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Investigating Heat Transfer of Manual Metal Arc Hard facing of Low Carbon Plates

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Abstract*: *This study presents the results of a computer simulation study of thermal processes in low-carbon Manual Metal Arc (MMA) hardfacing plates with E DUR600. The problems related to the thermal processes occurring during the heating of sheets of steel DD11, manual metal arc hardfacing with electrodes E DUR600, by examining the influence of temperatures, the heating time and the geometry of the test plates. By computer simulation using SolidWorks software, which have Finite Element Analysis (FEA) engineering systems resulting in simulations of temperature distribution over time and the direction of heat fluxes in the thermal influence zone after the MMA hardfacing process.The method aims to increase the exploitation qualities of the treated surfaces, which in turn leads to the need for experimental study of the heat processes occurring in the process of heating, retention and cooling.Based on the comparison of the theoretical and experimental study in MMA hardfacing of plates, it can be concluded that simulation studies through the mathematical model adequately represent the processes of distribution of the thermal field in depth of the real object.

Keywords*: *heat transfer; Manual Metal Arc (MMA); hardfacing; carbon plates; Finite Element Analysis (FEA).

I. INTRODUCTION

Un This work investigates the thermal processes occurring in Manual Metal Arc (MMA) hardfacing of samples of steel, grade DD11 BDS EN 10111: 2008 (15kp GOST 1050- 88) [1], with electrodes E DUR600. A computer simulation model is made using SolidWorks and COMSOL Multiphysics software to analyze the impact of heat flux propagation within the volume of the samples during their heating and cooling in the process of MMA hardfacing [2, 3]. These software products have systems for engineering analyses through the finite element method [4, 5, 6].

In creating the simulation analysis, as input data were used the results of the change in temperature over time obtained from the experimental tests carried out with a contactless IR device for manual electric arc hardfacing of samples of grade DD11 steel. In order to better evaluate the impact of temperature on the change of structure and properties in the different heat affected zones of the samples, micro-structural analysis was performed, which is a prerequisite for determining the adequacy of the created computer models and simulations. These computer simulation models can serve to predict the structural changes occurring from the impact of high-temperature heat sources [2, 4, 5].

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II. EXPERIMENTAL TEST

2.1. Object of experiment.

In order to carry out the experiment, samples of DD11 steel were prepared with dimensions: 64x15x15mm. According to literature data, steel is used for eccentric shafts, levers, axles, bushings, spindles, etc., and thin-sheet steel is intended for punching. It is well welded and cut. Table- I and Table- II shows, respectively, the chemical composition and mechanical and physical properties of steel DD11 (BDS EN 10111: 2008) [1].

Table- I: Chemical composition (in wt%) of the base metal

Material	C	Si	Mn	Ni	S	P	Cr	Cu	Nb	Fe
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	-	Bal

Table- II: Mechanical and physical properties of materials

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
392	230	8	30	143	0.28	790

For hardfacing we choose a hardfacing electrode E DUR600, BDS EN ISO 14700, with a diameter of 3.2 mm and a length of 350 mm. The weld metal has good wear resistance and impact resistance. Table- III shows the chemical composition of the weld metal [7].

Table- III: Chemical composition (in wt%) of weld metal

C	Si	Mn	Cr	Fe	Crequ.	Niequ.	Average hardness, HRC
0.5	2.3	0.4	9.0	Bal.	9.0	15.0	56-58

When hardfacing this steel, it is necessary to provide maximum heat sink, minimum linear energy, rigid fixing (it is susceptible to temperature deformation) and hammer peening of the weld seams (thus reducing the tensile stresses and temperature deformations). In many cases, it is necessary to weld some intermediate layers as well.

In order to test and prove the effectiveness of computer simulation analyzes, an experiment was conducted under the following conditions:

- MMA hardfacing in the open air;
- ambient temperature- t_{amb}=20°;
- modes of the source: current I = 130 (A); voltage U = 50 (V);
- coefficient of convective heat exchange of air α = 15 W/(m^2.K);
- feeding speed V = 1.5 (m/min);
- efficiency factor EF η_u = 0.8 (%).

