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NUMERICAL ANALYSIS OF STRESS AND STRAIN STATE IN MEMBRANE WALLS WELD JOINTS PERFORMED BY SUBMERGED ARC WELDING

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Abstract: The article presents investigation on stress and strain state in weld joints of boiler membrane wall by performing numerical analysis (finite element method). The main purpose was to create 3D model which will correspond to real membrane wall geometry under consideration, which will allow to perform strength simulation of numerical models considering variable parameters depending on the temperature. The model was fragment of boiler membrane wall made of X10CrMoVNb9-1 pipe and 10CrMo9-10 flat bar welded with submerged arc method. The research included the assumption of boundary conditions such as temperature cycles, welding method, type of mounting and base materials or heat treatment cycle. Three simulations have been performed depended on base material and temperature cycle adopted. As a result of the simulations, the distribution of temperature, displacement and stress in analyzed cases were obtained. The numerical simulation in dissimilar welded joints X10CrMoVNb9-1 pipe and 10CrMo9-10 flat bar heat treated afterwards, showed that the differences in linear expansion coefficients favour the development of cracks in the welds caused by increased level of stress. In parallel materials used for boiler membrane walls are the reason for difficulties in determine the proper technology of welding, preheating temperature and post-weld heat treatment parameters. Simulations indicated that the state of stress in weld joint is dependent on type of parameters adopted, and in closest scenario to real conditions, simulation showed that post-weld heat treatment had no positive effect on the stress state caused by discrepancy in linear expansion coefficients of both base materials.

Key words: stress, membrane, weld joints, arc welding

1. INTRODUCTION

Recent decades have resulted in dynamic development of the energy industry both in Poland and worldwide. The continuous increase in population amount, increasingly wider automation of production processes and economic development resulted in increased demand for electricity.

This period was characterized primarily by the development of technology, the use of new materials and increased attention to environmental protection problems. It all comes down to increasing the efficiency of the power plant, defined as the ratio of electricity obtained to the amount of thermal energy supplied to the boiler [1-3]. The efficiency of the power plant is increased by increasing the parameters of the steam i.e., pressure and temperature. During the discussed period, the operating pressure increased from 200 to 260 bar and the temperature from 535ºC to 580ºC.

The introduction of such high temperature and pressure in the power plant installation requires the use of new construction materials and the development of welding technologies ensuring the achievement of high-quality welded joints of boiler sheet pile walls [4,5]. Due to such a high temperature and pressure during operation, while maintaining the functional properties, martensitic chromium-molybdenum steels such as X10CrMoVNb9-1 achieving stability of properties at temperatures up to 600°C or alloy steels for pressure elements are used in this type of structures at elevated temperatures, such as 10CrMo9-10, the properties of which are determined when working at temperatures up to 550°C.

In addition to the advantages resulting from functional properties at elevated temperature, these materials also have a number of limitations in the technological and production process, such as the need to heat for welding or post-welding heat treatment [6-8]. PWHT often takes place in two stages. In the first phase, after welding, the heat treatment specific to the X10CrMoVNb9-1 steel is performed, consisting in cooling immediately after welding below the Mf temperature and then carrying out the main heat treatment at a temperature of 750°C with controlled heating and cooling [9,10].

2. MATERIALS AND METHODS

2.1 Materials

The purpose of the numerical analysis was to verify the state of stresses and distortion in the welded structure of the membrane wall made of X10CrMoVNb9-1 steel pipes with dimensions of Ø38x5.6mm welded with a submerged arc welding method with a 10CrMo9-10 flat bar with dimensions of 18x6mm, tables 1-3.

