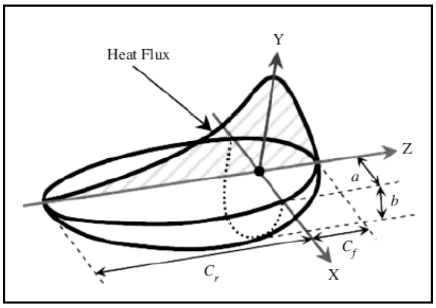


Fig. 4. Goldak's model of heat source [1]

The governing equation for transient heat transfer analysis is given by equation (1) and the spatial heat distribution which is different in front and in the rear of the thermal source can be computed by applying the equations (2) and (3) [1]:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t}(x, y, z, t) = \nabla q(x, y, z, t) + Q(x, y, z, t) \quad (1)$$

$$q_f = \frac{6\sqrt{3\eta} \cdot Q \cdot f_f}{\pi\sqrt{\pi} \cdot a \cdot b \cdot c_f} \cdot e^{-3 \cdot (\frac{x^2}{a} + \frac{y^2}{b} + \frac{z^2}{c_f})} \quad (2)$$

$$q_r = \frac{6\sqrt{3\eta} \cdot Q \cdot f_r}{\pi\sqrt{\pi} \cdot a \cdot b \cdot c_r} \cdot e^{-3 \cdot (\frac{x^2}{a} + \frac{y^2}{b} + \frac{z^2}{c_r})} \quad (3)$$

where $Q = U \cdot I$ and $f_f + f_r = 2$; *a*- width of heat source [m]; *b*- depth of heat source [m]; c_f- length of the front ellipsoidal [m]; c_r- length of rear ellipsoidal [m]; f_f - fraction of heat in front ellipsoidal; f_r- fraction of heat in rear ellipsoidal; *Q*- total heat input [W]; *U*- welding voltage [V]; *I*- welding current [A]; η- process efficiency.

The accuracy of numerical results depends on the input data accuracy and boundary conditions, which must reproduce as close as possible the real conditions of the process.

In the Table 2, the real dimensions - *a, b,* c_f, c_r - specific to thermal source and the welding parameters - *amperage, voltage and welding speed* - specific to the MAG-M welding process are respectively presented.

Table 2. Heat source dimensions and welding parameters used in FE analysis

Dimensions of heat sources [mm]		Location on surface	Welding Arc	I_w, [A]	U_a, [V]	v_w, [cm/min]
a	4	root	WA 1	158	21	7.5
b	4					
c_f	2.5	filler	WA 2	185	27	15
c_r	10					

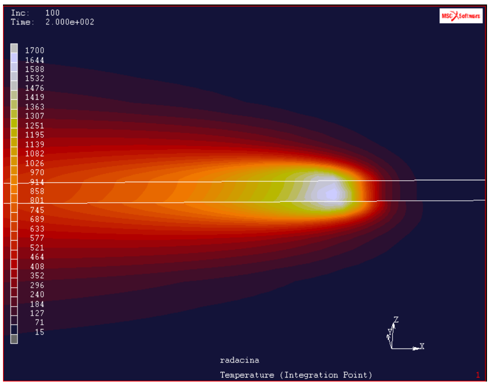
3. TEMPERATURE FIELD ANALYSIS

A non-uniform temperature field is generated at the beginning of the welding process and temperature distribution within the transient phase is influenced by heat developed by the electric arc. In order to determine the thermal fields during the welding processes, the infrared thermography method was used, which proved to be feasible for the monitoring of welding processes.

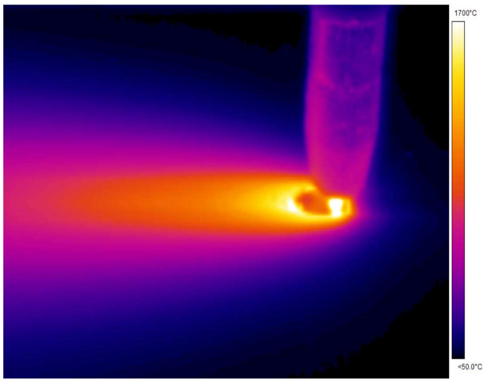
The welding process was recorded with thermographic camera and simulated by the finite element analysis, respecting all phases described above. Time of 200 seconds, enough to achieve a stable temperature field specific to steady-state of the process, was considered from the beginning of the process for the first pass and 180 seconds for the second pass.

The maximum temperatures recorded with the thermographic camera during the welding process were 1700^0C for the first pass and 1540^0C for the second pass, values corresponding to the temperatures obtained in the finite element analysis. General views of simulated thermal fields and thermal picture during the each pass of welding process are presented in Figures 5 and 6.

