Application of Numerical Simulations on 10GN2MFA Steel Multilayer Welding

Tomasz Kik, Jaromír Moravec and Iva Nováková

Abstract 10GN2MFA steel is used to produce wire and manufacturing of steam generators, pressure compensators, collectors and other equipment for nuclear power plants. In this area, there is no place to do any mistakes during manufacturing or carrying out extensive tests and producing a lot of prototypes. It is the main reason why we used modern software for numerical simulation of welding and heat treatment processes also on the very early stage of development. The aim of this paper is to describe how can welding processes be optimized by means of the numerical simulations mainly with respect to the structural changes, stresses and hardness distribution in the Heat Affected Zone (HAZ). On the real multilayer weld how to arrange whole experiment in order to obtain not only relevant input data but also verification data will be described. Additional aim of this paper is to propose mathematical description of the computational model that is usable for simulation computations of welding and heat treatment of real structure components.

Keywords Numerical simulation · 10GN2MFA steel · Welding · FEM SYSWELD · Hardness prediction

1 Introduction

Energy sector is generally responsible for substantial and comprehensive public development. Even that we have a lot of alternative energy sources, still the most

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critical for energy sector are two method: producing energy in coal steam power plants (powered by coal and others fossil fuels) and nuclear power plants (where the energy is produced from nuclear fusion).

As for April 2017 in 30 countries worldwide are operating 449 nuclear reactors for electricity generation. Another 60 new nuclear plants are under construction in 15 countries. Nuclear power plants provided 11% of the world's electricity production in 2014. In 2016, 13 countries relied on nuclear energy to supply at least one-quarter of their total electricity [1, 2].

In nuclear energy reactors, the heat from nuclear fusion is used to produce a steam. Steam next is transported to turbines and used to produce electricity. From a single uranium fuel pellet (size is like a pencil eraser) it is possible to produce same energy amount as from 17,000 cubic feet of natural gas, 1780 lb of coal or 149 gallons of oil [1]. It is important that proper used nuclear reactors do not emit any pollutions. There is no carbon dioxide, nitrogen oxides and sulfur dioxides as well. It can be also called second generation of clean energy because of no environment degradation comparing to wind turbines or dams. For example, the amount of electricity produced by a multi-reactor nuclear power plant would require about 45 square miles of photovoltaic panels or about six times more square miles of wind turbines. Additional advantage is that renewable energy sources is limited by their fuel—wind, sun or water. Nuclear energy produces electricity continuously, without breaks. Also it is important that there is enough uranium in the world to fuel reactors for 100 years or more [1–4].

Of course some of people can be afraid about the radiation, but it is worth to say, that normally operated nuclear power plant do not emits radiation. Of course they are also real-time monitored and the risk on some hazardous accident is very limited [1, 2, 4]. To assure the proper safety level, important is also to ensure the highest quality level of nuclear island equipment elements. 10GN2MFA steel is a widely used as also 16MND5 and A508 tempered bainitic pressure vessel steel used mainly in production of WWER-1000 reactor equipment as steam generator cases, collectors and pipes. Due to the big dimensions of elements, different conditions of plastic deformation involve in the manufacturing process can have big influence on mechanical properties [5, 6].

Due to the specific use and technologies for joining of these material, important is also to investigate properties of used materials as well as it possible. To achieve best results and also claim specific working conditions, applications of these materials and development of the technological processes for their processing is still more and more aided by numerical simulation computations. These computations help to understand the processing which takes place in the individual phases of a simulated process and with respect to that it is possible to process optimize. Eventually risks associated with unacceptable defects can be significantly eliminated. The information obtained from the simulations can be used to support or develop a methodology how to obtain not only input data, but also data which verify the validity and suitability of the computational procedures that are used [7, 8].

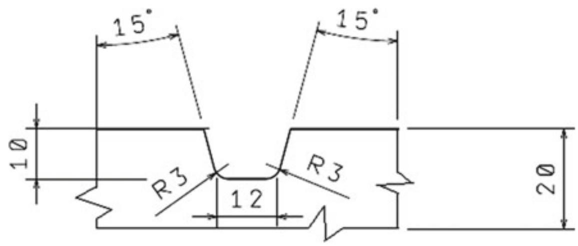


Fig. 1 Scheme of specimen preparation for welding tests

2 Realization of the Welding Experiment on 10GN2MFA Steel Specimens

Main aim of real tests was not achieve the best quality of welds but collect as more as it possible of input data's for numerical simulations. These data will help us to define boundary conditions and verification of calculation results, mainly hardness after welding and after post weld heat treatment.