Table 1. Chemical composition and mechanical properties of X10CrMoVNb9-1 steel

Chemical composition, [%]											
C	Mn	P_{max}	S_{max}	Si	Cr	Mo	V	Nb	N	Al_{max}	Ni_{max}
0.08 - 0.12	0.30 - 0.60	0.02	0.01	0.20 - 0.50	8.00 - 9.50	0.85 - 1.05	0.18 - 0.25	0.06 - 0.10	0.03 - 0.07	0.04	0.40

Mechanical properties			
Tensile strength R_m[MPa]	Yield point $R_{p0.2,}$ [MPa]	Elongation $A_{5,}$ [%]	Impact energy KV [J]
673	569	23	215

Table 2. Chemical composition and mechanical properties of 10CrMo9-10 steel

Chemical composition, wt.%							
C	Si_{max}	Mn	P_{max}	S_{max}	Cr	Mo	Cu_{max}
0.08 - 0.12	0.30 - 0.60	0.02	0.01	0.20 - 0.50	8.00 - 9.50	0.85 - 1.05	0.18 - 0.25

Mechanical properties			
Tensile strength R_m[MPa]	Yield point $R_{p0.2,}$ [MPa]	Elongation $A_{5,}$ [%]	Impact energy KV [J]
480-630	310	18	40

Table 3. Temperature dependence of the linear expansion coefficient

Temperature [°C]	Linear expansion coefficient - $\alpha \cdot 10^6$ [$^1/_{°C}$]						
	20	100	200	300	400	500	600
10CrMo9-10	-	11.1	12.1	12.9	13.5	13.9	14.1
X10CrMoVNb9-1	-	10.9	11.3	11.7	12.0	12.3	12.6

Assumption of research:
- creating of 3D geometric model of tested object;
- creating FEM models with CAE based on geometric models;
- supplementing the FEM models with appropriate boundary conditions;
- strength simulations of numerical models considering variable parameters depending on temperature.

2.2 Geometric 3D model

For simulation purpose, a 2-meter section model was created, consisting of two pipes Ø38x5.6mm and a flat bar 18x6mm. The geometrical model is presented in figure 1.

Fig. 1. Fragment of a membrane wall

2.3 Discrete model (FEM)

The simulation was performed using the Finite Element Method (FEM) with the use of professional CAE software by MSC.Software. Based on the 3D geometric model, a discrete model (FEM) was created, figure 2. Discretization was performed based on an 8-node solid element. The discrete model consists of approximately 116000 elements with 131000 nodes, which is approximately 390000 degrees of freedom (DOFs).

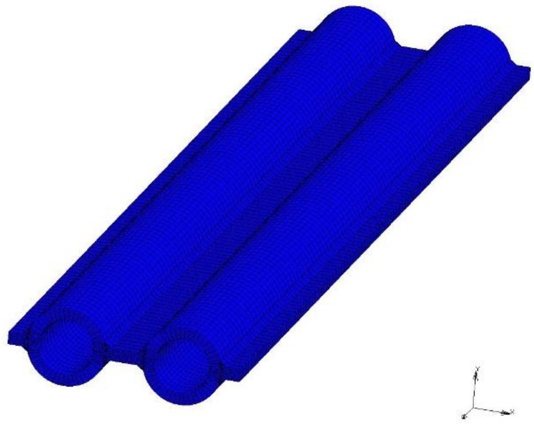


Fig. 2. Numerical model FEM.

Based on the analysis of material data and the welding process, the material distribution in the area of the welded joint was determined for the purposes of simulation, figure 3.

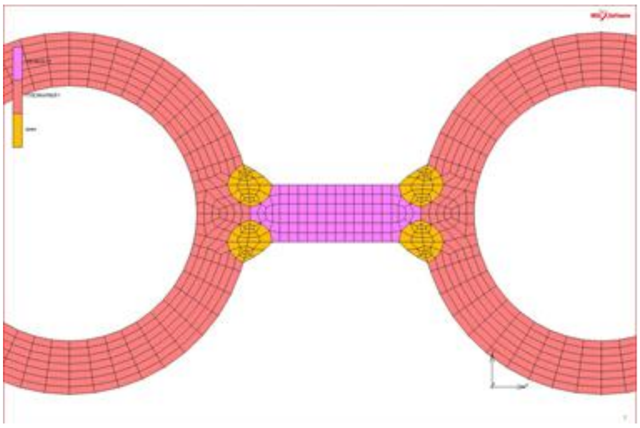


Fig. 3. Material distribution in the area of welded joint determined for the simulation purpose.

