INVESTIGATION OF STRAINED AND DEFORMED STATE OF LOW CARBON PLATES AFTER WELDING

Aneliya STOYANOVA[1], Tatyana MECHKAROVA [2] Mariya KONSULOVA-BAKALOVA [3] Krastin YORDANOV [4] Yaroslav ARGIROV[5]

The work is shown manual metal arc welding of steel with covered electrode. The study of the heat exchange processes and occurrence of the deformations and tensions during welding of steel plates is presented. For this purpose, a simulation analysis of the object was developed. Results for strain and deformation distributions at each point in the volume of the studied model were obtained by thermal and static analysis. Determination of stresses and deformations after welding under the conditions of non-stationary heat exchange and elastic-plastic displacement of the metal led to the necessity to use approximate methods by applying modern programming means.

Keywords: strained and deformed state, low carbon plates, welding, microstructural analysis, microhardness.

1. Introduction

Recovery of machine parts is a component of the general technological process for the repair of machines and mechanisms.

Its purpose is to recover completely or partially their resource through a complex of technological impacts on the defective parts and, on that basis, to extend their total service life [1, 2, 5].

The task to be solved in the present study is to give an answer to the question: with these recovery technologies, what residual stresses are obtained on the work surface of the treated parts, in view of the risk of cracks or breakage [3, 7, 9].

[1] Assistant, Department of Technology of Machine Tools and Manufacturing, Technical University of Varna, Bulgaria, e-mail: tatuna10@abv.bg
[2] Assistant, Department of Materials Science and Technology, Technical University of Varna, Bulgaria, e-mail:tatqna13@abv.bg
[3] Prof. assistant, Department of Technology of Machine Tools and Manufacturing, Technical University of Varna, Bulgaria, e-mail: mbakalova@tu-varna.bg
[4] Prof. assistant, Department of Thermal Engineering, Technical University of Varna, Bulgaria, e-mail: krastin_yordanov@tu-varna.bg
[5] Associate Professor, Department of Materials Science and Technology, Technical University of Varna, Bulgaria, e-mail: jaroslav.1955@abv.bg

Based on the fact that there is no data on this problem in the literature, the study explores the complex influence of manual metal arc hardfacing welding, as a method of recovering damaged parts, on the residual stresses of the hardfacing welded layer of metal [6, 8, 10]

The residual internal stresses resulting from the recovery of the parts affect the total stresses, taking into account the stresses of the operating loads during the operation of the machines and mechanisms. The magnitude of these stresses determines the long-term and safe operation of the recovered parts [1, 3, 12].

The residual stresses can be eliminated or significantly reduced in different ways. In this respect, it is necessary to pay attention to the choice of material, electrode, protective environment and to observe the correctness of the hardfacing welding process.

To solve the task, by modelling the processes of stressed and deformed state in hardfacing welding of steel laboratory specimens using SolidWorks, by performing thermal and static analysis [13].

2. Stresses and deformations occurring after Manual Metal Arc (MMA) hardfacing welding

Hardfacing welding of low alloy steels like DD11 with high Cr content electrodes causes the occurrence of its own stresses in the part being recovered, i.e. such stresses that existed in the machine part prior to the application of external forces. Regarding to the time of their occurrence, these own stresses are divided into temporary and residual. Unlike temporary residual stresses remain in the machine part after its cooling [3, 5].

It has been found that with reaching certain temperatures / critical points / during welding, a significant cause of stresses and deformations is the volume change associated with structural changes in the sample.

The causes of residual stresses in hardfacing welding are: the temperature cycle at which, the parameters are determined by the speed of the welding, nonuniform structural transformations in the metal and alteration of the solubility of the gases surrounding the hardfacing welded layer in the process of cooling and aging of metal [5, 13].

The following important factors influence the processes of distribution and distribution of heat in the machine part during hardfacing welding:

- Dimensions and shape of the hardfacing welded machine part;
- Thermo-physical properties of the metal;
- The amount of heat input;
- Duration of heating.

During the hardfacing welding, the heating in the hardfacing welded layer is strong enough and the stresses always exceed the yield limit, which results in plastic deformations and hence residual stresses as well.

