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# COMPUTER SIMULATION THERMAL ANALYSIS OF LOW CARBON PLATES WELDED WITH ELECTRODE ABRADUR64

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*In this work, a computer simulation model has been used for heat transfer process study in steel plates that were Manual Metal Arc Welded. The heat transfer process evolution was simulate using SolidWorks Thermal Analysis. The base material used for study was steel DD11, on which a hard deposit using ABRADUR 64 welding electrodes has been performed. The temperature distribution in the different areas of Heat Affected Zone has been determined, according the welding regime parameters. The simulation model of heat transfer during welding has demonstrate that at the surface level, the steel plates do not reach a high values of temperature which can promote some microstructural changes in the heat affected zone.*

**Keywords**: thermal analysis, low carbon plates, welding, microstructural analysis, electrodes.

## 1. Introduction

Hard facing welding is applied both for restoration of worn parts, design and production of new articles and for the production of bimetallic materials in which their surface layer should have special properties: wear resistance, corrosion resistance, heat resistance, hardness, abrasion resistance, etc. Through the welding method, new products can be repaired or manufactured such as: presses, flanges, rolled shafts, shafts, valves, hammers, knives, guillotine blades and various types of cutting tools [1, 3, 5].

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Hardfacing may be used to restore machine parts, whose surface has worn down thus shortening their service life, or it may be applied to new parts during production to increase their wear resistance. Extending the life of machine parts will reduce the cost and improve productivity.

As a result of high thermal stresses induced by contraction of the material during cooling, the cracks in the build-up layer propagate through the chromium carbide crystallographic plane and reach the base metal.

Heat Affected Zone (HAZ) is prone to cracking during welding of low-alloy and high-carbon steels, so all parts should be welded at room temperature. It is necessary that temperatures be selected in consideration of the chemical composition of both the base and build-up metals.

The aim of the present study is to build an adequate computer model and simulation thermal analysis of samples subjected to MMA hardfacing welding [2].

The results obtained allow a subsequent evaluation of the deformations and stresses in the parent metal and the zone of hardfacing welded metal[10], thus predicting the quality of the bond between the hardfacing welded metal [12] and the parent metal, cracking, inadmissible deformations and residual stresses [6].

For computer modelling, the heat transfer in the studied DD11 steel samples hardfacingwelded with welding electrodes the SolidWorks software was used in its Simulation-Thermal Analysis section [7, 8]. It allows a mathematical description and a physical explanation of the studied processes occurring during the process of hardfacing welding [2, 9, 13].

## 2. Structural changes in the specimens after MMA hardfacing welding

For the study were used steel plates type DD11, DIN (15кп ГОСТ 1050 - 88)having dimensionsof 200x15x15mm, according to the provisions of BDS EN ISO 10111 [15]. For hardfacing welding we choose heavy coated basic electrode ABRADUR64[14] with electrode diameter $d_e$=3.25mm, for restoration of structural and cast steel parts.

The chemical composition of the steel and of the hardfacing welded metal are shown in Table 1, their mechanical properties are shown in Table 2, and their thermal properties in Table 3a and 3b [4, 11, 14,15].

Pure hardfacing welded metal, with sufficient for practice precision, is obtained after application of the third layer and has a hardness of ~ 64HRC.For MMA hardfacing welding, an ESAB welding machine is used, type Arc251i, with a current varying from 140÷180 A, and a welding speed of $V_w$=1.5 m/min.

*Table 1*

**Chemical composition, %**

| Material | C | Si | Mn | Ni | S | P | Cr | Cu | Nb |
|---|---|---|---|---|---|---|---|---|---|
| DD11 | 0.12 - 0.19 | up to 0.07 | 0.25 - 0.5 | up to 0.25 | up to 0.04 | up to 0.035 | up to 0.25 | up to 0.25 | - |
| Abradur64 | 6.0 | - | - | - | - | - | 26.0 | - | 7.5 |

*Table 2*

**Mechanical and physical properties of materials**

| Material | Tensile strength, Rm N/mm² | Yield strength, Re N/mm² | Elongation at yield, A % | Elongation at break, Z % | Brinell Hardness HB | Poisson's ratio, μ - | Shear modulus, G N/mm² |
|---|---|---|---|---|---|---|---|
| DD11 | 392 | 230 | 8 | 30 | 143 | 0.28 | 790 |
| Abradur64 | 520-720 | 220 | - | 45 | 210 | 0.28 | 790 |