Material parameters such as stress-strain curve, thermal expansion coefficient, specific heat, thermal conductivity, Young's modulus in the simulations performer are variable depending on the temperature.

2.4 Boundary conditions determining

In order to carry out numerical simulations in accordance with the welding process, sets of boundary conditions and loads were developed. The boundary conditions were selected on basis of the method how the elements were fastened together (pipe and flat bar) during welding process. The loads were selected in accordance with the welding technology in the form of a moving heat source affecting the weld material. The boundary conditions and loads are shown in figures 4 and 5.

Fig. 4. Boundary conditions for a simple simulations of the influence of various types of material on state of stress and displacement

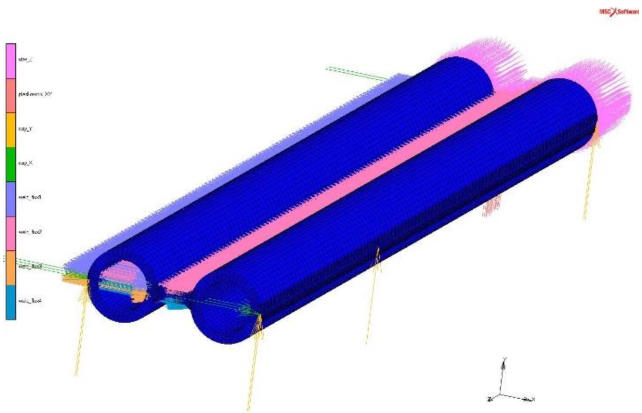


Fig. 5. Boundary conditions for complex case of the welding process.

3. RESULTS AND DISCUSSION

3.1 Numerical simulation

Welding is a thermal process in which there are specific boundary conditions related to high temperature, rapid heat (energy) input into the body, a moving heat source and a specific cooling course. In a correctly prepared model for calculations using the finite element method (FEM), all important parameters must be considered, which makes it possible to obtain a representation of the actual way of the process. Main process parameters such as heat source shape, welding speed, welding energy, bead shape etc. should be fully modelled. Most of them are modeled by parameters defining the heat source, the weld and the bead shape, and the simulation is conducted as a simulation of thermo-mechanical coupled fields. It is worth emphasizing that the simulation uses material parameters (stress-strain curve, Young's modulus, thermal expansion coefficient, specific heat, thermal conductivity, etc.) as a function of temperature.

The work includes three types of simulation:

• Simplified simulation considering the temperature steady state at 600°C (in entire structure), assuming the same material of pipes, flat bar and weld joint, with pipe material assumed as base material marked as

SYM1.

• Simplified simulation considering the temperature steady state at 600°C (in entire structure), assuming different materials of pipe, flat bar and weld joint marked as SYM2.

• Numerical simulation of welding process together with heat treatment (annealing) as a fully thermo-elastic process, considering movable heat source and different material of pipe, flat bar and weld joint. The parameters of the weld material were selected
as averaged values of pipe and flat bar material parameters marked as SYM3. Simulation SYM3 takes place in stages:

- welding process, state as welded;
- then free cooling until ambient temperature was reached;
- next the heat treatment process: increase the temperature up to 750°C for 298 minutes, holding the temperature at 750°C for 120 minutes, cooling to 300°C for 180 minutes and final cooling until ambient temperature was reached;
- final cooling. The SYM3 was performed for symmetrical model, considering the symmetry conditions.

As a result of the simulation, the distribution of temperature, displacements and stress in the analysed cases were obtained. These distributions are show in figure 6 to figure 9.