According to the literature [7, 8], when cooling the hardfacing welded metal, at the moment of austenite decomposition, intensive release of the absorbed hydrogen starts. Since the rate of diffusion of hydrogen through the ferrite structure is negligible, hydrogen accumulates in internal cavities of the metal and creates residual stresses.

Obviously, the difficulty in solving such tasks is not with their formalization, but with the identification and dynamics of temperature field distribution [1, 3]. This requires numerical calculation methods that are integrated in simulation and analysis software.

3. Studying the structure and quality of a metal hardfacing welded with ABRADUR54 electrodes

The subject of study are specimens of steel DD11 (BDS EN ISO 10111) sized 200x10x10mm – Fig.1. According to literature data [14], etc., this steel belongs to the group of low-alloy steels, which have low strength and high ductility. They are used for non-loaded workpieces, and the thin sheet steel is designed for stamping. The steels are used without heat treatment. They are shaped into bars, tubes, tapes, sheets and wires. They are well welded and cut. They are used for manufacturing workpieces through the technology of recarburising that work in wear-out conditions without high load, such as eccentric shafts, levers, axles, bushings, spindles and others.

Table 1 shows the respective chemical composition of steel [14].

Fig. 1. DD11 steel hardfacing welded with ABRADUR54 electrode

Table 1

Chemical composition- base metal, (wt %)

	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.

Has been selected an ABRADUR54 electrode designed specifically for hardfacing welding of machine parts and workpieces.

Table 2 shows the typical composition of a hardfacing welded metal [4, 11, 14] and Table 3 shows the mechanical properties of the base metal and of the hardfacing weld metal, respectively.

Table 2

Chemical composition- welded metal, (wt %)

C	Si	Cr	Nb	Mo	W	V	$Cr_{equ.}$	$Ni_{equ.}$	Average hardness, HRC	Fe
0.5	1.7	9.5	-	-	-	-	12.05	15	54	Bal.

Table 3

Mechanical and physical properties of materials

	Tensile strength, Rm N/mm²	Yield strength, Re N/mm²	Elastic modulus, $E.10^{11}$ N/m²	Mass density, ρ kg/m³	Poisson's ratio, μ -	Shear modulus, G N/mm²
DD11	392	230	2.1	7850	0,28	790
ABRADUR54	520-720	220	2	7900	0,28	790

In hardfacing welding, DC+ current is used, and before the electrodes are used, they are dried (calcined) for one hour at the temperature of 350°C.

The welding regime parameters values and equipment used are as follows:

- ✓ Electrode diameter, d_e = 3.25mm;
- ✓ Current, I = 130A;
- ✓ Current type, DC+;
- ✓ Speed of hardfacing welding, V_w = 5.0 m/h;
- ✓ Welding machine ESAB, type Arc251i;

Product preparation procedure and hardfacing technology by welding are presented below.

The welding area is carefully cleaned and the layer of hardfacing welded metal is mechanically removed. The sharp edges should be rounded and, for more specific shapes, a suitable bed for the hardfacing welded metal should be made.

The technology of manual electric arc hardfacing welding is similar to the one of welding. Minimum arc length is used in a mode that ensures a small penetration. Each subsequent seam should overlap 1/3 to 1/2 of the previous.

In order to conduct microstructural analysis of the test specimens and to determine the microhardness in the individual zones of hardfacing welding, standard procedures are used as described in [1]. The analysis of the microstructure was conducted with a NEOFOT 2 metallographic microscope, and to measure the hardness in the cross section of the specimen, an optical microscope equipped with Vickers microhardness head was used.

Fig. 2 shows a macrographic cross section of a specimen made of DD11 steel hardfacing welded with ABRADUR54 electrode. Fig. 3 shows microsections of the individual zones of the hardfacing welded specimen, according to the designations shown in Fig. 2.