For real tests, $180 \times 80 \times 20$ mm specimen was prepared with milled grove for welding as on Fig. 1. Chemical composition of 10GN2MFA measured on TASMAN Q4 spectrometer was shown at Table 1. Complete specimen was welded by 8 beads in 4 layer by manual arc welding, where two beads were placed side-by-side in each layer using Boehler FOX EV 85 electrode, Table 2. All process was completely monitored by the Weld Monitor system and all information's about the relevant processes parameters were available. Test specimen monitored by six thermocouples and partially coated with Sibral isolation (Fig. 2) was placed into the furnace and heated on temperature 200 °C with heating rate about 1.5 °C/min. After reaching preheating temperature on whole specimen, Sibral isolation was also placed on the top and welded. During all welding procedure the interpass temperature at 350 °C was respected. After welding, specimen with welds was heat treated by heating up to the 650 °C and cooled with furnace to the 300 °C and then in the free air to the ambient temperature.

3 Numerical Simulation of Welding Process in SYSWELD Software

SYSWELD software package is the most used commercial simulation software for welding and heat treatment processes. The whole computation process consists of two separate analyses—the thermo-metallurgical and the mechanical one. First of them makes it possible to compute non-stationary temperature fields, phase transformations, hardness or size of the austenitic grain. The second part of analysis—mechanical analysis uses the results of the temperature-metallurgical analysis as input

Table 1 Chemical composition tested on TASMAN Q4 spectrometer, % and basic mechanical properties of 10GN2MFA steel

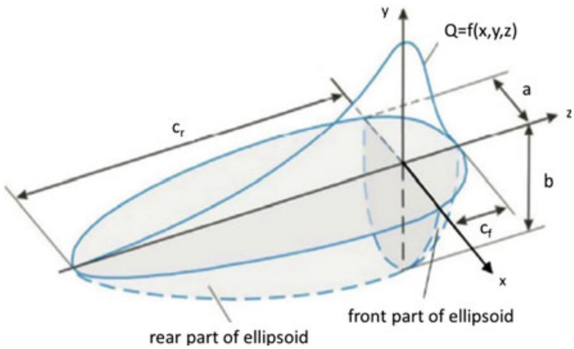
C	Mn	Si	P	S	N	Cu	Ni	Cr	Mo
0.117	0.954	0.223	<0.005	<0.15	<0.02	0.048	1.970	0.041	0.583
V	Al	B	Ti		Nb	As	Sn		Fe
0.052	0.014	0.001	0.0012		0.001	0.012	<0.005		95.71
Yield point, MPa			Tensile strength, MPa			Elongation, %			
345–590			540–700			18			

Table 2 Chemical composition of the Boehler FOX EV 85 filler material, %

C	Mn	Si	P	S	N	Cu	Ni	Cr	Mo
0.05	1.7	0.4	–	–	–	–	2.1	0.4	0.5

Fig. 2 View of 10GN2MFA steel specimen with thermocouples and Sibral isolation before heating (on the left side) and during welding (on the right side)

Fig. 3 Double ellipsoid heat source model [10]



data and the most common results here are mainly stress and strain fields but also distortions [7–9].

Nowadays there are known a many numerical heat source models used in the welding FEM simulations. One of the most popular for typical arc welding methods is a double-ellipsoidal heat source model also called Goldak's model. This heat source model (defined as heat flux density into material) is described by Eqs. (1) and (2). The efficiency of the heat transfer into parent material is given by the applied welding method [4]. Geometry of double-ellipsoidal model can be modified by changing coefficients 'a', 'b' and 'c' in the Eqs. (1) and (2) [9–11] (Fig. 3).