3.2 Simulation results analysis

The simulation marked as SYM1 showed an even displacement distribution and no stress in the system, which is obvious in case of free deformation, Figure 6. The results of the simplified SYM2 simulation showed an uneven distribution of normal stresses □z, due to the use of different materials of pipes and flat bar, Figure 7. Big difference in thermal expansion coefficient (over 10%) is the main cause of stress in the system. The variety of materials causes stress after heating to 600°C, with a value of approx. 100 MPa in the area of the flat bar and to the value of approx. 20 MPa in the area of the pipe. This is definitely an unfavourable factor that reduces the load capacity of welded joint. These values increase at the higher temperature observed during welding process. Detailed simulation of SYM3 indicates higher value of stress in weld joint, which adversely affects the state of its stress during operation, Figure 8. Repeated passage through high temperature causes quite large differences in the displacement of the system, Figure 9. Heat treatment process does not reduce stress, because elongation change fixed during the welding process does not disappear, as produced due to the difference in the thermal expansion coefficient of the materials, even before the step of joining the parts. The use of different materials of pipes and a flat bar introduces unnecessary differences in material parameters, which during a variable welding process prior to heat treatment still causes a heterogeneous variable distortion process of elements. It results in stresses (also changing in direction) and deformations, which have a direct impact on the possibility of crack formation.

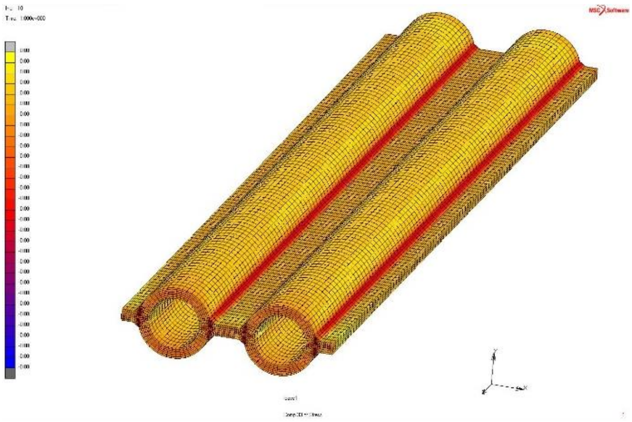


Fig. 6. Normal stress distribution (σ_z) for SYM1 (MPa)

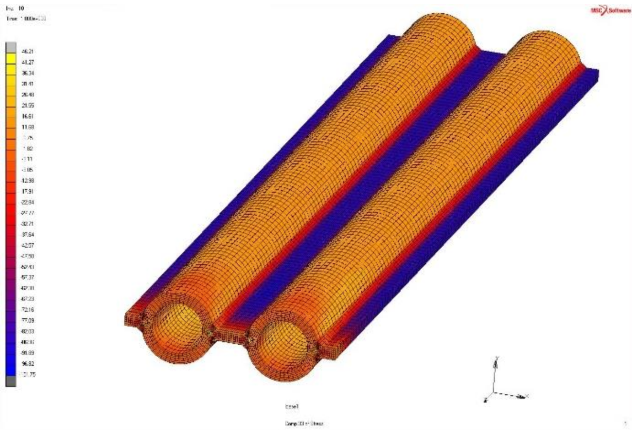
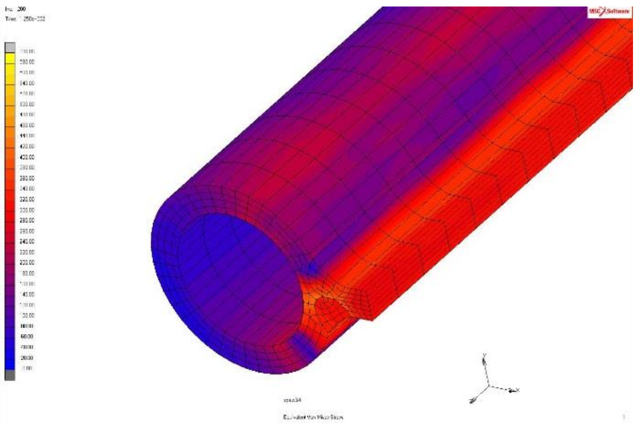
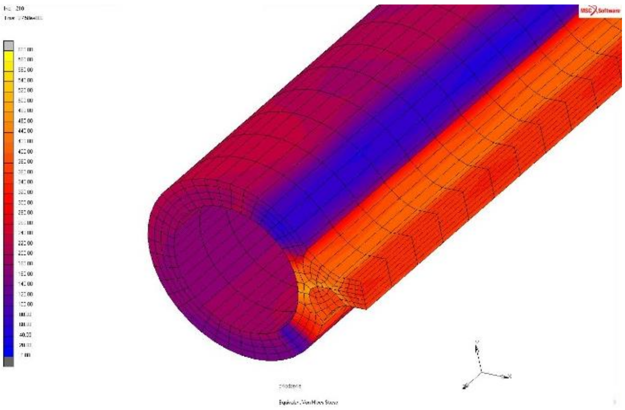


