APPLICATION OF NUMERICAL SIMULATIONS ON X10CRWMOVNB9-2 STEEL MULTILAYER WELDING

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Creep-resistant martensitic steel X10CrWMoVNb9-2 (P92) is suitable for high-temperature application used in the ultra-supercritical (USC) power plants at temperatures within the limits from 600 to 620°C and pressures about 26 MPa. It is steel alloyed with vanadium and with controlled content of boron and nitrogen. The aim of this paper is to describe how can be optimized welding processes by means of the numerical simulations mainly with respect to the structural changes and hardness in the HAZ. On the real multilayer weld will be described how to arrange whole experiment in order to obtain not only relevant input data but also verification data. 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, X10CrWMoVNb9-2 steel, welding, SYSWELD, hardness prediction

1 INTRODUCTION

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

Coal steam power plants produce nearly 40% of the world electricity. In spite of reality that they belong among the intensive global producers of carbon dioxide emissions, there is a presumption for continuing of their running time in another 30 years [Hald 2010]. This means that every improvement of thermal efficiency in these devices has a strong influence not only on the financial saving for investor but also on the environment.

Presently most popular are supercritical (SC) coal power plants which are works on the temperature range for 540 to 566C and steam pressure up to the 25 MPa. Also very popular are ultra-supercritical (USC) coal power plant. They are works on the temperature range between 580 up to 620°C and steam power max. 28 MPa. Efficiency of typical SC coal power plant is about 46% when the USC achieve efficiency close to the 50% [Abson 2007]. However such improvement of efficiency is limited by the properties of construction materials that are used. Among these materials which have a potential for further improvement of processing parameters are the martensitic 9 – 12% Cr steels. These steels offer a better combination of strength properties, resistance against high-temperature oxidation, low price and good processability [Hald 2010].

One of the most popular material is X10CrWMoVNb 9-2 steel. 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 optimize whole process. Eventually risks associated with unacceptable defects can be 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. That is why in subsequent chapters there will be presented the procedures used at planning and carrying out experiments with regard to the obtaining of relevant data which will enable to define the definition of a double ellipsoidal heat source model. Moreover they will enable subsequent verification of computed temperature fields and hardness of structure.

2 NUMERICAL SIMULATION OF WELDING PROCESS IN SYSWELD

SYSWELD belongs to the most used commercial simulation software for welding and heat treatment processes. The whole process consists of two analyses – the thermo-metallurgical and the mechanical one. The first analysis makes it possible to compute non-stationary temperature fields, phase transformations, hardness or size of the austenitic grain. Mechanical analysis uses the results of the temperature-metallurgical analysis as input data and the most common results here are mainly stress and strain fields.

For the simulation of most fusion welding methods (except laser and electron beam welding) double-ellipsoidal heat source model is used. The heat source (defined as heat flux density into material) is described by equations (1) and (2). Heat source location ξ is expressed by equation (3). The efficiency of the heat transfer into parent material is given by the applied welding method [Moravec 2010]. Geometry of double-ellipsoidal heat source model (also called Goldak's model) can be modified by changing coefficient KX, KY, KZ contained in the equations (1) and (2) [Moravec 2012].

$$q(x,y,\xi)=\frac{6\cdot\sqrt{3}\cdot f_1\cdot Q}{a\cdot b\cdot c\cdot\pi\cdot\sqrt{\pi}}\cdot e^{\frac{-KXx^2}{a^2}}\cdot e^{\frac{-KYy^2}{b^2}}\cdot e^{\frac{-KZ\xi^2}{c^2}} \qquad (1)$$

$$q(x,y,\xi)=\frac{6\cdot\sqrt{3}\cdot f_2\cdot Q}{a\cdot b\cdot d\cdot\pi\cdot\sqrt{\pi}}\cdot e^{\frac{-KXx^2}{a^2}}\cdot e^{\frac{-KYy^2}{b^2}}\cdot e^{\frac{-KZ\xi^2}{d^2}} \qquad (2)$$

$$\xi = z_k - v(\tau - t) \qquad (3)$$

q(x,y, ξ) - Thermal flow density into the material (W.m-3)
Q - Total source power (W)
a, b, c, d - Parameters of the melting area (m)
ξ - Source location depending on the welding time (m)
x, y, z - Point coordinates (m)
f_1, f_2 - Constants which influence energy flow intensity into the material (-)
τ - Total welding time (s)
t - Immediate welding time (s)
v - Welding rate (m.s-1)
z_k - Z axis coordinate when concluding welding (m)

