STUDY OF THE INTERACTION BETWEEN THE WELDING ARC AND THE WELDING SEAM PROPERTIES AT UNDERWATER WELDING

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1. ABSTRACT

The present paper develops a mathematical model of heat interaction between the plasma arc and the welded metal. The data about structure and mechanic properties have been obtained experimentally and a thermoкinetic diagram of the decomposition of austenite at underwater welding has been drawn. On the basis of calculating the temperature, the thermo-cycles and the cooling rate, data about the structure and mechanical properties for any point in the thermal influence zone can be obtained.

2.INTRODUCTION

In the welding practice, the determining of temperatures in the welding pool zone, i.e. at distances commensurate with the dimensions of the heat source is of interest to specialists. In most cases, when determining the temperature, some initial distribution of temperatures in the cross section is assigned, which later on is redistributed in accordance with Fourier's law. Such a solution to the temperature problem can satisfy researchers in case they are not interested in temperature distribution in the welding pool, e.g. when the internal tensions at welding are being determined.

When the mechanical properties of the seam and the chemical reactions in the welding pool have to be determined this scheme is not applicable. In such cases the scheme of thermal energy exchange between the heat source and the metal should be used, which is the subject of this paper.

In paper [1, 2, 3] a mathematical arc model is presented which allows us to determine the temperatures in any point in space. Further on the task of heat transfer between the arc and the metal is solved.

3. MATHEMATICAL MODEL OF HEAT PROPAGATION

The non stationary temperature field in the region of the body is described with the help of the following differential equation:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+\left(\rho c\frac{\partial T}{\partial t}Q\right)=0 \quad (1)$$

at boundary conditions:

a) at the boundary the values of the unknown function T are assigned:

$$T=T_\beta \quad (2)$$

b) at the boundary the condition for convection heat transfer is fulfilled:

$$k_x\frac{\partial T}{\partial x}l_x+k_y\frac{\partial T}{\partial y}l_y+k_z\frac{\partial T}{\partial z}l_z=-\alpha\left(T-T_a\right) \quad (3)$$

c) at the boundary the condition for radiation heat transfer is fulfilled:

$$k_x\frac{\partial T}{\partial x}l_x+k_y\frac{\partial T}{\partial y}l_y+k_z\frac{\partial T}{\partial z}l_z=-\alpha_r\left(T-T_a\right)^4 \quad (4)$$

d) at the boundary a heat flow is assigned:

$$k_x\frac{\partial T}{\partial x}l_x+k_y\frac{\partial T}{\partial y}l_y+k_z\frac{\partial T}{\partial z}l_z+q=0 \quad (5)$$

Equation (1), together with the boundary conditions (2) – (5) and the initial conditions determine the task uniquely. To arrive at a final element solution of the problem, it is necessary to pass onto the variation formulation of the problem. As can be seen, equation (1) is equivalent to the requirement for minimization of the functional:

$$\chi=\int_V\left\{\frac{1}{2}\left[k_x\left(\frac{\partial T}{\partial x}\right)^2+k_y\left(\frac{\partial T}{\partial y}\right)^2+k_z\left(\frac{\partial T}{\partial z}\right)^2\right]-\left(Q-c\rho\frac{\partial T}{\partial t}\right)T\right\}dV+$$

$$+\int_S \left(qT + \frac{1}{2}\alpha_T T^2 \right) dS \quad (6)$$

If we introduce a presentation of the unknown function for the temperature T in the usual way:

$$T = [N_i, N_j, ..] \begin{Bmatrix} T_i \\ T_j \\ \cdot \\ \cdot \end{Bmatrix} = [N]\{T\}^e \quad (7)$$

where T_i, etc., are the basic parameters, then the functional can be minimized approximately. Following the standard order we will obtain the matrix differential equation:

$$[H]\{T\} + [C]\frac{\partial}{\partial t}\{T\} = \{\overline{F}\} \quad (8)$$

in which all matrixes are compound till the standard rules from the corresponding sub-matrixes for final elements, in accordance with standard rules:

- rigidity matrix with elements:

$$h_{ij}^e = \int_{V_e} \left\{ k_x \frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + k_y \frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y} + k_z \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z} \right\} dV + $$
$$+ \int_{S_e} \alpha_T N_i N_j dS \quad (9)$$

where the integral along the boundary corresponds to additional(attached) rigidity. The latter results from the boundary condition of heat loss from convection or radiation.