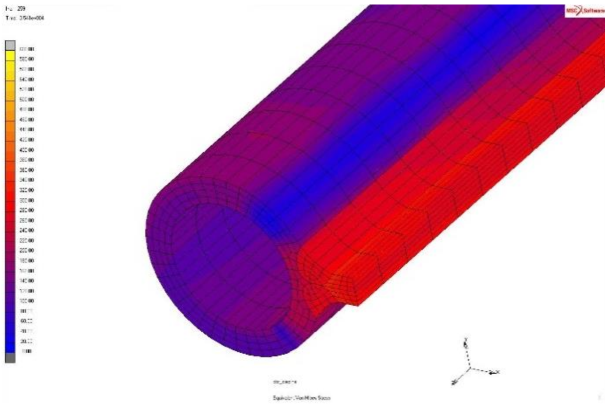
Fig. 7. Normal stress distribution (σ_z) for SYM2 (MPa)



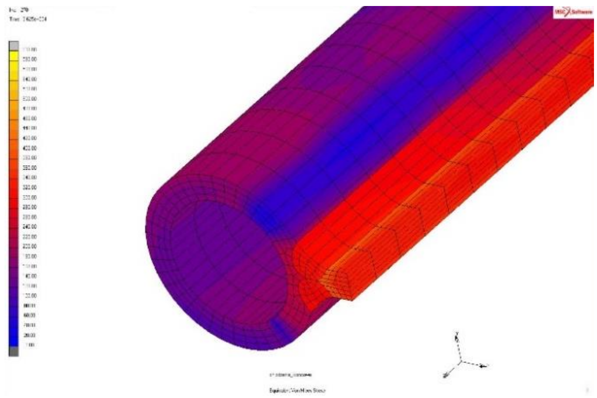
a. reduced stress after welding



b. reduced stress after cooling to ambient temperature (before heat treatment)