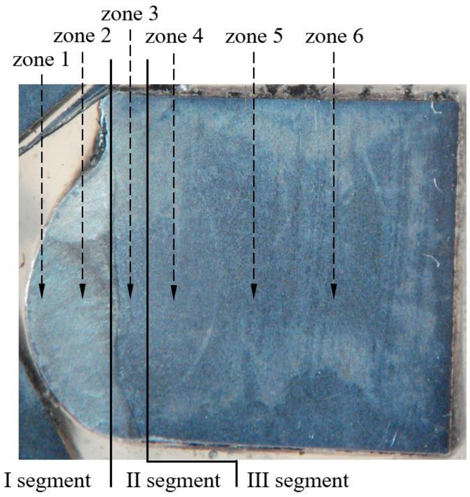
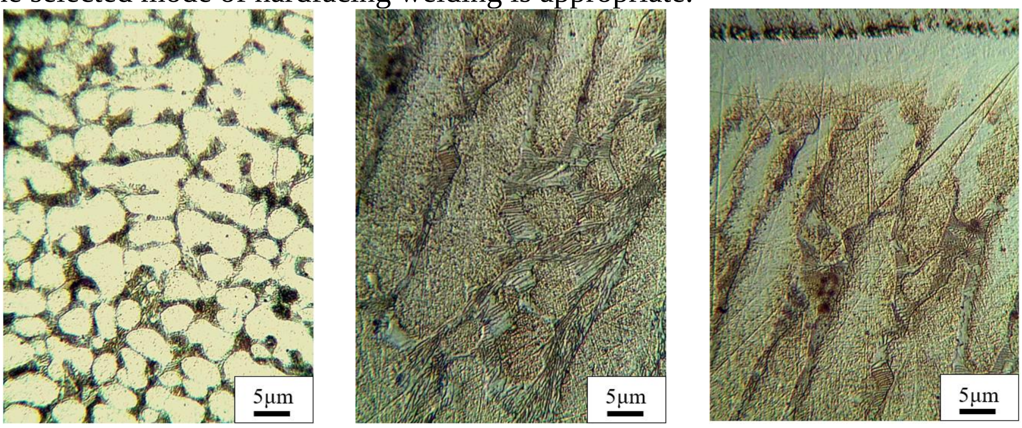


Fig. 2. Macrographic cross section of a DD11 steel specimen, hardfacing welded with ABRADUR54, consisting of three segments: I-Weld Metal; II-Heat Affected Zone (HAZ); III-Base Metal and six zones

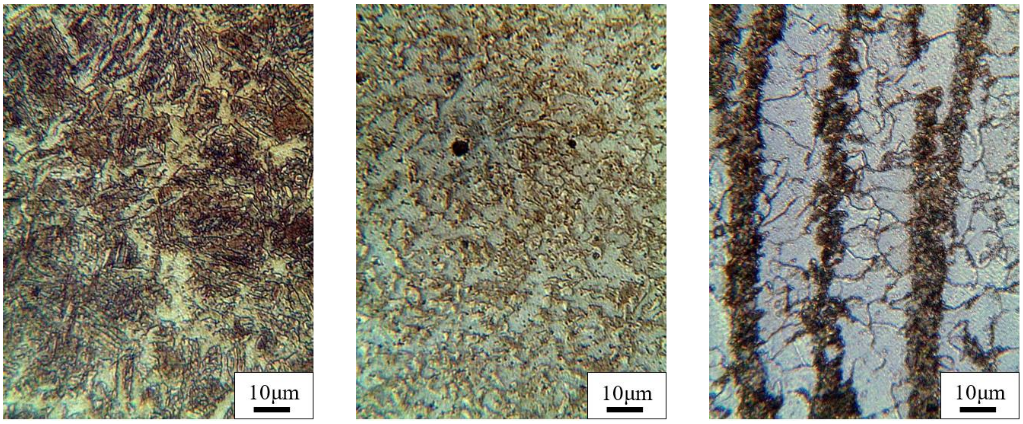
Fig. 4 shows the evolution of HV0.05 micro-hardness in the different zones of hardfacing.

Not of quenching structures are observed in the hardfacing welded metal [1, 12, 14]. This is visible from the distribution of the hardnesseses in the different zones of the joint (Fig. 4).

The hardness measured in the hardfacing welded metal is probably due to the amount of carbon in the electrode metal (~ 0.5). The structure is austenite with a certain amount of complex carbides phase ((Fe, Cr)$_{23}$C$_6$+Cr$_7$C$_3$) shown at fig. 4. The base metal has a completely ferrite-perlite structure. Fig. 3 and Fig. 5 show that the selected mode of hardfacing welding is appropriate.



a) b) c)



d) e) f)

Fig 3. Micrographic of the hardfacing welded specimen, according Fig. 2:
a) hardfacing layer zone 1-x800; b) hardfacing layer zone 2-x800; c) HAZ zone 3-x800; d) base metal zone 4-x400; e) base metal zone 5-x400; f) base metal zone 6-x400.