- damping matrix with elements:

$$c_{ij}^e = \int_{S_e} c\rho N_i N_j dV \quad \text{and} \quad (10)$$

$$F_i^e = \int_{V_e} Q N_i dV - \int_{S_e} q N_i dS + \int_{S_e} \alpha_T T_a N_i dS \quad (11)$$

To solve the system of differential equations obtained, we will use Galerkin's method, using linear temperature interpolation in the interval $(t, t+\Delta t)$. We obtain the following system of linear algebraic equations for the temperature at the units for the end of the interval multiplied by the time:

$$\left(\frac{2}{3}[H] + \frac{[C]}{\Delta t} \right) T = \left(\frac{[C]}{\Delta t} - \frac{1}{3}[H] \right) T_0 + \frac{2}{\Delta t^2}\int_0^{\Delta t} \{\overline{F}\} t dt \quad (12)$$

The above recurrent correlation can be applied with all subsequent intervals of time.

The temperature problem will be solved using isoparametric elements of the Serendip family , of the second order. With isoparametric elements it is not only the unknown functions that are interpolated but also the coordinates.

$$\begin{Bmatrix} \frac{\partial N_i}{\partial \xi} \\ \frac{\partial N_i}{\partial \eta} \\ \frac{\partial N_i}{\partial \zeta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} & \frac{\partial z}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} & \frac{\partial z}{\partial \eta} \\ \frac{\partial x}{\partial \zeta} & \frac{\partial y}{\partial \zeta} & \frac{\partial z}{\partial \zeta} \end{bmatrix} \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial z} \end{Bmatrix} = [J] \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial z} \end{Bmatrix} \quad (13)$$

To present the functions of those elements form it is most expedient to use the local coordinates ξ, η and ζ, which vary in the interval (-1,1). In the equations cited above there are derivatives of the form functions with respect to the global coordinates x, y and z. To calculate them we can use the interdependence between the derivatives (in a matrix form) with respect to the local and the global coordinates.

In the above equation [J] is the Jacobian of the coordinates transformation. The left side of this expression is easily calculated since the form N_i functions are assigned in local coordinates. If we reverse the correlation (13) we will get the global derivatives:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial z} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial z} \end{Bmatrix} \quad (14)$$

where $[J]^{-1}$ is the correlational Jacobian.

If [*J*] is expressed by the functions of form $[N']$, determining the transformation of the coordinates (for the isoparametric elements they coincide with the functions of form [*N*], we get:

$$[J] = \begin{bmatrix} \sum \frac{\partial N_i'}{\partial \xi} x_i & \sum \frac{\partial N_i'}{\partial \xi} y_i & \sum \frac{\partial N_i'}{\partial \xi} z_i \\ \sum \frac{\partial N_i'}{\partial \eta} x_i & \sum \frac{\partial N_i'}{\partial \eta} y_i & \sum \frac{\partial N_i'}{\partial \eta} z_i \\ \sum \frac{\partial N_i'}{\partial \zeta} x_i & \sum \frac{\partial N_i'}{\partial \zeta} y_i & \sum \frac{\partial N_i'}{\partial \zeta} z_i \end{bmatrix} =$$

$$=\begin{bmatrix} \frac{\partial N_1'}{\partial \xi} & \frac{\partial N_2'}{\partial \xi} & \dots \\ \frac{\partial N_1'}{\partial \eta} & \frac{\partial N_2'}{\partial \eta} & \dots \\ \frac{\partial N_1'}{\partial \zeta} & \frac{\partial N_2'}{\partial \zeta} & \dots \end{bmatrix} \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \end{bmatrix} \qquad (15)$$

To calculate the integrals in the above formulae, the change of variables is used. In this case the minimum volume is transformed in the following way:

$$dx\ dy\ dz = \det[J]\ d\xi\ d\eta\ d\zeta \qquad (16)$$

So, because of the use of normalized coordinates the integrals in the above formulae are presented in the following form:

$$\int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} [G(\xi,\eta,\zeta)]\ d\xi\ d\eta\ d\zeta \qquad (17)$$

in which case we have simple integration boundaries. Irrespective of the complexity of the integration boundaries, the expressions we have to integrate are much more complex which necessitates the application of numerical integration at forming the elements matrixes. We use Gaus's method with 3 integration points in each direction.