The test samples were subjected to MMA hardfacing in 6 different zones at the same retention time in the contact spot for about 3 seconds. This method of treatment with hardfacing electrodes of different mechanical properties leads to phase transformations in both the molten and adjacent zones, Figure 1.

Fig. 1.Welding Machine Arc 251i, ESAB and hardfacing electrode E DUR600

2.2. Testing the structure and quality of the samples.

In manual arc hardfacing, it is likely that cold cracks occur in the heat affected zone. Therefore, the purpose is to trace more precisely the structure change in depth of the sample. To perform the test, polished sections of the sample are prepared and hardfacing with a hardfacing electrode E DUR600.

The polished section is smoothed on a grinding wheel and then polished with waterproof sandpapers №240, 400, 500, 600. When changing from one sandpaper to another, the treated section is thoroughly washed with water to avoid scratching by the remaining abrasive grains from the previous sandpaper number. The polishing is carried out on a Metasinex machine. After the last sandpaper has been used, the polished section is washed with water and dried [8, 9].

The polishing is carried out on a polishing machine with diamond paste and denatured alcohol. The polished section is washed with pure alcohol and dried well. Corrosion is carried out with 4% alcohol solution of nitric acid. The micro-structure and imaging testing is performed on a NEOFOT-2 metallographic microscope, with eyeglass and lens kits, as well as accessories enabling for micro-structures to be observed in polarized light or oblique light. The microscope is further equipped with a Caplio R530 digital camera. The total magnification of the metallographic structure is determined by use of a micrometer, photographed and treated by analogy to the corresponding structure. Magnifications of 100, 400 and 800 times are used (x100, x400, x800 respectively). Photos of the polished cross sections are processed by the software Image ready in Photoshop CS3 [9].

Figure 2 shows a macro-section of a sample from DD11 steel welded with a hardfacing electrode E DUR 600.

Fig. 2.Metallographic Microscope NEOFOT-2 and macro-section of a sample from DDD11 steel welded with E DUR 600; WM-Weld Metal; HAZ-Heat Affected Zone; BM-Base Metal

Figure 3 shows the microstructures of the different zones shown in Figure 2 of the sample welded with electrode E DUR 600.