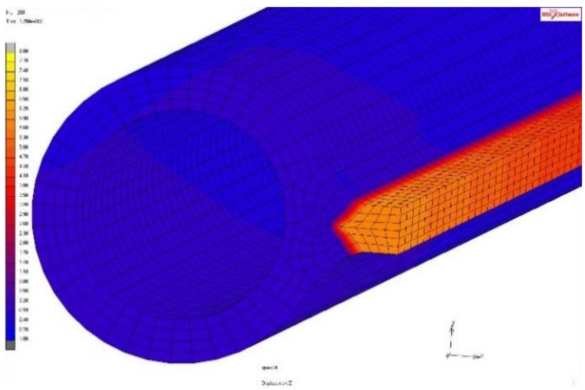


c. reduced stress after heat treatment and cooling to 300°C

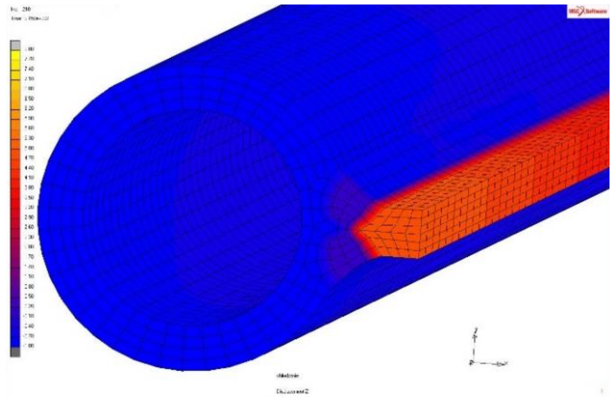


d. reduced stress after heat treatment after cooling to ambient temperature

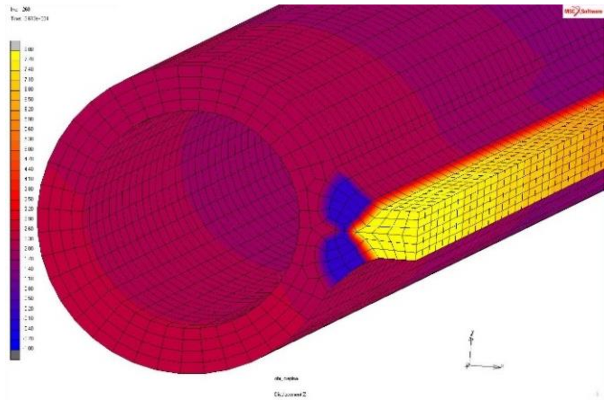
Fig. 8. Normal stress distribution σ_z [MPa] for SYM3 after welding and heat treatment



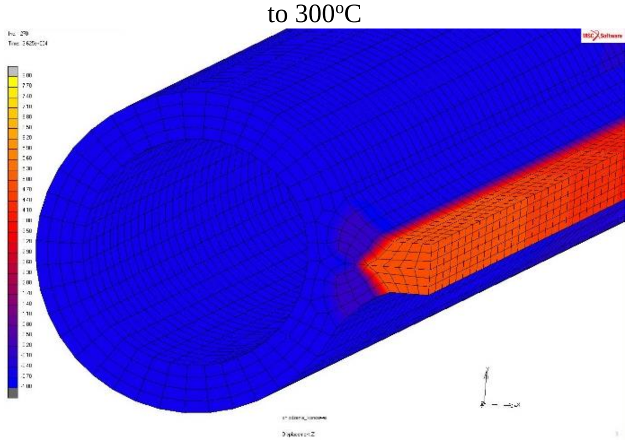
a. reduced displacements after welding



b. reduced displacements after cooling to ambient temperature (before heat treatment)



c. reduced displacements after heat treatment and cooling to 300°C



d. reduced displacements after cooling to ambient temperature

Fig. 9. Displacement distribution u [mm] for SYM3 after heat treatment: a. after welding, b. after cooling, c. after heat treatment, d. final cooling

4. CONCLUSIONS

The materials used in the analysed case to produce the boiler membrane wall of the X10CrMoVNb9-1 (pipe) and 10CrMo9-10 (flat bar) joined by submerged arc welding method differ significantly in their chemical composition, physical properties, including linear expansion coefficients (tables 1 to 3) and functional properties, creep resistance, oxidation resistance, etc. Mixing the alloy components and impurities of both steels with the welding material representing chemical composition of 10CrMo9-10 steel in the weld joint causes the welds to obtain properties that are difficult to predict, depended on the mixing degree of welding material with the base material. It also makes it difficult to determine the proper welding technology for membrane wall, selection of a welding material, preheating temperature and post-welding heat treatment parameters. The trials of numerical modelling of the stress state in dissimilar welded joints X10CrMoVNb9-1 pipe and 10CrMo9-10 flat bar, heat treated, showed that differences in linear expansion coefficients favour the creation of cracks in the weld joints. The difference in the linear expansion coefficients of X10CrMoVNb9-1 and 10CrMo9-10 steel causes an increase in longitudinal stresses in the weld. This promotes the development of transverse cracks in the joints. The high level of longitudinal stresses in the joints of membrane wall also remains after heat treatment and after service. Transverse cracks can occur after heat treatment, especially when the welds show low plastic properties.

5. REFERENCES

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