Transferred heat is described by equations below [9]:

for the front part of heat source model is

$$Q_f(x, y, z) = \frac{6\sqrt{3} f_f Q}{abC_f \pi \sqrt{\pi}} exp\left(\frac{-3x^2}{a^2}\right) exp\left(\frac{-3y^2}{b^2}\right) exp\left(\frac{-3z^2}{c^2}\right) \quad (1)$$

and for the rear part of heat source model is

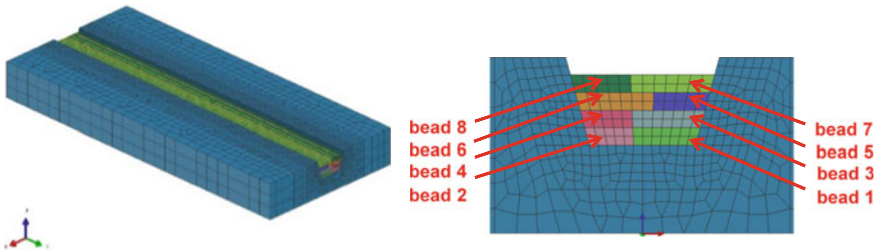


Fig. 4 View of 3D discrete model of weld created on the basis of real experiment and cross section with each bead description and model mesh

$$Q_r(x,y,z) = \frac{6\sqrt{3} f_r Q}{abC_r\pi\sqrt{\pi}} exp\left(\frac{-3x^2}{a^2}\right) exp\left(\frac{-3y^2}{b^2}\right) exp\left(\frac{-3z^2}{c^2}\right) \quad (2)$$

where:

Q_f, Q_r heat introduced into the front and the rear part of the model,
Q total power source,
a width of the molten pool,
b depth of the molten pool,
c_f, c_r length of the front and the rear part of the molten pool,
f_f, f_r constants which influence energy flow intensity into the material.

Total energy introduced by the heat source model to the welded material is [9]:

$$P = \int_{structure} Q_R \quad (3)$$

Hardness and stresses calculations in SYSWELD requires to calculate the temperature distribution on the welded specimen. That is why the proposal of the experiment to optimize the computational model in program SYSWELD arises both from such requirement to define Goldak´s heat source model and from the necessity to know the change of the hardness in multilayer welding. Therefore the aim of the experiment was not only to define the geometry of every weld (including necessary welding parameters used in process) but also to determine hardness changes in the parent material, HAZ and in the weld at application of at application of multiple multiple temperature cycle. Very important is also an unambiguous definition of boundary conditions for the experiment which are given both by used clamping method and the technological parameters (preheating, interpass temperature) but also by the way of thermal conductivity into surrounding. For the possibilities of beads geometry and HAZ areas examinations, in real experiments beads were moved each other.

Thanks to this it was possible just by means of one experiment to gain all necessary data both for a definition of Goldak´s heat source model and also for subsequent verification and eventual optimization of computational model. Numerical model was built from 50,704 3D elements and 44,999 nodes, Fig. 4.

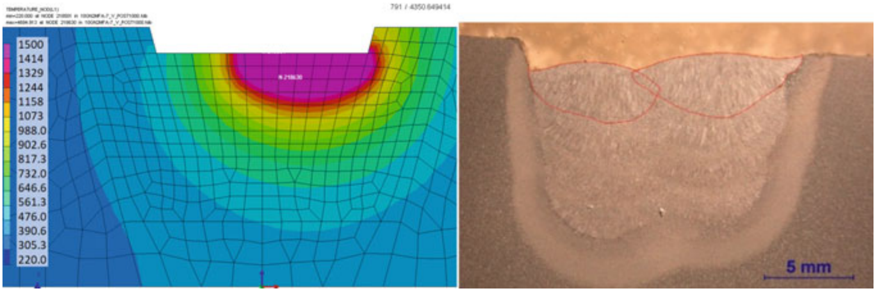


Fig. 5 An example of temperature distribution during heat source calibration for 8th bead (on the left) and macro view of real welded beads used for calibration comparison

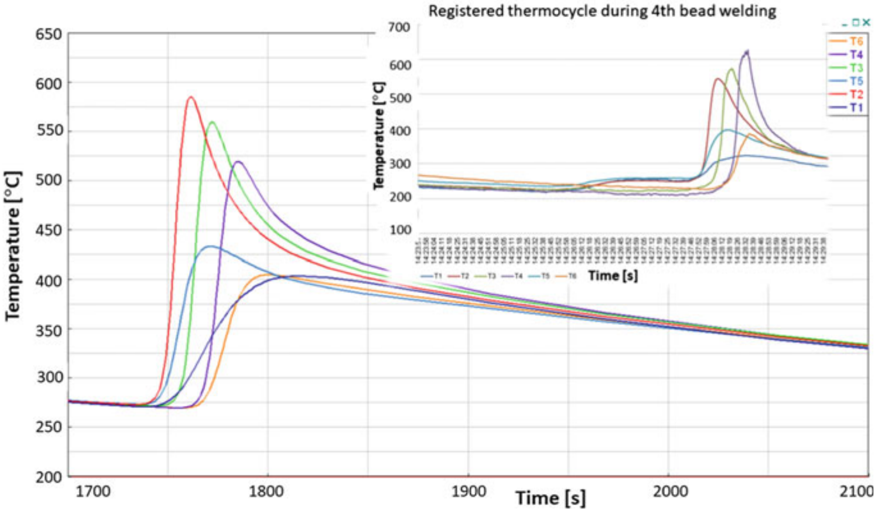


Fig. 6 Comparison of registered and calculated thermal cycles for all six thermocouples during welding 4th bead