4.TWO- DIMENTIONAL PROBLEM

The plane problem is solved by using an eight-unit isoparametric element (fig.1)

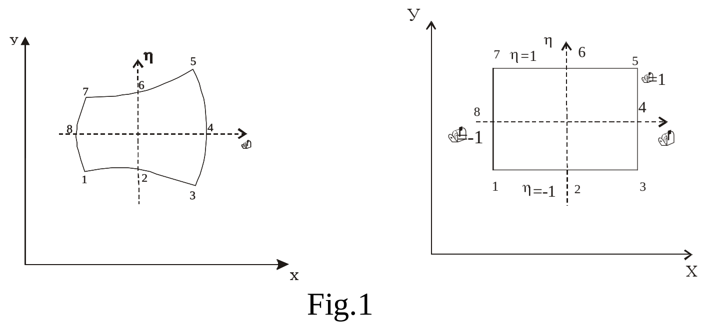


Fig.1

of the Serendip family (a second order element).

With isoparametric elements, the unknown functions are interpolated, as well as the coordinates. It is more convenient to express the functions through/by the units at the element boundary. The local coordinates ξ and η are used, in which the element boundary correspond to values ±1. The form functions are:

$$\begin{aligned} N_1 &= \frac{1}{4}(1-\xi)(1-\eta)(-\xi-\eta-1), \\ N_2 &= \frac{1}{2}(1-\xi^2)(1-\eta), \\ N_3 &= \frac{1}{4}(1+\xi)(1-\eta)(\xi-\eta-1), \\ N_4 &= \frac{1}{2}(1+\xi)(1-\eta^2), \\ N_5 &= \frac{1}{4}(1+\xi)(1+\eta)(\xi+\eta-1), \\ N_6 &= \frac{1}{2}(1-\xi^2)(1+\eta), \\ N_7 &= \frac{1}{4}(1-\xi)(1+\eta)(-\xi+\eta-1), \\ N_8 &= \frac{1}{2}(1-\xi)(1-\eta^2) \end{aligned} \qquad (18)$$

The problem of determining the temperature field in the weld seam is related to the problem of heat feed in the seam, as well as the dependence of coefficient values of heat conduction and particular calorific capacity on temperature values. This problem, which turns the problem of determining the temperature fields into a non linear one can be solved by determining these coefficient values at any moment as dependent on the temperature values at the end of the transit time interval for integrating the differential equations. The program provides for the introduction of values for all coefficients in a uniform network of temperature values, determined by the user, providing also an opportunity interruption points to be introduced, in which the coefficients on the left and on the right have different values.

The plane problem of determining the temperatures in the field of the seam and the surrounding material is solved with the assumption that the seam is welded instantly (with high speed).With the conventional scheme of heat feeding, on the basis of a certain quantity of heat introduced into the seam, its volume, the heat capacity and specific mass coefficient, the average temperature in the seam can be determined. The latter temperature values can be introduced as initial ones and the process of cooling of the seam can be studied. Since, however, our aim is to study the heat feeding at plasma welding we should take into consideration the radiation heating of the material. That's why in the initial stage the reading of this variant of heat feeding can provide approximate data. We assume that the material is available from the initial moment of time but has a temperature, equal to the ambient one and is later heated by the plasma source of heat by radiation. To present the consecutive passing of the arc over individual points of the seam and the different temperature in the arc points depending on the distance to the arc center, we make the assumption that for the period of time equal to the time of passing of the heat source, there is a radiation heat exchange between the seam metal and the plasma heat source. To work out this heat exchange numerically, a special boundary element is assigned. That element is also isoparametric along the boundary curve with units coinciding with the plane units of the element at the boundary. The input data describes with which elements the radiation heat exchange is possible and for that element at numeric integration in the three integration points in each moment of the passing of the heat source it can be found out whether the point is in the plasma source spot and the temperature of the corresponding source point can be calculated using the following formula:

$$T_r = T_1 + T_0\left(1-\frac{r}{\delta}\right)^p\left(1+\frac{pr}{\delta}\right) \qquad (19)$$

where the parameters T_1, T_0, p and δ are introduced by the user , r is the distance from the integration point studied to the source center. Depending on the distance of the point studied to the source center, the heat exchange is calculated with respect to boundary conditions (3) or (4).