*Table 3a*

**Thermal properties of materials- Base metal**

| Temperature, t °C | Elastic modulus, $E.10^{11}$ N/m² | Coefficient of thermal expansion, $\alpha.10^{-6}$ $K^{-1}$ | Thermal conductivity, k W/(m.K) | Mass density, ρ kg/m³ | Specific heat capacity, Cp J/(kg.K) |
|---|---|---|---|---|---|
| 20 | 2.01 | - | - | 7850 | - |
| 100 | 1.92 | 12.4 | 53 | 7827 | 465 |
| 200 | 1.85 | 13.2 | 53 | 7794 | 486 |
| 300 | 1.72 | 13.9 | 49 | 7759 | 515 |
| 400 | 1.56 | 14.4 | 46 | 7724 | 532 |
| 500 | - | 14.8 | 43 | 7687 | 565 |
| 600 | - | 15.1 | 39 | 7648 | 586 |
| 700 | - | 15.3 | 36 | 7611 | 620 |
| 800 | - | 14.1 | 32 | 7599 | 691 |
| 900 | - | 13.2 | 30 | 7584 | 708 |
| 1000 | - | 13.3 | - | - | - |

*Table 3b*

**Thermal properties of materials- Weld metal**

| Temperature, t °C | Elastic modulus, $E.10^{11}$ N/m² | Coefficient of thermal expansion, $\alpha.10^{-6}$ $K^{-1}$ | Thermal conductivity, k W/(m.K) | Mass density, ρ kg/m³ | Specific heat capacity, Cp J/(kg.K) |
|---|---|---|---|---|---|
| 20 | 2.00 | - | 15 | 7900 | 440 |
| 100 | 1.94 | 16 | 17 | - | - |
| 200 | 1.86 | 16.5 | 18 | - | - |
| 300 | 1.79 | 17 | 19 | - | - |
| 400 | 1.72 | 17.5 | 20.5 | - | - |
| 500 | 1.65 | 18 | 22 | - | - |

For investigation of the specimen structure, sample has been cut to an appropriate size and cast in a mounting medium.The section was prepared for metallographic analysis by grinding with waterproof abrasive paper with different progressive granulations № 240, 400, 500, 600.The polishing was performed on a machine type “Metasinex”. After polishing with the last sandpaper, the specimen was washed with water and dried. The fine polishing was performed on a polishing machine with diamond paste and combustion alcohol. The polished surface was washed with pure alcohol and dried well.

