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Development of Simulation Models in Welding

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Abstract **– Automation of the welding processes requires understanding and modeling the influence of welding parameters on the distribution of power in the electric arc, heat and mass transfer in the welding area and the geometry and structure of the metal. Welding processes are nonlinear and complex and require knowledge of the various fields of science. Therefore the modeling of the welding process is very complex and difficult.**

Keywords **– welding, simulations, geometric approximation, heat sources, boundary conditions**

I. INTRODUCTION

Welding is the dominant method for joining materials by indissoluble connection in most industrial applications: automotive, shipbuilding, manufacture of pressure vessels, pipeline, etc.. The trend of automation and robotization of welding process is exponential and it takes a deep understanding of the physical basis of welding in order of continuous development. Welding processes are nonlinear and complex and require more knowledge of the various fields of science. Therefore modeling of the welding process is very complex and difficult.

The development of simulation models on a macroscopic scale represents thermomechanical problem involving temperature distributions, displacements, stresses and strains. At the microscopic level, there are problems of phase transformations and microstructure. Interaction of factors relevant to the development of simulation models in welding is shown in Fig. 1.

Influence of microstructure and mechanical strain on the process of heat transfer during welding is not great but the reverse impact of the heat exchange on the microstructure of the welded joint and the stress–strain conditions is very important. In sake of simplicity, model shown in Fig.1 does not include the effect of flow of molten metal on the process of heat transfer, microstructure and stress and strain states in the welding process.

Rate of transformation (development of microstructure and weld heat affected zone) depends on the thermal cycle of welding:

3. latent heat (phase transformations are heat sinks/sources)
4. phase transformation (material properties depend on the material microstructure)
5. rate of transformation (eg, microstructure development. martensitic and bainitic transformations depend on the deformation of welding parts)

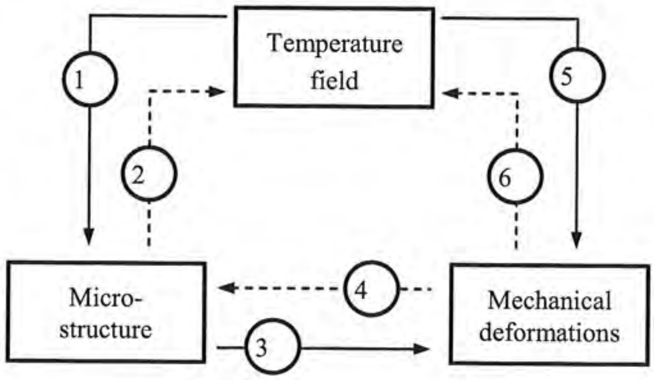

Fig. 30 Coupling between different fields in welding analysis [1]

6. thermal expansion (mechanical deformations depend on the temperature),
7. plastic deformation (mechanical deformations generate heat and affect the boundary conditions).

In the field of modeling of the welding process, there are three basic approaches:

- Analytical models were first developed by Rikaline (Rykalin)[3] and Rosenthal (Rosenthal)[2] in the late forties of the last century. These models include two – dimensional and three – dimensional heat conduction but does not provide sufficiently reliable results in the molten pool.
- Numerical models have been developed on the basis of partial differential equations of heat conduction. Finite difference and finite element method can be used in order to find solutions that involve a more complex geometry of welding parts, more complex initial conditions, the temperature dependent physical properties of material, the effect of latent and so on. Numerical methods became possible with the development of computers powerful enough to perform many mathematical operations in real time.
- Experimental models are an attempt to take on the results of a series of experiments to develop transfer functions that can be used to automate and control the welding process.

II. CREATION OF SIMULATION MODEL

A large number of welding processes is based on the rapid change of temperature in the welding area where the material is heated to a plastic state, or to the melting point.

Various physical and chemical processes take place during welding: melting of base and filler materials, metallurgical reactions, crystallization processes, etc. In order to predict and simulate these changes we need to establish a process simulation model with appropriate accuracy. The formation process of the model can be divided into three phases:

- geometric approximation
- model of heat source,
- initial and boundary conditions.

A. The geometric approximation

Heat transfer during welding depends among others on the shape and dimensions of the body. Welded elements can have a complex shape which makes computations of heat distribution difficult. Therefore, to calculate the temperature fields we use computational models of the heated body.

The basic models which are used in the calculations are:

- infinite solid body,
- semi–infinite solid body
- plate of medium thickness,
- thin plate,
- rod.