Boundary condition (4) is remodelled into

$$k_x\frac{\partial T}{\partial x}l_x + k_y\frac{\partial T}{\partial y}l_y + k_z\frac{\partial T}{\partial z}l_z = -\alpha(T-T_a), \quad (20)$$

where: $\alpha = \alpha_r(T-T_a)^3$ (21)

α - coefficient, reading the radiation heat exchange, which is determined in such a way as to read the level of blackness of the material , as well as the presence of convection heat exchange.

5. THREE- DIMENTIONAL PROBLEM

The three-dimentional problem of heat conduction is solved by using a 20-unit isoparametric element of the Serendip family. (fig.2). This element is viewed in the normalised local coordinates ξ, η and ζ, in which element boundaries correspond to values ±1.

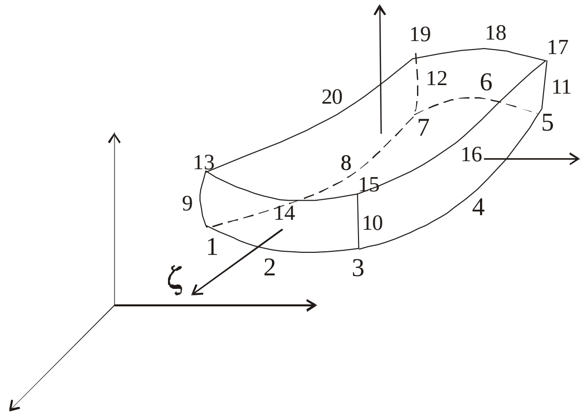


Fig.2

The form functions of the elements units are:

$$N_1 = \frac{1}{8}(1-\xi)(1-\eta)(1-\zeta)(-\xi-\eta-\zeta-2),$$
$$N_2 = \frac{1}{4}(1-\xi^2)(1-\eta)(1-\zeta),$$
$$N_3 = \frac{1}{8}(1+\xi)(1-\eta)(1-\zeta)(\xi-\eta-\zeta-2),$$
$$N_4 = \frac{1}{4}(1+\xi)(1-\eta^2)(1-\zeta),$$
$$N_5 = \frac{1}{8}(1+\xi)(1+\eta)(1-\zeta)(\xi+\eta-\zeta-2),$$
$$N_6 = \frac{1}{4}(1-\xi^2)(1+\eta)(1-\zeta),$$
$$N_7 = \frac{1}{8}(1-\xi)(1+\eta)(1-\zeta)(-\xi+\eta-\zeta-2),$$
$$N_8 = \frac{1}{4}(1-\xi)(1-\eta^2)(1-\zeta),$$
$$N_9 = \frac{1}{4}(1-\xi)(1-\eta)(1-\zeta^2),$$
$$N_{10} = \frac{1}{4}(1+\xi)(1-\eta)(1-\zeta^2),$$
$$N_{11} = \frac{1}{4}(1+\xi)(1+\eta)(1-\zeta^2), \qquad (22)$$
$$N_{12} = \frac{1}{4}(1-\xi)(1+\eta)(1-\zeta^2),$$
$$N_{13} = \frac{1}{8}(1-\xi)(1-\eta)(1+\zeta)(-\xi-\eta+\zeta-2),$$
$$N_{14} = \frac{1}{4}(1-\xi^2)(1-\eta)(1+\zeta),$$

$$N_{15}=\frac{1}{8}(1+\xi)(1-\eta)(1+\zeta)(\xi-\eta+\zeta-2),$$
$$N_{16}=\frac{1}{4}(1+\xi)(1-\eta^2)(1+\zeta),$$
$$N_{17}=\frac{1}{8}(1+\xi)(1+\eta)(1+\zeta)(\xi+\eta+\zeta-2),$$
$$N_{18}=\frac{1}{4}(1-\xi^2)(1+\eta)(1+\zeta), \qquad (22)$$
$$N_{19}=\frac{1}{8}(1-\xi)(1+\eta)(1+\zeta)(-\xi+\eta+\zeta-2),$$
$$N_{20}=\frac{1}{4}(1-\xi)(1-\eta^2)(1+\zeta).$$