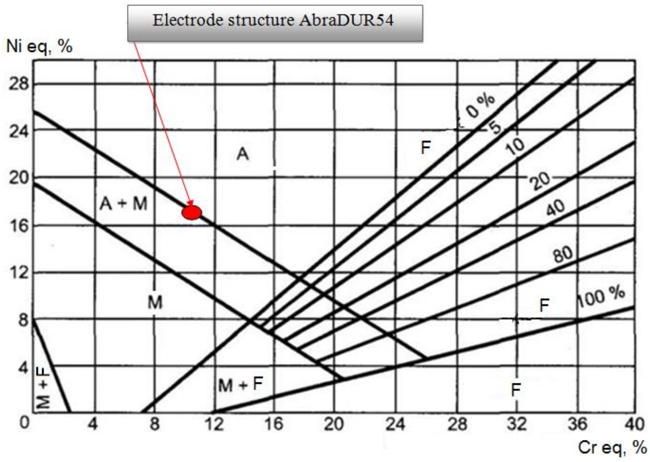


Fig.4. Schaeffler Diagram of the weld metal

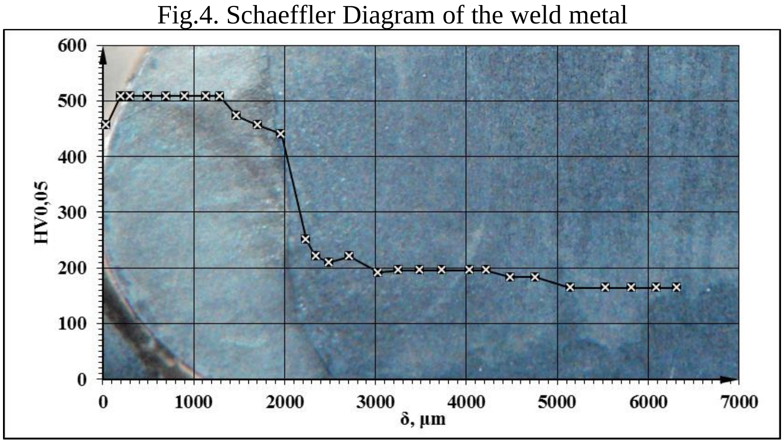


Fig.5. Distribution of microhardness HV0.05 after hardfacing welding with ABRADUR54 electrode

4. Simulation modelling of stressed and deformed state

4.1. Task formulation

Subject of study: specimens of low-carbon structural steel DD11 sized 200x10x10mm, which are hardfacing welded with an electrode for hardfacing welding ABRADUR 54.

The modes of processing of the specimens and the selection of hardfacing welding machines are presented in [14].

To determine the stresses and deformations caused by the temperature impact, a 3D model was created in SolidWorks (Fig. 6).

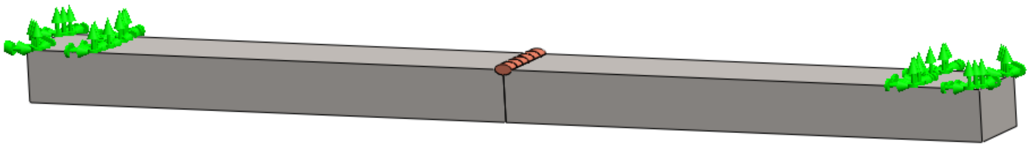


Fig.6. A model of specimens

For the needs of the computer simulation analysis, a preliminary thermal analysis of the subject under study was carried out from the beginning of its non-stationary heating to its complete cooling. The results obtained for the temperature field serve as initial data for the static analysis of the stressed and deformed state in the specified interval.

To simulate static analyses in the model of a moving high temperature heat source along the joint being formed, we used the Simulation/Static program module.

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

- ✓ initial temperature 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;
- ✓ speed of MMA hardfacing welding V_w = 5m/h.

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.

It is of practical interest to evaluate the stressed and deformed state of the subject under study after hardfacing welding.