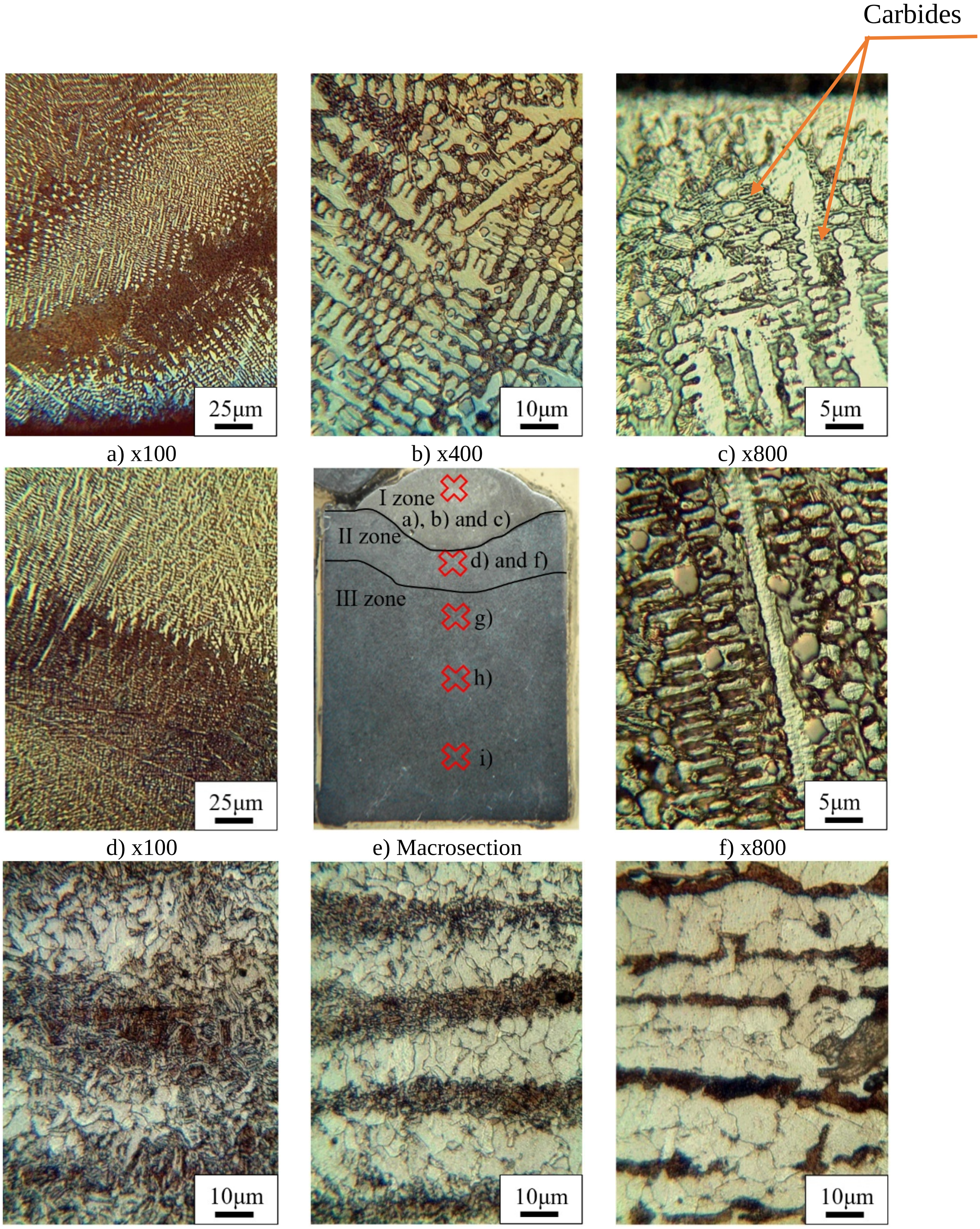



Fig. 1.Macrosection and microsection of a DD11 steel specimen hardfacing welded with ABRADUR64, consisting of three segments: I zone –Weld Metal (with magnification x100-a), x400-b) and x800-c)); II zone – Heat Affected Zone (HAZ) (with magnification x100-d) and x800-f)); III zone – Base Metal (with magnification x400-g), h) and i) in three zones)

For revealing the microstructure details etching solution of 4% alcohol solution of nitric acid was used. The microstructure and imaging examination were performed on a “Neophot-2” metallographic microscope.

Fig. 1 shows the macrosection and microsection of a hardfacing welded D11 steel specimen with a welding electrode ABRADUR64 [11, 14] at different magnification in different zones of the specimen.

A significant amount of carbide phase separation is observed along the boundary between the dendrites. In the HAZ, there is a fragmented ferrite-perlite structure, which is also characteristic of the base metal.

### 3. Experimental details

Thermoelectric converters are mainly used for accurate temperature measurements and for determining the thermal cycle. To measure the temperatures, three thermocouples, chromium-alumel type by ANSI (NiCr-NiAl), operating in temperatures up to 1100°C, are attached to the test specimens.

To measure the temperature over time, small openings are drilled on the specimen with a diameter and depth of channels of 1mm. In these channels, thermocouples, insulated with chamotte and $Al_2O_3$, are placed only at the points of contact between the thermocouple and the plate so that the result of the experiment should not be affected by the ambient temperature. For better visualization, the location of the thermocouples is shown in the schematic diagram of Fig. 2.

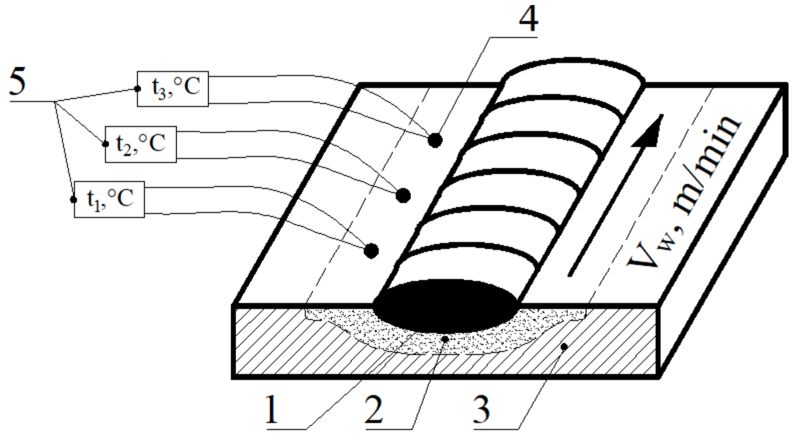



Fig. 2. Schematic diagram of the location of the thermocouples in the specimen: 1- Weld metal;2- Heat Affected Zone; 3- Base metal; 4-Thermocouple with thermal protection; 5-Thermometer