1) Model of infinite solid body: It represents a body whose dimensions are infinite in the direction of the axes x, y, z, so that none of its surface does not affect the propagation of heat in it, Fig. 2. The heat source is located at point O. In this case, the isotherms have the form of a sphere with the center at the point O.

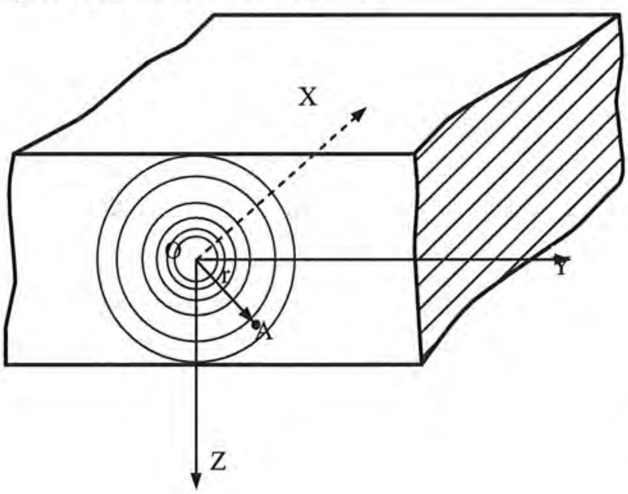

Fig. 2 Infinite solid body [4]

2) Semi infinite body model is a body with only one border area with coordinate Z = 0, which acts on the heat source, ie, limited thickness than the other two directions,. Other areas do not affect the propagation of heat. This scheme is commonly used when joining the surface of solid bodies. Isotherms have a shape half sphere centered at point A, Fig 3.

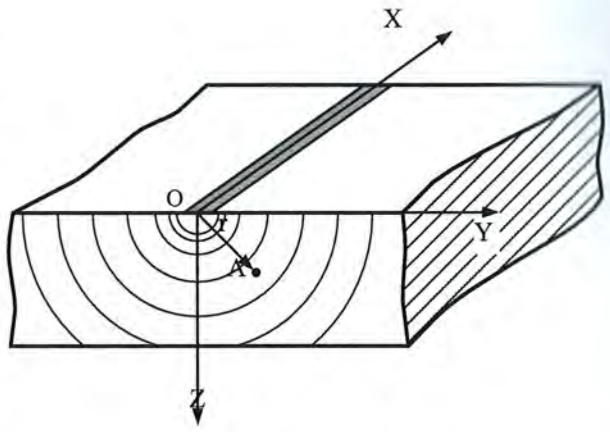

Fig. 3 Semi - infinite solid body [4]

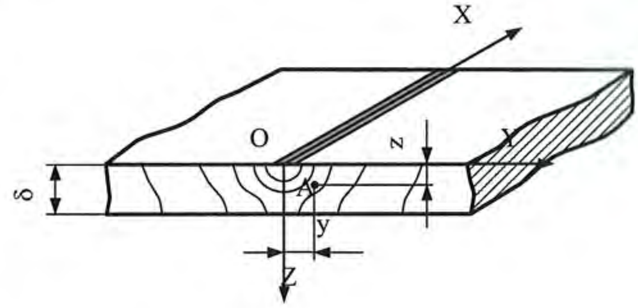

Fig. 3 Plate of medium thickness [4]

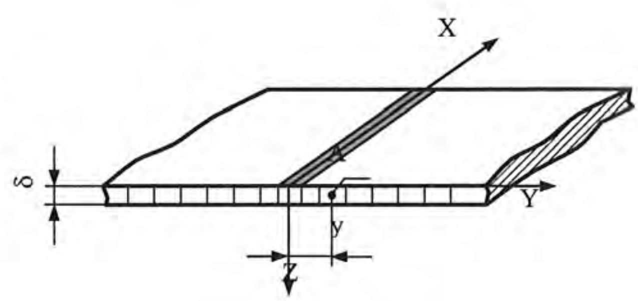

Fig. 4 Thin plate [4]

3) Model of a plate of medium thickness: represents a body which is limited with two parallel planes placed at z = 0 and z = δ. Plane Z = δ affects on the propagation of heat in the body. It is used for modeling of surfacing and for initial modeling of welding, Fig. 4.

Thin plate, Figure 5.10, has a small thickness δ. In

4) Model of thin plate: it can be considered that the temperature is equal by the sheet thickness. It is used in the modeling of butt welding of two thin plates.