4.2. Algorithm for performing simulation analysis using SolidWorks software:

Drawing a 3D model of a hardfacing welded steel specimen DD11 with an ABRADUR 54 electrode [14] using SolidWorks software Figure 6.

Defining the bonds between the two types of materials: the base one and the hardfacing welded one.

Performing a simulation analysis of the created 3-D model:

✓ setting the mesh of the modelled specimens in order to determine the stresses and deformations in the different areas after MMA hardfacing welding;

✓ specifying input data for the study: setting a material in the program library by defining its mechanical and thermo-physical characteristics;

✓ setting boundary conditions.

✓ Performing a Simulation/Static analysis and obtained results for the specified time intervals.

✓ Analysis of the results.

4.3.Results and analysis.

To solve the task, has been performed modelling of the stress and distortions evolution during welding processes using SolidWorks, by thermal and static analysis. To determine stresses and distortions caused by temperature effects, using a computer simulation model in the SolidWorks environment requires a preliminary thermal analysis of the object under consideration from the start of non-stationary heating to full cooling. The results obtained for the temperature field serve as output data for the static analysis of the stressed and distorted state within the specified range.

Fig. 8 shows the static analysis during hardfacing welding of the specimens with the hardfacing welding electrode ABRADUR 54, and in Fig. 9 - after cooling.

The results of the simulation analysis for the heating and cooling process for the 7 sensors (Fig.7) placed in the plate are given in Table 4 and Table 5.

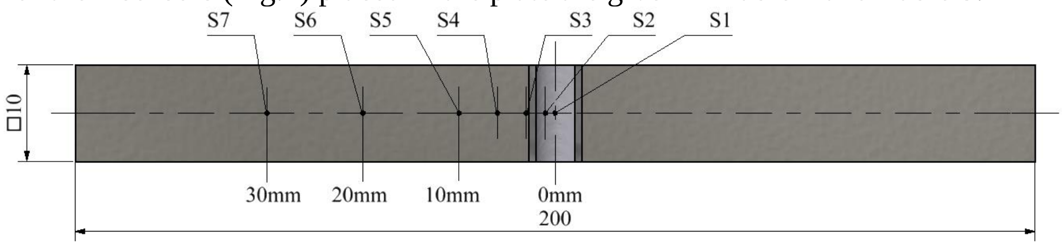
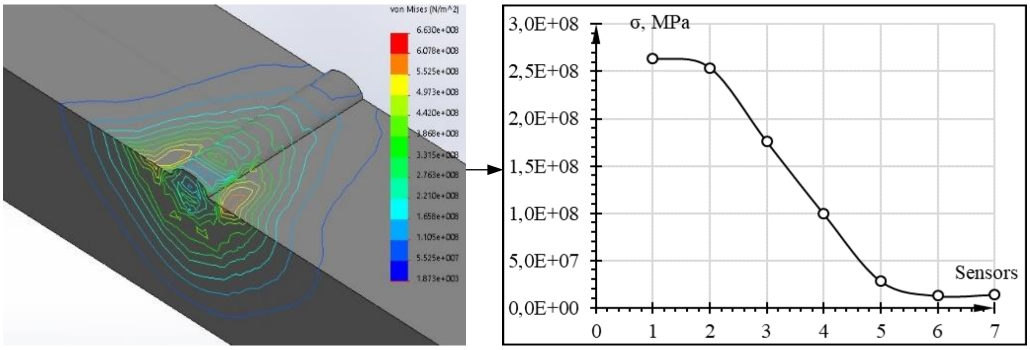