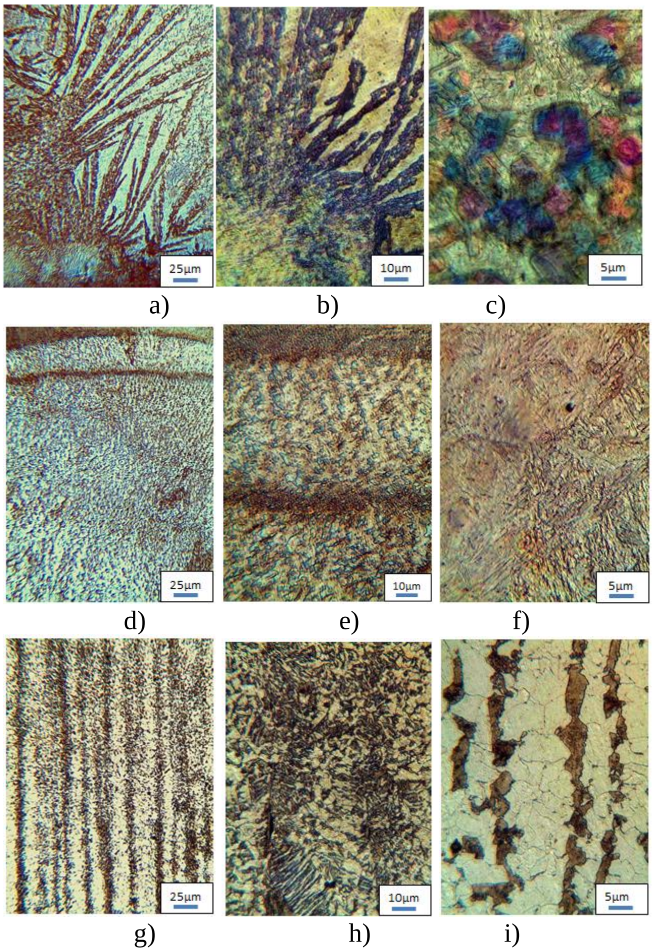


Fig. 3.Micro-section of weld metal with E DUR 600:a) weld layer, zone 1 x100; b) weld layer, zone 1 x400; c) weld layer, zone 1 x800; d) heat affected zone, zone 2 x100; e) heat affected zone, zone 2 x 400; f) heat affected zone, zone 2 x800; g) DDD11 base metal, zone 3 x100; h) DDD11 base metal, zone 3 x400; i) DDD11 base metal, zone 3 x800

The metallographic analysis of the sample shows that three zones are visualized: the weld metal zone; the heat affected zone and the base metal zone.

In the different zones, the micro-structural analysis shows that non-homogeneous needle martensite and residual austenite are observed in the uppermost layers of the weld metal. At the boundary of alloying, the structure undergoes transition into residual austenite and troostitis. In the base metal, an entirely ferrite-perlite structure is observed, which is characteristic of this steel.

2.3. Equipment and tool kits for measuring the temperature in the heat affected zone:

One of the methods for testing metals and alloys is through thermal analysis. This method is based on the fact that phase transformations are accompanied by changes in the temperature. The purpose here is to determine the temperature during manual arc hardfacing and to experimentally determine the thermal cycle of a given point on the workpiece [10, 11].

The conditions of heat introduction into the samples are not the same for the different hardfacing methods, which results in a different efficiency in the use of the heat sources.

That is why the thermal distribution in the workpiece depends on the thermo-physical characteristics of the metal, the geometric dimensions of the workpiece, the power of the source and the conditions of heat introduction. Taking into account all these factors is of great importance for the choice of a scheme for calculating the temperature field in the test sample.

The thermal analysis is routine. It is easy, fast and can be conducted with lab-accessible equipment. The temperature is measured using a K – probe thermocouple from a contactless IR temperature measuring device Raytek MX6 (Figure 4). The recording device provides recording and monitoring of the change in temperature as a function of time [12, 13].

Fig. 4.Contactless IR temperature measuring device Raytek MX6 with a K – probe thermocouple

The contactless IR temperature measuring device Raytek MX6 with a K–probe thermocouple is used as a tool for diagnostics, inspection, maintenance and control of quality. Generally, it consists of a thermocouple and a measuring device and can measure temperatures up to 900°C with an accuracy of ± 0.75°C. Therefore, during the experiment, the temperature measured with this device is the one in the heat affected zone, i.e. in the immediate vicinity (~3mm from the center of the seam) to the weld zone. Repeatability of readings is made for greater accuracy, with readings ranging from ≤ ± 1°C.

The measurement is carried out in a room with an operating temperature of 23°C. To determine the surface temperature of the sample, the K– probe thermocouple is placed close to the weld zone (~3mm) and is secured with insulation wadding and chamotte. After the measurement, a digital photo of the zone is stored with the date, time and temperature included in the image. The device is connects to a computer with special software and records in real time, taking into account the temperature changes and drawing a temperature chart. The maximum temperature reading is 325.1°C, because the thermocouple is positioned in the heat affected zone, despite the weld zone temperature being around 2000°C. Upon completion of the hardfacing process, a gradual decrease in temperature is observed until room temperature is reached.

The results of the measurements with the contactless device are shown graphically in Figure 5, the temperature being measured using the K–probe thermocouple on the device.