In that case the consecutive formation of the seam by deposition of the material in the seam zone is studied. At the initial moment, the elements forming the seam are empty. In the process of seam welding the elements which are in the arc zone are formed step by step. As the seam formation is done in several steps with regard to height, temporary boundary elements are introduced, which read the interaction of the plasma heat source with the material of the seam elements, which subsequently, following the deposition of the next layers of material, will become internal. The interaction is found using formulae (21) and (22), a special boundary two-dimensional isoparametric element/gradient being developed to provide opportunities for realization of different conditions at arc boundary.

6.ANALYSIS

On the basis of the obtained model for heat distribution at welding we can obtain the temperature field in the weld pool and the piece at different moments (fig3, a) and b)) from the beginning of the welding process.

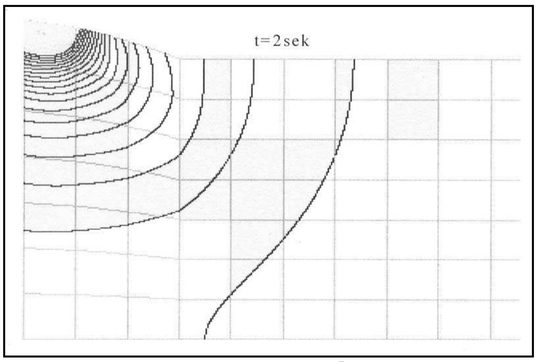


Fig.3, a) t = 2 sek

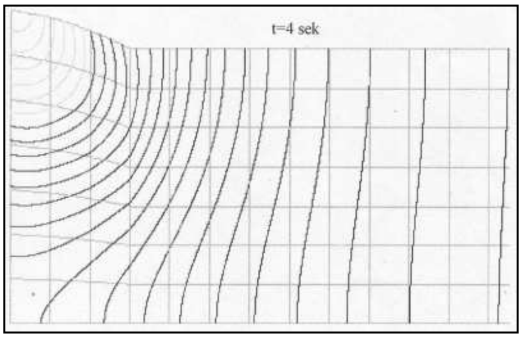
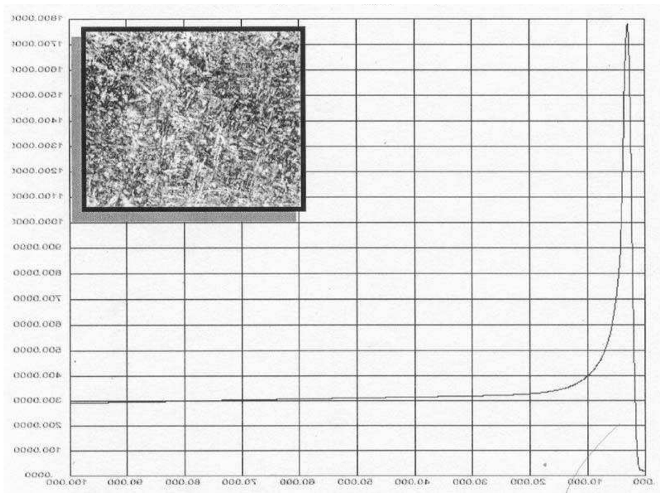


Fig.3, b) t = 4 sek

The model allows to obtain the thermal cycles at each point of the welded metal as well as the cooling velocities in the temperature range that is of interest to us (fig.4).

Point 46, Vcooling(850÷500)°C = 134 °C/s



Point 101, Vcooling(550÷300)°C = 3.3 °C/s

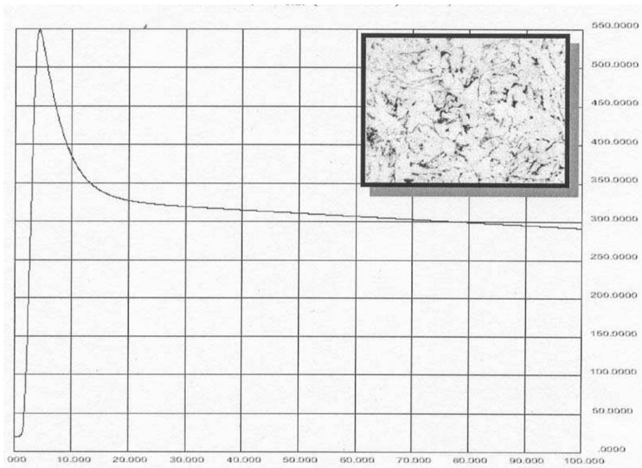


Fig.4

The determining of the structure and mechanical properties in the zone of thermal influence at underwater welding has been done on a specially developed at the University of Rostock installation [4].