Fig.7. Placement of sensors in the model

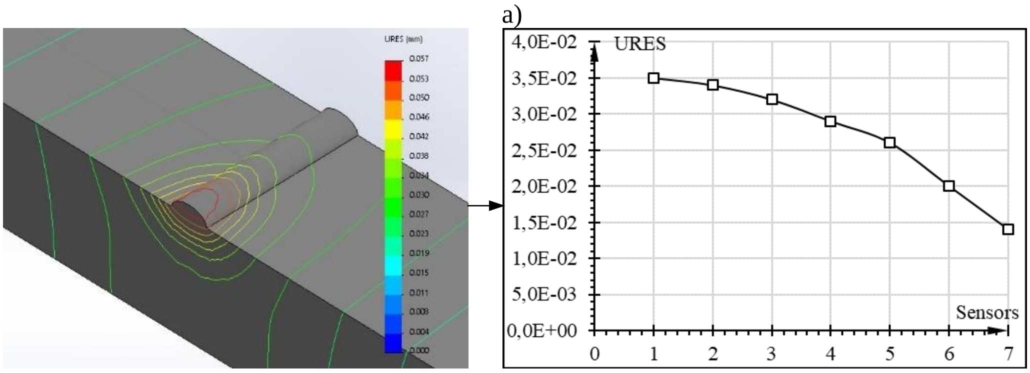
Table 4

Results of the simulation analysis in heating

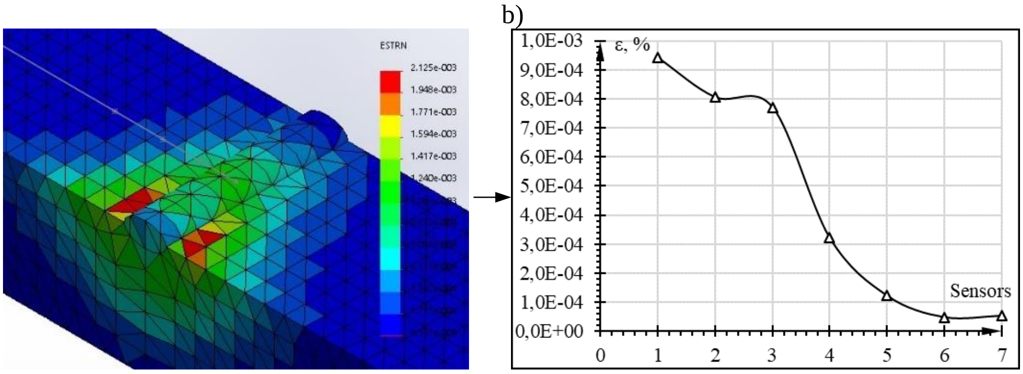
Sensors	Distance mm	Stress N/m²	Displacement mm	Deformations -
1	0	2.64E+08	0.035	9.41E-04
2	1	2.54E+08	0.034	8.05E-04
3	3	1.76E+08	0.032	7.71E-04
4	6	9.96E+07	0.029	3.21E-04
5	10	2.83E+07	0.026	1.22E-04
6	20	1.26E+07	0.02	4.81E-05
7	30	1.39E+07	0.014	5.33E-05



a)



b)



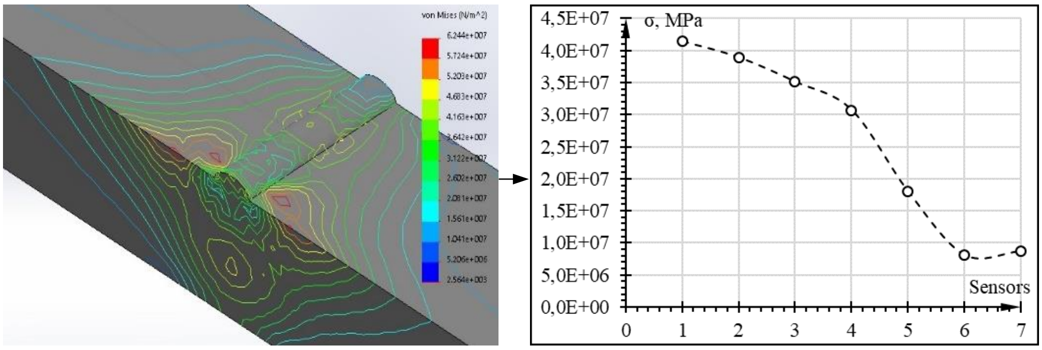
c)

Fig.8. Results and graphic representation at heating a) Stresses; b) Displacement; c) Deformations