For each welded bead, individual 3D model was calculated. Heat source model was calibrated to achieve the best correspond with real welding tests (comparison of molten areas on macro views and registered thermal cycles) as on Figs. 5 and 6. Based on the our experience, main attention was placed on the size and dimensions of the molten area as more efficient in heat source calibration procedure. Differences between the measured and calculated thermal cycles were because of the numerical model do not take into consideration that some of the beads were not welded to the end of specimen due to the macro investigation and hardness measurements (as it was explained earlier). As it was mentioned earlier, in the real experiment, first layer was welded to the end, second to 4/5 of the specimen length, third to the 3/5 etc. It means that in numerical model, total heat input was finally higher.

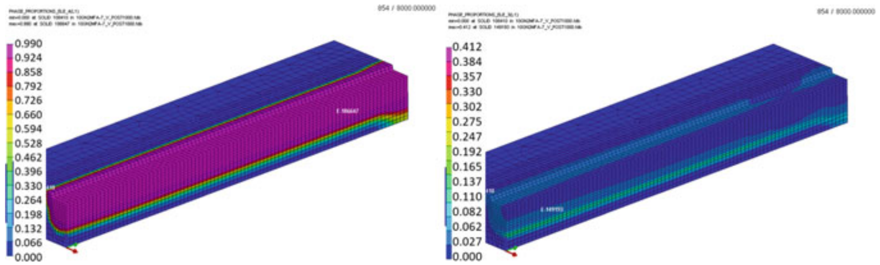


Fig. 7 Calculated bainite and martensite distribution after welding (longitudinal cross section in weld axis)

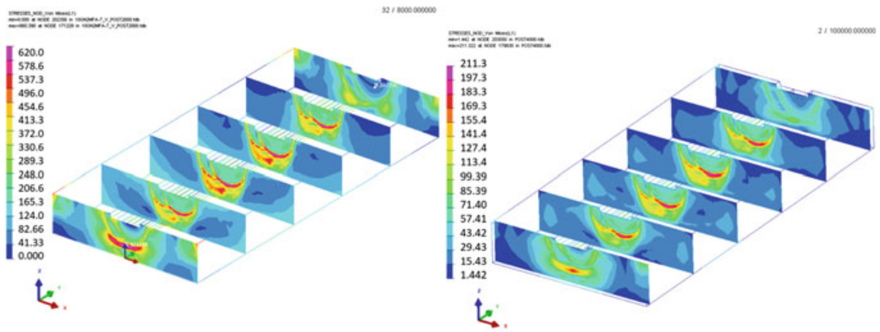


Fig. 8 Cross sections of calculated equivalent stresses (vonMises) distribution after welding (on the left side) and after post weld heat treatment (on the right side)

Metallurgical phases calculation indicates that in the area of weld is almost 100% bainitic structure. In the heat affected zone are present also small areas of martensite, up to the 15%, Fig. 7. Calculated values corresponds with the material properties and provided welding technology, especially used preheating and interpass temperatures.

Numerical analyses of stresses distribution confirms the thermo-metallurgical results. Values of calculated equivalent stresses (vonMises) and cumulative plastic strains are corresponds with used material. Maximal values of equivalent stresses are about 700 MPa which corresponds well with bainitic structure. After post weld heat treatment, values of stresses were decreased on level about 200 MPa. Also cumulative plastic strains values about 8% are acceptable for used base material, Figs. 8 and 9.