For hardness and stresses calculations, first we need 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 is not only to define the geometry of every weld (including necessary welding parameters used in process) but also to determine hardness changes in parent material, HAZ and in the weld at application of 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 by technological parameters (preheating, interpass temperature) but also by the way of thermal radiation into surrounding. For the possibilities of beads geometry and HAZ areas examinations, beads were moved each other – shown at Figure 1. At the Fig. 1, there are also shown holes for the thermocouples dedicated to the monitoring process of temperature field and preheating temperature. 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. Description of the boundary conditions is presented via description of experiment itself in the chapter 3.

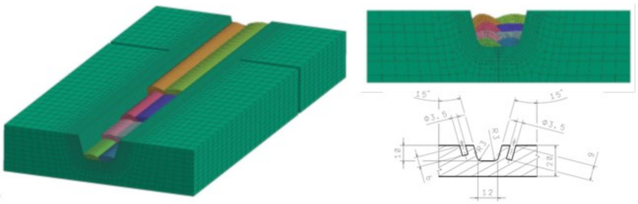

Figure 1. 3D discrete model of weld created on the basis of real experiment

3 REALIZATION OF THE WELDING EXPERIMENT ON X10CRWMOVNB 9-2 STEEL SPECIMENS

X10CrWMoVNb 9-2 steel is a steel from group of martensite steels with chromium content for 9 to 12%. This grade of steel (9% Cr, 1,75% W, 0,5% Mo) refers to steel alloys incorporating vanadium and niobium with controlled amount of boron and nitrogen. Developed by Nippon Steel Corporation industry, at the beginning was signed with NF 616 designation. According to ASTM standards of X10CrWMoVNb 9-2 steel designation is P92 [Moravec 2013].

P92 steel is modification of the P91 steel by alloying 1.7 wt% of tungsten which results in the solid solution substitutional strengthening that increases its thermal strength [Svobodova 2009]. Another creep resistance increase is achieved by alloying the nitrogen and also by precipitation the vanadium nitride inside the grain. Micro-structural stability of this steel is positively influenced by the low coarse rate of the $M_{23}C_6$ grains which is closely associated with the boron atoms solution in the given phase. That is because during the creep loading there is growth and subsequently also coarsening of these particles. The coarse rate of the $M_{23}C_6$ carbides increases by the increasing chromium content in the steels. Moreover, under the temperature exposition there is also precipitation of the Laves phase rich in W and Mo [Svobodova 2009].

Table 1 present results of Tasman Q4 test of chemical composition of P92 steel specimens used in the experiments.

Table 1. Chemical composition of X10CrWMoVNb9-2 steel tested on Tasman Q4 spectrometer

	C	Mn	Si	P	W
[wt.%]	0,101	0,409	0,246	0,023	1,688
	Cr	Mo	Nb	V	N
[wt.%]	8,939	0,429	0,055	0,193	0,057

These types of steel are produced for using in USC coal power plant equipment. They are very often used on elements of steam systems working on combined cycles. It is because of high thermal stability and thermal fatigue resistance during heating and cooling [Hayashi 1998]. High amount of chromium and others alloying elements moves CCT diagram curves into longer cooling times and results in fact that thicker elements made from this grades of steel are hardenable also in the air. Mechanical properties of these steels are also good in ambient and working temperatures, Table 2.