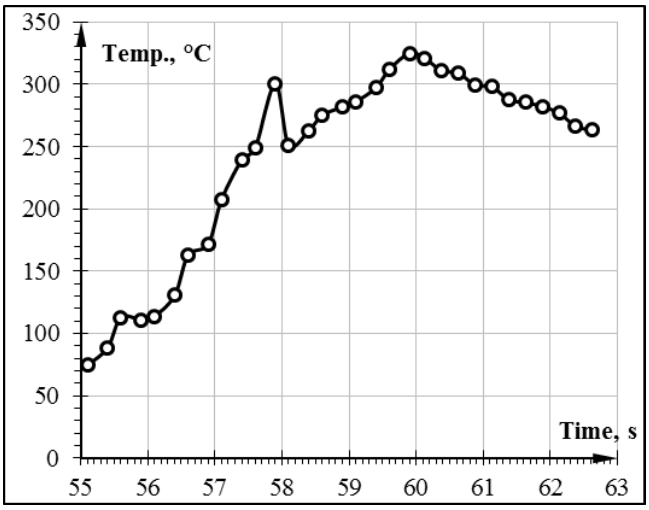


Fig. 5.Results of the measurements with K–probe thermocouple from a contactless IR temperature measuring device Raytek MX6

III. COMPUTER SIMULATION ANALYSIS

In parallel with the experimental tests, a computer simulation analysis was carried out of the manual arc hardfacing of the samples by using the capabilities of the above described software products. Non-stationary thermal analysis was used to study the parameters of the temperature field.

3.1. 3D models and initial modes.

To determine the heat transfer caused by the temperature impact, a 3D model was created in SolidWorks (Figure 6). The object of investigation here are the heat processes flowing in a sample of steel grade DD11, welded with an electrode E DUR 600. For the successful computer modelling and simulation of the distribution and change of temperature and heat fluxes in the 3D model, the input parameters used are the type of the base material and of the layers of weld metal, their thermophysical properties as well as the hardfacing mode parameters, [14,15].

For the needs of the computer simulation analysis, a preliminary thermal analysis of the subject was carried out. The analysis starts from the beginning of the object heating (welding) to its complete cooling. The results obtained for the temperature serve as initial data for the static stress analysis.

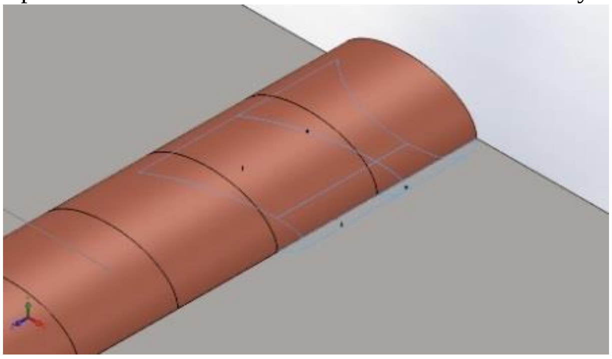


Fig. 6.Model of samples

For the needs of the computer simulation analysis, a preliminary thermal analysis of the subject was carried out. The analysis starts from the beginning of the object heating (welding) to its complete cooling. The results obtained for the temperature serve as initial data for the static stress analysis.

To simulate heat transfer analyses in the model of a moving high temperature heat source along the joint being formed, we used the Simulation module [16].

In that module are input the initial boundary conditions of the MMA hardfacing welding process:

- initial temp of the modelled specimen: 20°C;
- temperature in the welding area: 1500°C;
- temperature in the joint area: 2000°C;
- from the specified surfaces of the workpiece, we defined convective heat exchange with a coefficient of h_c=15 W/(m².K) at room temperature 20°C.

The experimental data on the electrode's speed indicate that at the assigned dimensions (length of the formed joint), the MMA hardfacing welding time for the 6 results is 18s in total. To simulate the hardfacing welding process, the area under is study of the resulting welding joint is divided along zones equal in length with 3s time of process running in each zone. In this case, 6 analyses of the hardfacing welding process were performed. No initial temperature is defined for each subsequent analysis because the results of the previous one are used as initial conditions. The contacts between the two types of material (base and hardfacing welded) are determined - they are to be tightly bonded to each other using the contact function of the Bonded type. The subject is not fixed - only internal connections are defined.