5) Rod: represents a body of cylindrical shape. Temperature distribution in the cross sections of rod is equal. Rod is used for the modeling of electric resistance butt welding, Fig. 5.

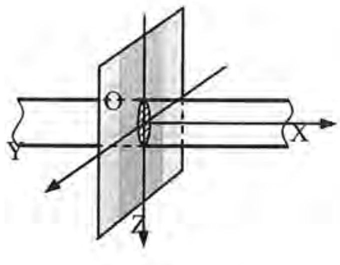

Fig. 5 Rod [4]

B. Model of heat source [1]

The interaction between the heat source (arc) and moltel pool is a complex physical phenomenon which has not been described accurately. Power arc is approximately equal to its electrical power:

$q_l = U \cdot I$

U – arc voltage, V
I – welding current, A

Effective power of arc is equal to:

$q = \eta_i \cdot U \cdot I$

η_i - coefficient of efficiency of welding arc, Table 1.

TABLE 1. COEFFICIENT η_I

Welding process	η_i
GTAW	0,50 - 0,60
GMAW/active gas	0,58 – 0,75
GMAW/inert gas	0,70 – 0,80
SMAW	0,70 – 0,85
FCAW	0,80 – 0,95

Considering the complexity of the physical phenomena in electric arc, numerous authors have developed a thermal model of electric arc in order to reduce the complexity of the model to an acceptable level and to thereby obtain sufficiently reliable simulation results.

The most commonly used model in the study of thermal processes in welding are:

- normal surface flux distribution,
- hemi–spherical power density distribution,
- ellipsoidal power density distribution,
- double ellipsoidal power density distribution

1) normal surface flux distribution: In the model proposed by Pavelic, specific heat flux is normally distributed.

$$q(r) = q(0) \cdot e^{-Cr^2}$$

q (r) – the specific surface heat flux at radius r, [W/m^2]
q (0) – maximum flux at the center of the heat source, [W/m^2]
C – the width of the distribution coefficient, [m^{-2}]
r – radial distance from the center of heat source, [m]

An alternative to this model was offered Friedman, a Krutz and Segerland. Their model has the form:

$$q(x,z) = \frac{3Q}{\pi c^2} e^{-3\frac{x^2}{c^2}} e^{-3\frac{z^2}{c^2}}$$

Q – energy input rate, [W]
c – characteristic radius of heat flux distribution, [m]

2) hemi–spherical power density distribution: Models with the normal surface distribution have had success in those situations where penetrating depth is small. For sources with high power density distribution, this model is not sufficiently accurate for neglecting penetrating component of the electric arc that transfers heat below the surface of the molten poll. In such cases, hemi–spherical source is better solution:

$$q(x,y,z) = \frac{6\sqrt{3}Q}{c^3 \pi \sqrt{\pi}} e^{-3\frac{x^2}{c^2}} e^{-3\frac{y^2}{c^2}} e^{-3\frac{z^2}{c^2}}$$

Q – energy input rate, [W]
c – characteristic radius of heat flux distribution, [m]

3) ellipsoidal power density distribution: This model is an ellipsoid with semi–axis a, b, c that are parallel to the axes of the coordinate system. The general form of the equation of this model is:

$$q(x,y,z) = \frac{6\sqrt{3}Q}{abc\pi \sqrt{\pi}} e^{-3\frac{x^2}{a^2}} e^{-3\frac{y^2}{b^2}} e^{-3\frac{z^2}{c^2}}$$

Q – energy input rate, [W]
a, b, c – semi–axis of the ellipsoid axes parallel to coordinate axes x, y, z

4) double ellipsoidal power density distribution: To overcome limitations of ellipsoidal heat source model, a new model that is a combination of two ellipsoidal model, The front half of the model is one quarter of the ellipsoidal source, while the rear half, the second quarter of the ellipsoidal sources. Inside the front half of the model, the distribution of power density takes place according to the equation:

$$q(x,y,z) = \frac{6\sqrt{3}f_f Q}{a_1 bc\pi \sqrt{\pi}} e^{-3\frac{x^2}{a_1^2}} e^{-3\frac{y^2}{b^2}} e^{-3\frac{z^2}{c^2}}$$

while within the second half of the model, the distribution of the power density has the form:

$$q(x,y,z) = \frac{6\sqrt{3}f_r Q}{a_2 bc\pi \sqrt{\pi}} e^{-3\frac{x^2}{a_2^2}} e^{-3\frac{y^2}{b^2}} e^{-3\frac{z^2}{c^2}}$$

Following condition must be satisfied:

$$f_f + f_r = 2$$

f_f – fraction of heat that deposited in the front of the model,

f_r – fraction of heat that deposited in the back of the model.