The three thermocouples are connected at their other ends with a thermometer of the type THERMOMETER CEM DT-610B, which registers the changes in the temperature during heating and cooling. The value of one grade is 0.1°C over the entire measurement range, and reading is possible up to 1300°C.

The device is calibrated by help of drawing time-temperature curves of pure lead.

The results of the experiment are presented in Table 4, and Fig. 3 shows the time-temperature (τ-t) curves of the temperature distribution in hardfacing welding upon the three thermocouples placed in the HAZ.

*Table*4

**Temperature distribution over time when the specimen is hardfacing welded**

| τ, °C | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $t_1$, °C | 23 | 480 | 720 | 890 | 734 | 615 | 500 | 410 | 400 | 380 | 372 | 370 | 365 | 322 | 300 | 280 |
| $t_2$, °C | 23 | 146 | 300 | 500 | 680 | 820 | 880 | 600 | 506 | 470 | 450 | 445 | 400 | 350 | 330 | 300 |
| $t_3$, °C | 23 | 50 | 80 | 132 | 202 | 299 | 580 | 800 | 838 | 750 | 700 | 650 | 576 | 480 | 400 | 330 |

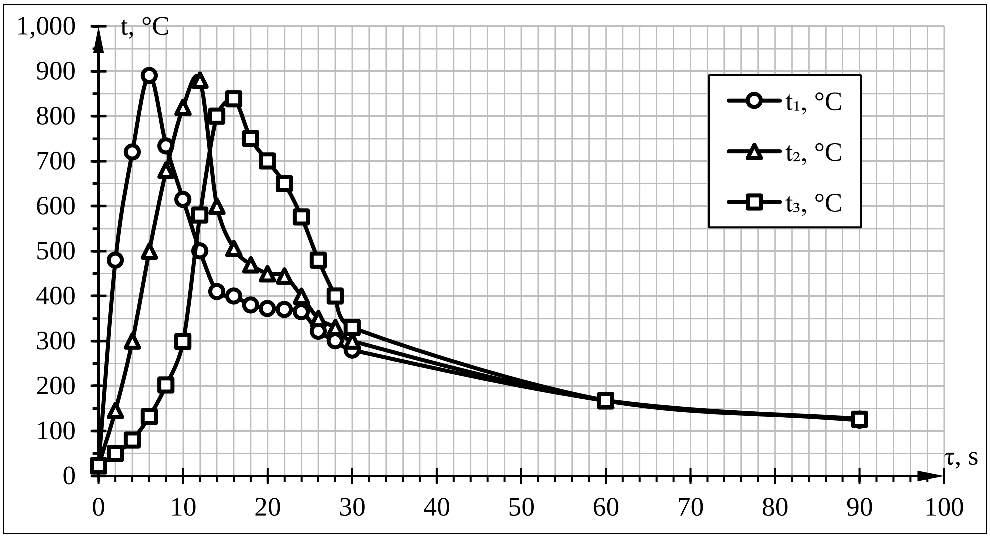



Fig.3. Time-temperature curves of temperature distribution registered by the three thermocouples located at the HAZ

## 4. Discussions

### 4.1. Theoretical approaches

It has been found that the temperature field in the investigated surfaces is non-stationary in its nature because of the highly concentrated, high temperature heat source, moving at high speed and leading to an instant increase in temperature. Therefore, the general equation of thermal conductivity (1) is most appropriate.

$$\frac{\partial T}{\partial \tau} = \alpha.\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q_v}{C_p.\rho} \quad (1)$$

where:
$T$– temperature, K
$\tau$ – time, s;
$\alpha$–thermal diffusivity, m²/s;
$q_v$–internal heat intensity in unit volume, W/m³;
$C_p$–specific heat capacity, J/(kg.K);
$\rho$–density, kg/m³.
The analysis consists of as follow [3]:

- ✓ Drawing a 3D model of hardfacing welded steel samples DD11 using SolidWorks software - Figure 4
- ✓ Setting the mesh of the patterned models for the purpose of applying the finite element method to determine the distribution of the temperature field in the different zones after the hardfacing welding process;
- ✓ Determining of input data for the heat process study: defining a material by creating one in the material library;
- ✓ Setting the boundary conditions;
- ✓ The mode parameters to be tested will serve as initial data for the analysis.
- ✓ Output - graphical results, animations, results of the introduced temperature sensors, etc.
- ✓ Analysis of the results.