3.2. Governing equation for heat transfer analysis

In the heat transfer analysis, the transient temperature field T of manual arc hardfacing is a function of time τ and the spatial coordinates (x, y, z) and is determined by the non-linear thermal conductivity equation for anisotropic media [17, 18].

$$\rho(t).c(t)\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\cdot\left(\lambda_{xx}\cdot\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\cdot\left(\lambda_{yy}\cdot\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\cdot\left(\lambda_{zz}\cdot\frac{\partial T}{\partial z}\right)+q_V \quad (1)$$

where: q_v is the volumetric heat source term which varies with beam power and welding speed.

λ, c, and ρ are the thermal conductivity, specific heat, density of the sheet material, and velocity of the workpiece, respectively.

Figure 6 shows the schematic representation of the region considered for mathematical formulation.

The differential thermal conductivity equation has an infinite number of solutions. To find the only solution characterizing the particular process, it is necessary to set boundary conditions.

Boundary conditions include initial (temporal) and boundary (spatial) conditions[14, 17].

Initial boundary condition necessary for the non-stationary process characterizing the temperature distribution at the initial moment of time:

$$T(x, y, z, 0) = f(x, y, z) \quad (2)$$

Often accepted:

$$T(\tau=0) = T_0 \quad (3)$$

The boundary conditions are characterized by the shape of the body and the conditions for their heat exchange with the environment. Distinguish four types of boundary conditions:

- Under boundary conditions of the first kind on the surface of the body, the temperature distribution is set at any moment of time:

$$T_{ms}=f(x_{ms}, y_{ms}, z_{ms}, \tau) \quad (4)$$

T_{ms}- Metal surface temperature, °C

In particular, the surface temperature can be kept constant over time, such a limit is called isothermal:

$$T_{ms}=const \quad (5)$$

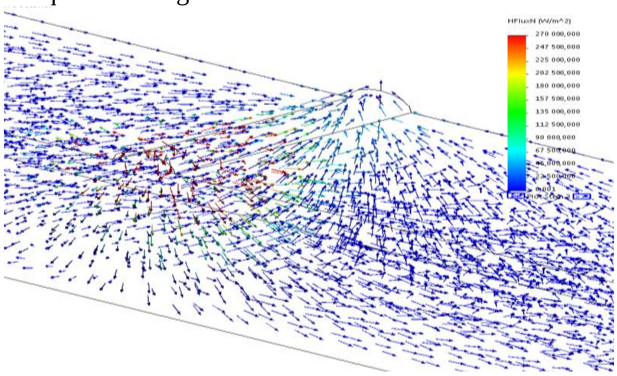
- Under boundary conditions of the 3rd kind on the surface of the body, at any moment of time the temperature of the environment and the law of convective heat exchange between the surface of the body and the environment are set:

$$q_{ms}=\alpha(T_{ms}-T_a) \quad (6)$$

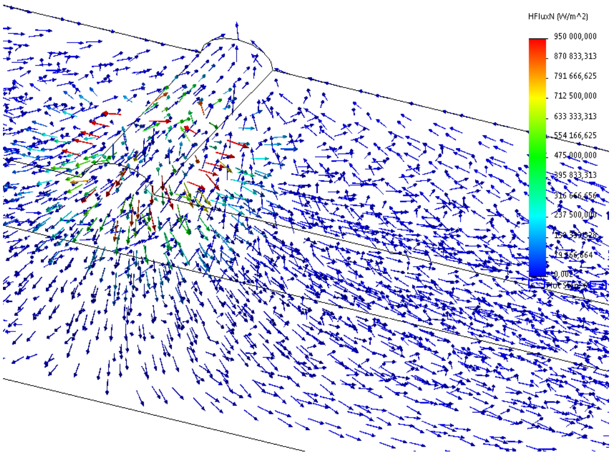
T_a- Ambient temperature, °C

3.3. Results and analysis.

Based on the simulation modelling, the following results are obtained, which are presented in Fig. 7 during heating and in Fig. 8 during cooling. They enable conclusions both about the propagation direction and the magnitude of the heat flux along the surface and in depth of the sample during the hardfacing and the subsequent cooling. The results of the heat flux distribution are given at retention of 3 seconds for the different heating zones in the modelled sample and for the subsequent cooling.