More relevant are the temperature charts plotted on top of joint for each pass simulated, illustrated in Figure 7. The correlation factor of finite element analysis and thermography data has a value of 0.999 which shows that the finite element model considered is valid and can be used as a basis for further research on stress and strain analysis.



a)



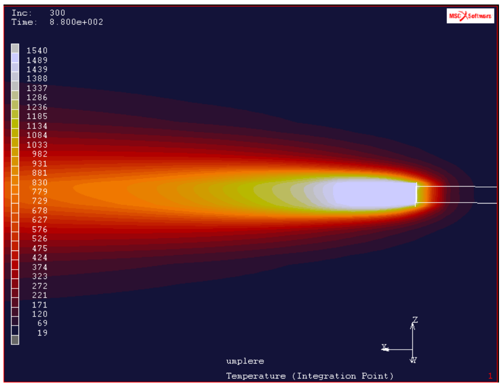
b)

Fig. 5. Temperature field for root layer at t = 300s, a) FEM, b) thermographic camera picture

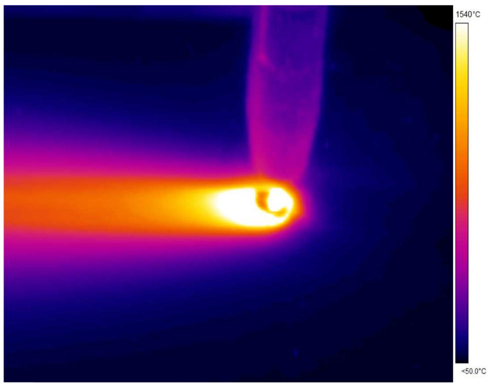
At the beginning of the process, so called transient phase, due to the low temperature of the plates and the instability of the process, heat affected zone (HAZ) is less extended.

In the steady-state or equilibrium phase, the welding process is stabilized and the temperature field has the same shape in each moment. In the areas of the heat sources, the temperature gradients are high, involving a specific behaviour of the base material and a degradation of its metallurgical and mechanical properties.

Based on the finite element modelling, the numerical results were processed and a chart representing temperature vs. time, shown in Figure 9 - of the nodes marked on the upper surface of joint - were plotted, as Figure 8 a).



a)



b)

Fig. 6. Temperature field for filler layer at t = 160s, a) FEM, b) thermographic camera picture

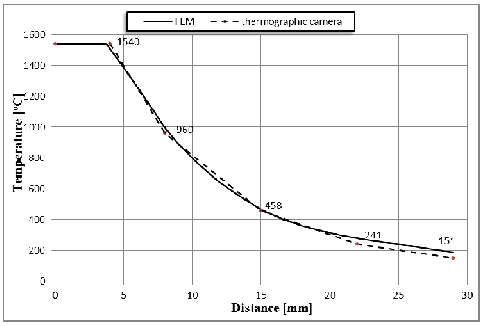
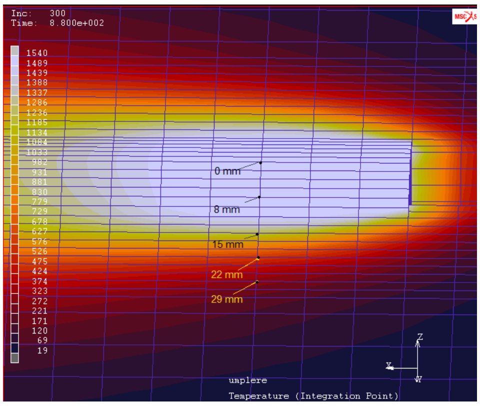
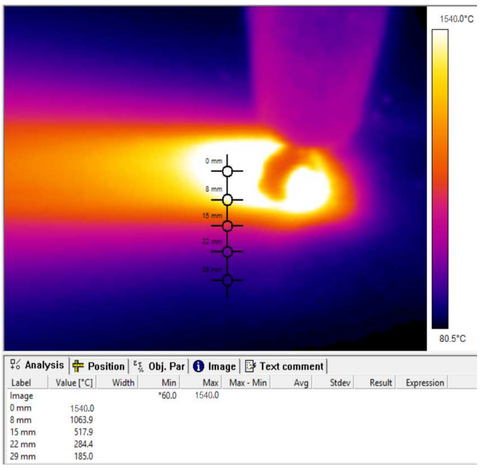


Fig. 7. Temperature profile in cross section FEM and thermographic camera



a)



b)

Fig. 8. Position of nodes used for thermal cycles' analysis a) FEM, b) thermo-camera picture

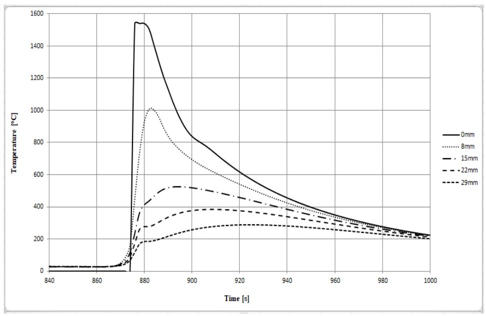


Fig. 9. Thermal history of nodes shown in Figure 8 a)

Similarly, for thermographic data, the chart representing temperature vs. time is shown in Figure 10 - of the nodes marked on the upper surface of joint - were plotted, as in Figure 8 b). It can be noticed the specific shape of thermal cycles achieved in the case of double-arc welding.