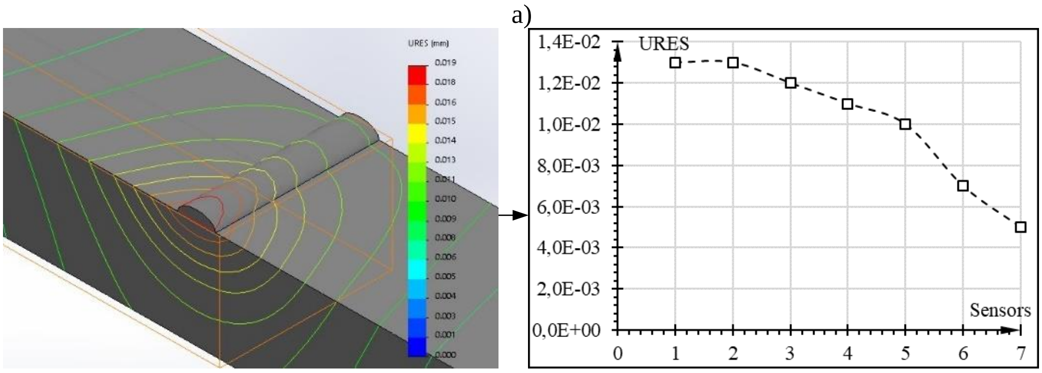
Table 5

Results of the simulation analysis in cooling

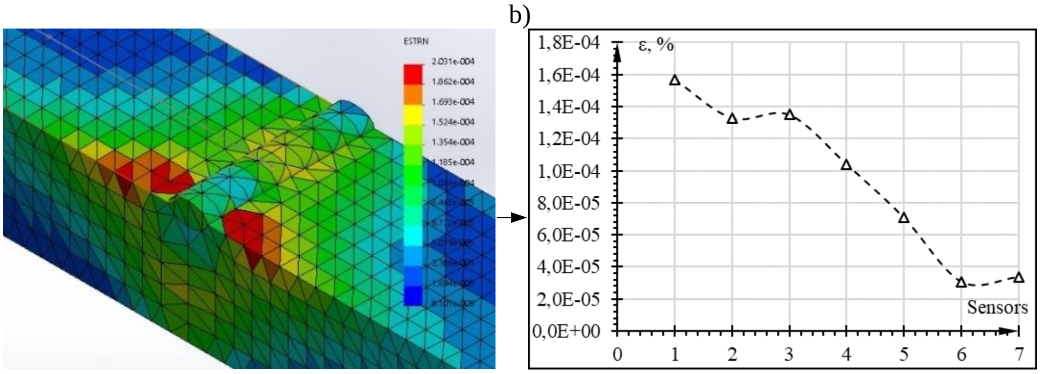
Sensors	Distance mm	Stress N/m²	Displacement mm	Deformations -
1	0	4.14E+07	0.013	1.57E-04
2	1	3.89E+07	0.013	1.33E-04
3	3	3.51E+07	0.012	1.35E-04
4	6	3.07E+07	0.011	1.04E-04
5	10	1.80E+07	0.01	7.07E-05
6	20	8.10E+06	0.007	3.08E-05
7	30	8.66E+06	0.005	3.38E-05



a)



b)



c)

Fig.9. Results and graphic representation at cooling: a) Stresses; b) Displacement; c) Deformations

5. Conclusions

It is evident from the metallographic analysis at Figure 2, that both in the metal which was hardfacing welded with ABRADUR54 and in the different joint zones none of macrodefects (cracks, non-penetrations, undercuts, etc.) are available. In only a few cases, random macro pores can be observed, but these are of sporadic occurrence. It is evident from the microstructural analysis at Figure 3b, that dendrites directed towards the boundary of alloying are observed in the hardfacing welded zones.

The results of the simulation analysis are fully consistent with the theoretical formulations regarding the occurrence and distribution of thermal stresses in hardfacing welding of the model under study. The diagrams (Figures 7 and 8) clearly show the difference in the displacements, registered by 7 sensors at simulate the heating and cooling processes of hardfacing welded. The determination of the maximum total deformations in the hardfacing welded structures is essential for solving the accuracy problems when installing them.

The colour visualizations shown in Figures 7 and 8 establish the maximum values of stresses, strains and displacements in the depth of the samples. The results of all sensors placed on the sample when heated and cooled are shown in Tables 3 and 4. The maximum values are recorded by the 1st sensor located in the welding zone, and they do not exceed the maximum permissible for the material. Similarly, the highest data are recorded by the 4th base metal sensor and do not exceed the maximum permissible for the base metal.