a)



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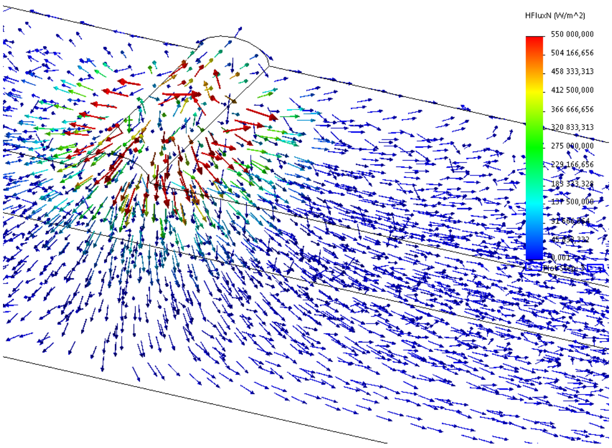

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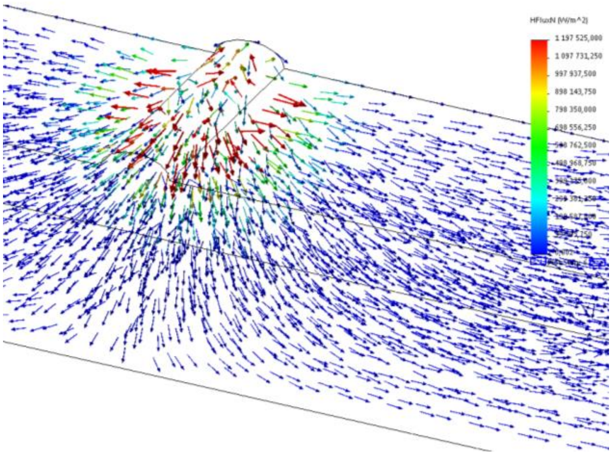

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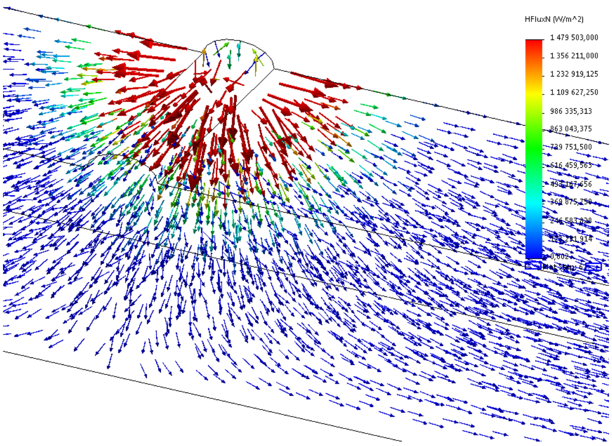
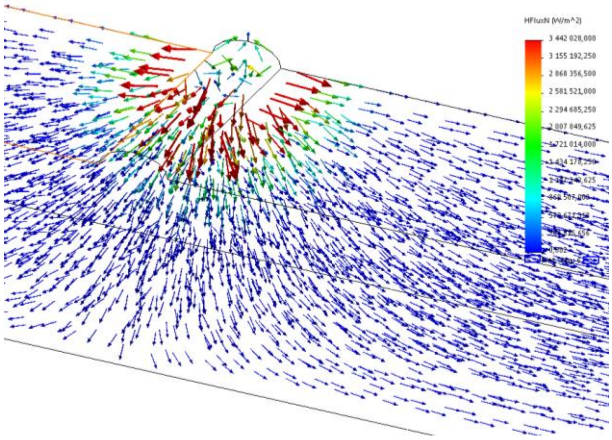
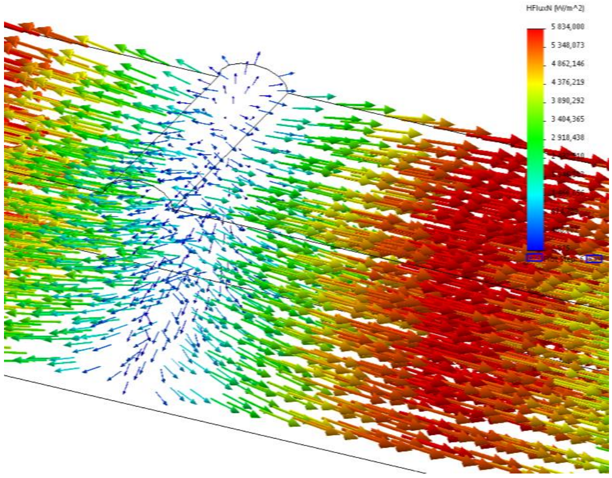