On the basis of the investigations carried out – thermal, dilatometric and metalographhjc – on samples of steel 3, a thermokinetic diagram of the decomposition of austenite at underwater welding has been drawn fig.5.

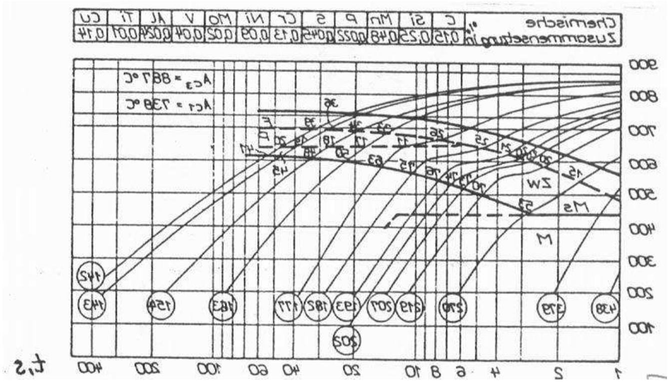


Fig.5

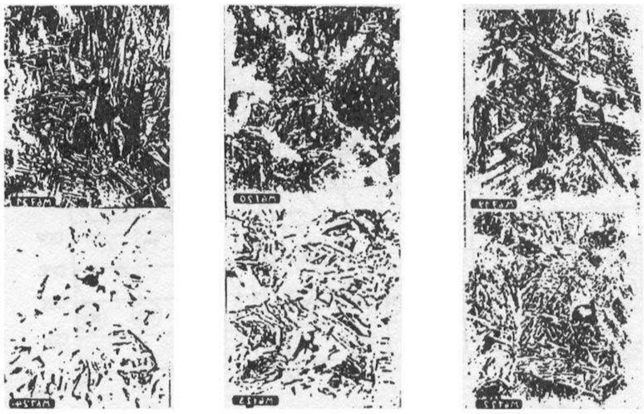


Fig.6

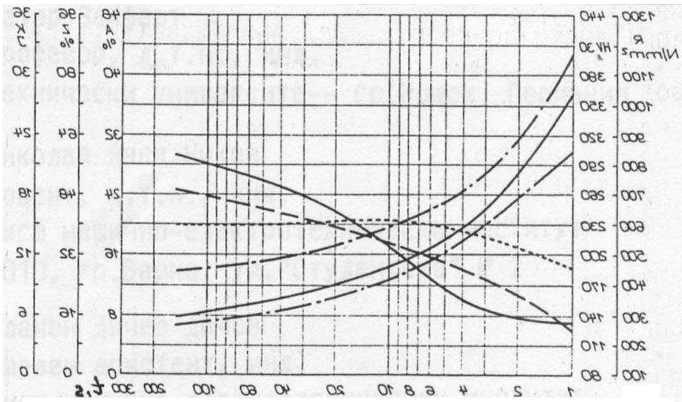


Fig.7

Fig.6 shows the structural changes at different cooling velocities, and fig. 7 – the corresponding mechanical characteristics at different cooling velocities.

The developed model for calculating the temperature allows us to determine the structure and mechanical properties of the metal (fig.4) using fig. 5, 6 and 7 from the experimental data.

Comparative research at underwater welding done at NPL-TWP the TU of Varna show similar results to those obtained by computation.

4.COMCLUSIONS:

- A model for heat transfer from the arc to the weld metal has been developed.
- Experimentally, data on the thermal, dilatometric, metalographic and mechanical properties have been obtained and the thermokinetic curve of the decomposition of austenite and the interdependence between the mechanical properties and the velocity of cooling has been drawn.
- The methods developed allow data on the thermal, structural and mechanical properties of each point in the zone of thermal influence to be obtained.

5.REFERENCES:

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