In the cooling process (table 5), the largest stresses are grouped into the hardfacing welding area, which is explained by their different coefficients of thermal expansion and mechanical properties. The determination of the maximum stresses makes it possible to predict the risk of cracking or destruction of the layers while hardfacing welding.

After the complete cooling of the subject, the residual stresses can be assessed according to their direction and size, and their effect on the operating stresses of the structure can be predicted.

The demonstrated method for 3D modelling of heat transfer processes and evaluation of the stressed state in MMA hardfacing welding has a universal character. Using a product like SolidWorks enables testing different welding technologies, by changing the initial parameters of the modes or by using various materials.

R E F E R E N C E S

[1]. *Arsic´, D., Lazic´, V., Samardžic´, I., Nikolic´*, R., Aleksandrovic ´, S., Djordjevic´, M. and Hadzima, B. (2015), “Impact of the hard facing technology and the filler metal on tribological

characteristics of the hard faced forging dies", Tehnicˇki Vjesnik – Technical Gazette, Vol. 22 No. 5, pp. 1353-1358.
[2]. *Bakalov I.*, 2014., "Methods and instruments for measuring torque and speed of marine diesel engines"., Machines Technologies Materials – Issue 7., ISSN 1313-0226., p. 26 - 28
[3]. *Bakalov I.,* 2015., "A testing station for studying the combustion of fuel with mechanical centrifugal and rotating cup burners"., Machines Technologies Materials – Issue 8 ISSN 1313-0226., p. 11 – 13
[4]. Catalogue of filler materials Electrode Jesenice, Slovenia (2015).
[5]. *Chang, C., Chen, Y. and Wu, W.* (2010), "Microstructural and abrasive characteristics of high Carbon Fe–Cr–C hardfacing alloy", Tribology International, Vol. 43 Nos 5/6, pp. 929-934.
[6]. *Kolev Z. D., S. Y. Kadirova, T. R. Nenov,* 2017, Research of reversible heat pump installation for greenhouse heating. INMATEH - Agricultural Engineering, No 2, pp. 77-84, ISSN 2068 – 2239. (SJR rank: 0.19)
[7]. *Lazic´, V., Jovanovic´, M., Milosavljevic´, D., Mutavdžic´, M. and C ˇukic´, R.* (2008), "Choosing of the Most suitable technology of hard facing of mixer blades used in asphalt bases", Tribology in Industry, Vol. 30 Nos 1/2, pp. 3-10.
[8]. *Lazic´, V., Mutavdžic´, M., Milosavljevic´, D., Aleksandrovic´, S., Nedeljkovic´, B., Marinkovic´, P., C ˇukic´, R.* (2011), "Selection of the most appropriate technology of reparatory hard facing of working parts on universal construction machinery", Tribology in Industry, Vol. 33 No. 1, pp. 18-27.
[9]. *Lin, C.M., Chang, C.M., Chen, J.H. and Wu, W.* (2010), "The effects of additive elements on the microstructure characteristics and mechanical properties of Cr–Fe–C Hard-facing alloys", Journal of Alloys and Compounds, Vol. 498 No. 1, pp. 30-36.
[10]. *Markovic´, S., Milovic´, L.J., Marinkovic´, A. and Lazovic´, T.* (2011), "Tribological aspect of selecting filler metal for repair surfacing of gears by hard facing", Structural Integrity and Life, Vol. 11 No. 2, pp. 127-130.
[11]. Prospekt, ELEKTRODI –AD, IHTIMAN, 2002÷2003.
[12]. *Thongchitrugsa, N., Chianpairot, A., Hartung, F. and Lothongkum, G.* (2014), "Effect of molybdenum on wear resistance of Cr-Nb Hard-faced S355JR steel", Materials Testing, Vol. 56 No. 3, pp. 191-197.
[13]. *Truhan, J., Menon, R., LeClaire, F., Wallin, J., Qu, J. and Blau, P.* (2007), "The friction and wear of various hard-faced claddingsfordeep-holedrilling", Wear, Vol.263 Nos 1/6, pp. 234-239.
[14]. *Yankova R., Spassova D., Petrov P.,* 2017, Wear of built-up hard-faced welded layers in dry friction conditions, Scientific News, Year XXV / Issue 1 (216), June 2017, p.258-261, ISSN 1310-3946.