### 4.2. Experimental results

In the present work SolidWorks (DassaultSystems) is used in order to perform a finite element analysis. The welding zone is modelled as separated body. The material properties of the base material and welding zone are different (Table 2, 3a, 3b). The welding surface is split in zones with equal area (commands Split Line and Linear pattern). The area is same as electrode's diameter. For each zone a Thermal study is carried out and each subsequent analysis uses the results of the previous as initial conditions. The materials used, the mesh of finite elements and the conditions for the individual zones are the same for each analysis.

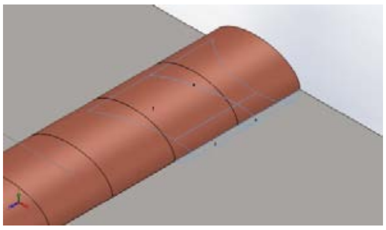


Fig.4. Model of samples

Next is the definition of a parent and hardfacing welded material from the program library. For the analysis needs, a mesh of finite elements is introduced by “create mesh” command – Fig. 5.

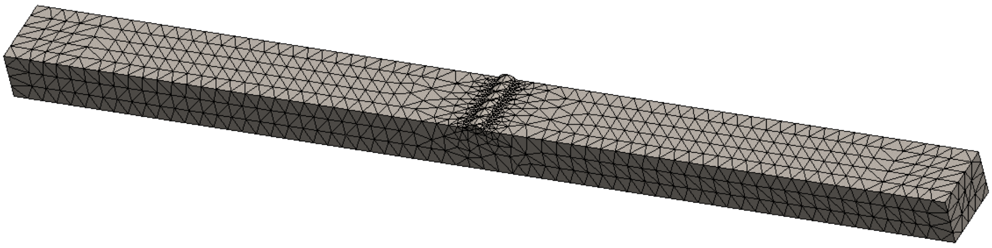


Fig.5. Mesh of object

To simulate the temperature distribution in the model of a moving high temperature heat source along the length of the formed joint, we use the Simulation-Thermal Analysis module of the program.

The initial boundary conditions of the process of MMA welding with an ABRADUR 64 electrode are introduced into it:

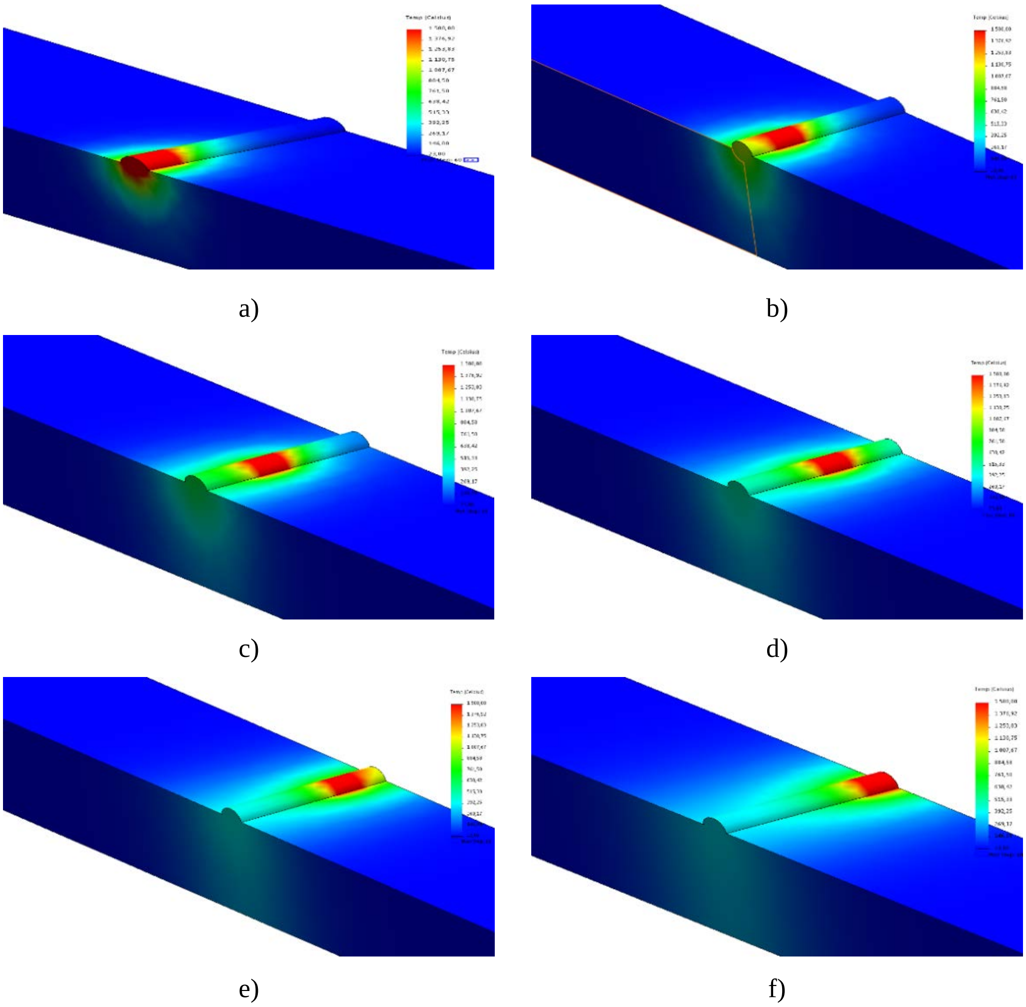
- ✓ Initial temperature of the modelled sample of 23°C;
- ✓ temperature in the welding area – 1500°C;
- ✓ Temperature in the joint area – 2000°C;
- ✓ from these workpiece surfaces we define convective heat exchange with a coefficient of $h_c$=15 W/(m².K) at room temperature 23°C;
- ✓ MMA hardfacing welding speed - $V_w$=1.5(m/min);
- ✓ After the thermal analysis was made, 6 results (analyses) were obtained for the high-temperature impact zones, each with a period of 3 seconds. Fig. 6 and two for cooling Fig. 7, in 30 and 90 seconds.

Experimental data on the speed of the burner indicate that at the given dimensions (length of the formed joint) the welding time for all the 6 results under study is 18s.

The materials used, the mesh of finite elements and the initial conditions for the individual zones are the same for each analysis.

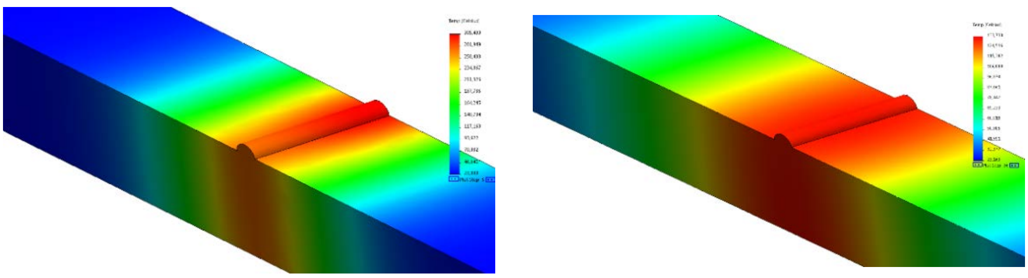
Each subsequent analysis uses the results of the previous as initial conditions.

Additional temperature distribution results in different sections of the simulated object are carried out by adding three temperature sensors, from the hardfacing welding zone, the thermal impact zone and the parent metal zone, Fig. 8.



a) b) c) d) e) f)

Fig.6. Simulation analysis of heating in the MMA hardfacing welding process:
a)3s; b)6s; c)9s; d)12s; e)15s; f)18s;



a) b)

Fig.7. Simulation analysis of cooling in the process of MMA hardfacing welding:
a)30s and b)90s

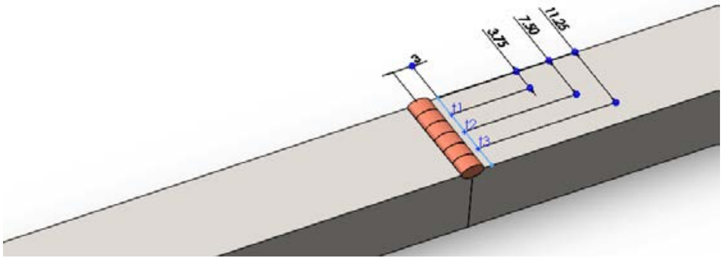


Fig.8. Location of the temperature sensors in the model

The results of the temperature distribution with the additional three temperature sensors are presented as a table (Table 5) and as a graph Fig. 9.