e)

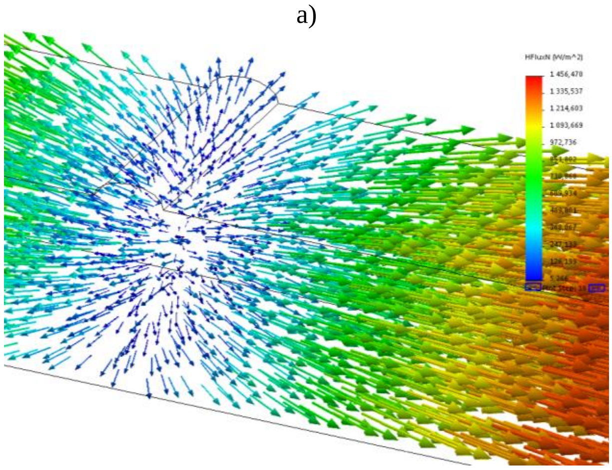


f)

Fig. 7. Heat flux during heating of the samples with MMA hardfacing: a) in 3 s; b) in 6 s; c) in 9 s; d) in 12 s; e) in 15 s; f) in 18 s



a)



b)

Fig. 8.Heat flux during cooling of samples after MMA hardfacing: a) in 30 s; b) in 90 s

For better visualization, in Table- IV are shown the results for the magnitude of the heat flux in the sample every 3s when heated and subsequently cooled to room temperature.

Table- IV: Results for the magnitude of the heat flux in the sample

Time, τ [s]	3	6	9	12	15	18	30	90
q_{max}, [W/m^2]	26,000	95,000	541,000	1,198,000	1,479,500	3,442,028	5,833.3	1456.5
q_{min}, [W/m^2]	2.270	2.343	2.703	3.500	4.597	7.658	2.875	5.266

IV. INFERENCES AND CONCLUSION

1. From the micro-structures in Figure 3 it is evident that there are no cracks, non-metallic inclusions, undercuts and other defects at the boundary of alloying or in the weld metal.

2. The presented results of the computer simulation model, as well as those measured with the contactless temperature measuring device, show that the increase in the heating time results in a decrease in the rate of heat flux distribution. The reason for that is rooted in the high energy of the arc and the speed of the electrode movement, which do not allow rapid distribution of the temperature field near the welding zone.

3. The computer simulation analysis clarifies the influence of heat fluxes on the structure change in the samples. This is most clearly seen in Figure 3 a), where the direction of the dendrites in the weld metal is directed upwards, as shown in the computer simulation for the direction of movement of the heat flux (Figure 7 and Figure 8), whereas the change in magnitude of the grains directly corresponds to the change in the heat inside the samples.

4. Based on the comparison of the results from the computer simulation and those obtained from the conducted experiment with the samples with the help of the K – probe thermocouple on the contactless device, it can be concluded that the simulation studies using the computer-mathematical model adequately reproduce the real distribution processes of the temperature, the thermal field in the depth of the object under study in the process of manual arc hardfacing and subsequent cooling.

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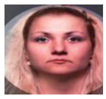

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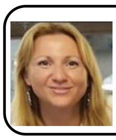

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