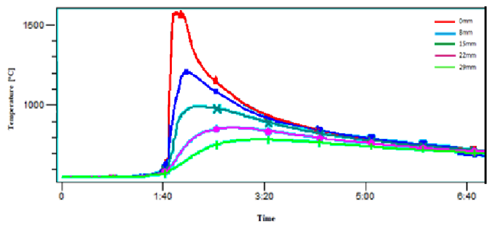


Fig. 10. Thermal history of nodes shown in Figure 8 b)

4. CONCLUSION

Three dimensional finite element model of longitudinal butt welded joint was developed and described in this paper. This original model can be applied for simulation of heat transfer in naval steel joint performed by MAG-M welding process. There are few specific aspects which have to be emphasised when MAG-M welding process is applied:

- The peak temperatures reached within the heating phases is strongly dependent on the transverse distance from the welding line. They decrease with distance increasing.

In order to have a complete view on the naval steel behaviour, the research should be continued with investigation of mechanical and metallurgical changes, so that the optimum welding parameters - corresponding to the achievement of best properties of the base material - should be set, according to the data on the temperature field and thermal cycles described in this work. The correlation factor of finite element analysis and thermography data has a value of 0.999 which shows that the finite element model considered is valid and can be used as a basis for further research on stress and strain analysis.

REFERENCES

[1] **J. Goldak, A. Chakravarti and M. Bibby**, "*A new finite element model for heat sources"*, Metallurgical Transactions B, vol. 15 B , 299-305, 1984.

[2] **J. Goldak, M. Bibby, J. Moore, R. House, B. Patel**, "*Computer modelling of heat flow in welds"*, Metallurgical Transactions B, vol. 17 B , 587-600, 1986.

[3] **P. N. Sabapathy, M. A. Wahab, M. J. Painter**, "*Numerical models of in service welding of gas pipeline"*, Journal of Materials Processing Technology, vol. 118, 14-21, 2001.

[4] **G. Ravichandran, V. P. Raghupathy, N. Ganesan**, "*Analysis of temperature distribution during circumferential welding of cylindrical and spherical components using the finite element method"*, Journal of Computer and Structures, vol. 59, No. 2, 225-255, 1996.

[5] **Y. Ueda, T. Yamakawa**, "*Analysis of thermal-elastic stress and strain during welding by finite element method"*, JWRI, vol. 2, 1971.

[6] **H. D. Hibbitt, P. V. Marcal**, "*A numerical thermo-mechanical model for the welding and subsequent loading of a fabricated structure"*, Journal of Computers and Structures, 3, 1153-1174, 1973.

[7] **E. Friedman**, "*Thermo-mechanical analysis of the welding process using the finite element method"*, ASME Journal of Pressure Vessel Technology, 206-213, 1975.

[9] **J. M. McDill, A. S. Oddy**, "*A non-conforming eight to 26-node hexahedron for three dimensional thermal-elasto-plastic finite element analysis"*, Journal of Computers and Structures, vol. 54, no. 2, 183-189, 1995.

[10] **J. M. McDill, A. S. Oddy**, "*Arbitrary coarsening for adaptive mesh management in three dimensional automatic finite element analysis"*, Mathematical Modelling and Science Computing, vol. 2, 1072-1077, 1993.

[11] **J. M. McDill, J. A. Goldak, A. S. Oddy, M. J. Bibby**, "*Isoparametric quadrilaterals and hexahedrons for mesh-grading algorithms"*, Communications in Applied Numerical Methods, vol. 3, 155-163, 1987.

[12] **J. M. McDill, A. S. Oddy, M. E. Klien**, "*Data transfer for 3-D adaptive thermal-elasto- plastic finite element analysis"*, Simulation of Materials Processing: Methods and Applications, Shen & Dawson, 1995.

[13] **E. Constantin, E. Scutelnicu, C. C. Rusu, L. Mistodie, C. Voicu, D. Boazu**, "*FEA and experiments in case of pipelines welding"*, Proceedings of the 2nd South East European IIW International Congress, Welding - HIGH-TECH Technology in 21st century, Pipeline Welding Current Topic of the Region, Bulgaria, 254-257, 2010.

[15] **D. C. Birsan, C. C. Rusu, E. Scutelnicu, L. R. Mistodie**, "*Heat transfer analysis in API X70 steel joints performed by double submerged arc welding process"*, Metalurgia International, sp. vol. XVIII no. 1, 62-65, 2013.

[16] **St. N. Florescu, D. Mihăilescu**, „*Stand for data acquisition on field thermal stresses and deformation to the mechanized welding MAG-M"*, Scientific Conference of Doctoral Schools, 5th Edition of CSSD-UDJG, 8th and 9th of June 2017, Perspectives and challenges in doctoral research!, Poster.

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