*Table 5*

**Results of the analysis**

| **τ, s** | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 30 | 60 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| **$t_1$, °C** | 23 | 547 | 901 | 719 | 513 | 420 | 375 | 275 | 173 | 131 |
| **$t_2$, °C** | 23 | 151 | 405 | 813 | 866 | 606 | 482 | 285 | 174 | 131 |
| **$t_3$, °C** | 23 | 43 | 120 | 279 | 558 | 824 | 720 | 290 | 172 | 131 |

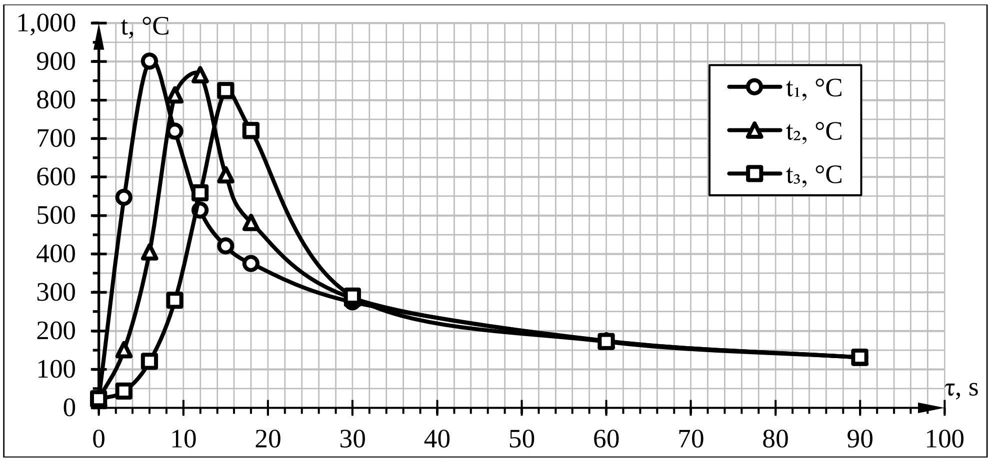



Fig.9. Time-temperature curves obtained from the three sensors: $t_1$- Temperature in hardfacing welded metal zone;$t_2$ - Temperature in heat affected zone;$t_3$ - Temperature in base metal zone

On the graph of the ordinate axis are shown the temperatures in °C and on the axis of abscissa - the temperature evolution over time in s.

The curves given in Fig.9 show the distribution of the temperature field at each moment of the hardfacing welding process along the formed joint and subsequent cooling of the sample. It can reasonably be argued that the chosen simulation model adequately reflects the temperature distribution of the three sensors in MMA hardfacing welded samples.

## 6. Conclusions

It is evident from the metallographic analysis that some pores of random nature exist in the specimen. There are no defects of another kind. There are no cracks, non-metallic inclusions, undercuts or others at the boundary of alloying, or in the heat affected zone (HAZ) or in the hardfacing welded metal. There is a strong dendrite structure in the zone of the hardfacing welded metal. The alloyed electrode metal strengthens the hardfacing welded surface.

Summing up the results of the set parameters with the help of the developed computer simulation model of the heat transfer processes in plane MMA hardfacing samples welded, we can detect with sufficient accuracy the distribution of the temperature in real objects.

On the basis of the created computer model, it was found that in MMA hardfacing welding of the samples, the area of thermal impact does not reach the critical temperature, which is a prerequisite to believe that there will be no structural changes in it leading to destruction. This is evidenced by the metallographic analysis. The experimental results confirm results obtained with the computer model. The temperature fieldresearch allows to predict defects in the hardfacing welding zone andin the heat affected zone, as well as the occurrence of residualstresses.

The proposed computer model could be used in further experiments. A possible change in the structure of the processed samples could bepredicted. The model could be useful in the process of education, too. Basedon the obtained temperature distribution, students could be trained torecognize the appearance of different structures in the samples.

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