As it was written above, also results of hardness are important in this kind of analyses. Hardness on real specimen was measured in horizontal lines on the cross section of specimen on every welded layer. On Fig. 10 was shown as an example, distribution of hardness measured and calculated. Additionally there was presented standard and modified hardness calculation model. In case on 10GN2MFA steel differences are small because due to the chemical composition of welds it is possible to use standard SYSWELD hardness calculation model. In the area of base material these differences are higher. It can be explained with thesis that most of the hardness

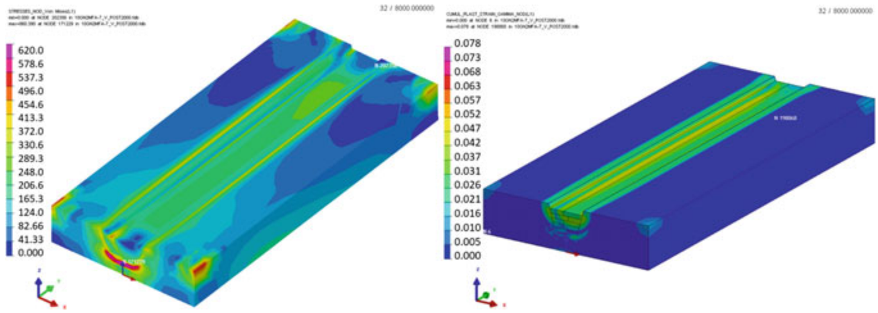


Fig. 9 Calculated equivalent stresses (vonMises) distribution after welding (on the left side) and cumulative plastic strength distribution (on the right side)

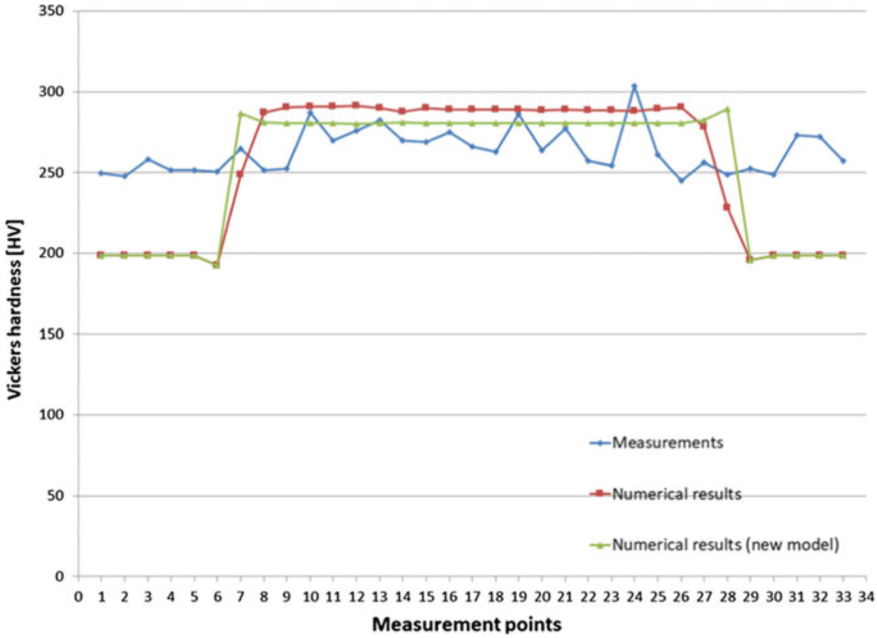


Fig. 10 Comparison of measured and calculated hardness distribution on 4th welded bead

prediction model are calibrated usually for "primary hardened" structures but in this case, base material of 10GN2MFA steel is usually hardened and tempered. And then, in case of primary structure definition for example martensite, values for primary hardened martensite are automatically calculated. In the results high values are calculated. Summarizing, it is recommended to define in every numerical analysis so-called initial hardness value independent on present primary structure [12].

4 Conclusions

Welding experiments are the most frequent method of numerical simulations input or verification data's collection. Aim of this work was to show how to correctly prepare and provide these experiments which are useful during acquiring input data's for numerical simulation of welding with preheating. It is good to provide the experiments for multilayer welds, because of every next bead multiplying eventually inaccuracy of simulation previous layer. Second thing is, that usually after 3 beads it is visible if used numerical model is correct or not. At multilayer welds is questionable mainly hardness calculation after application individual weld runs. New methodology of calculating hardness in SYSWELD results in situation that calculated values are closer to the measured in real tests. Of course it is still needed to improve hardness calculation models, because in the present, commercial simulation software unfortunately there is no exist hardness prediction models for high-alloy martensitic and bainitic steels. It is also very difficult to generally determine the influence of individual alloy elements on substitution reinforcement of solid solution and also precipitations with different thermodynamical stability. Because of it now is developed new equation which will be suitable for hardness calculations on tempering for martensitic and bainitic Cr-steels.

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