C. *Initial and boundary conditions*

Partial differential equation describes heat transfer inside the body. At the same time, it provides a connection between time and space coordinates within the body, ie. shows the temperature field at any point of time.

Partial differential equations in general have an infinite number of solutions. To obtain the solution which describes the problem additional conditions are necessary, which are of infinitely many solutions it selects which describe the given problem. These additional conditions are called initial and boundary conditions.

In the area in which we are looking for solutions to problems described by partial differential equation, value of the function must be known, in this case the temperature at some time $t = t_0$. These conditions which must be fulfilled by partial differential equations, are called initial conditions. Mathematically expressed, these conditions are as follows:

$$for\ \tau = 0, \qquad T = T(x,y,z)$$

The boundary conditions are usually classified into three groups, Fig 6:

- first order conditions, $T = T(x,y,z,\tau)$,
- second order conditions, $q_s = q_s(x,y,z,\tau)$,
- third order conditions, $q_s = \alpha(T_s - T_0)$ or $q_s = -\lambda \partial T/\partial n|_s$

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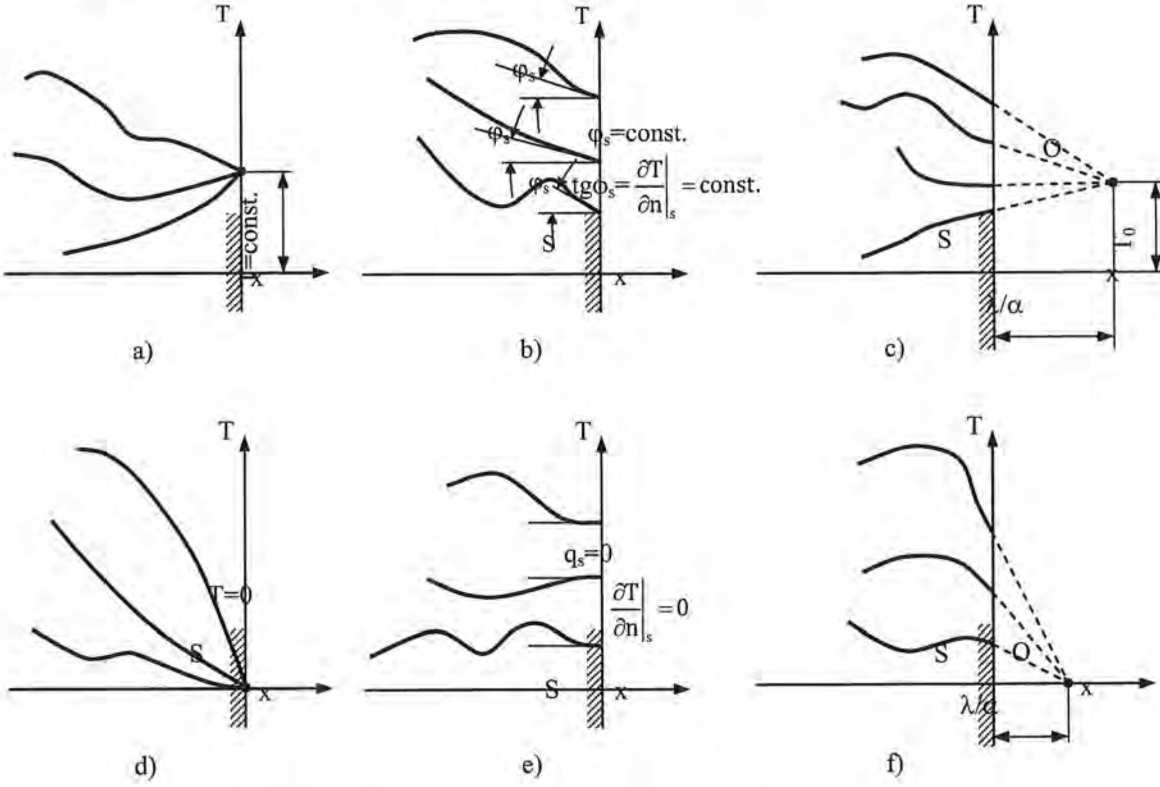

Fig. 6 Boundary conditions: a - b) first order, c – d) second order, e – f) third order [3]

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