Table 2. X10CrWMoVNb9-2 steel base mechanical properties

Yield strength Rp0,2 at 20°C [MPa]	Yield strength Rp0,2 at 650°C [MPa]	Tensile strength Rm at 20°C [MPa]	Elongation A5 at 20°C [%]	Impact strength 20°C [J]
≥ 440	248	620 – 850	≥ 19	40

These steels are self-hardening so that prior to welding, preheating must be used and interpass temperature needs to be checked. There are two possible welding methods – welding in the austenite zone with preheating up to Ms temperature or welding in the martensite zone with preheating at approximately 250°C. At lower preheating temperatures origin in the weld and also in HAZ enormous internal stresses which can result in cracks initiation. Nevertheless for the verification of the computational model is suitable to achieve boundary material properties values. That is why for the experiment it was used the second technology variant – welding in the martensite zone with the preheating temperature of 250°C and the interpass temperature of 300°C.

Time demands of such experiment is quite high because of higher number of runs and also for requirement to comply interpass temperature. For this reason a welding jig was made (see Fig. 2) whose supporting structure consists of 50 mm thick cast iron plate which is able to transfer heat to the tested specimen during the duration of the test. Moreover this plate is equipped with grips to fix welded part. Due to that there is possible to accurately define place and clamping stiffness – thus relevant simulation computation boundary condition.

Figure 2. Welding jig with clamped specimen during heating in the furnace (on the left) and isolated during welding (on the right)

Clamped specimen with added thermocouples was preheated in the furnace at temperature 270°C with heating rate 1C.min-^{1} and subsequent hold on that temperature for 520 min. After this operation, preheated jig with specimen was placed into isolation mineral wave (Fig. 2). For all heating and holding time, and welding process was recorded temperature by all thermocouples. Welding was carried out by MMAW method with filler material Thermanit MTS 616 – diameter 2,5 mm, Table 3. [Havelka 2014]

Table 3. Chemical composition of Thermanit MTS 616 electrodes

	C	Mn	Si	W	V
[wt.%]	0,11	0,6	0,2	1,6	0,2
	N	Nb	Ni	Cr	Mo
[wt.%]	0,05	0,05	0,7	8,8	0,5

Complete specimen was welded by 8 beads in 4 layer, where two beads were placed side-by-side in each layer. Thus there is temperature influence both within the one layer and between layers mutually. In order to determine the geometry of individual layers metalographically, every subsequent layer has its origin offset by 25 mm towards the previous layer. All process was completely monitored by the WeldMonitor system and all information's about the relevant processes parameters are available. In Table 4 there are summarized values of welding parameters including information about preheating and interpass temperature. The initial structure of the X10CrWMoVNb9-2 steel corresponded to the high tempered martensitic phase with the initial hardness of 248 HV.

Table 4. Measured process and technological values for individual runs

Number of bead	Eff. current [A]	Eff. voltage [V]	Weld. rate [m.min^{-1}]	Introduced heat [kJ.cm^{-1}]	Pre-heat. temp.[°C]	Interpass temp. min. [°C]	Interpass temp. max. [°C]
Run 1	88,8	24,2	0,135	9,889	271	279	296
Run 2	88,6	24,6	0,153	8,547	269	273	289
Run 3	83,7	24,3	0,133	9,176	268	271	287
Run 4	83,8	24,3	0,145	8,426	270	274	292
Run 5	83,7	24,5	0,141	8,726	268	276	295
Run 6	83,7	23,8	0,121	9,878	267	270	291
Run 7	83,9	24,0	0,147	8,219	268	271	288
Run 8	83,6	24,3	0,140	8,706	266	Air free cooling	

After finishing welding process the isolation wrapper was removed because of cooling. Under the temperature 100°C the part of the tested specimen in the groove zone (Fig. 1) was separated. This separated part was heated again the furnace to the tempering temperature of 760°C, by using: 3°C.min^{-1} heating rate, holding at temperature for 120 min and subsequent slow cooling in own. Cooling rate at value 3°C.min^{-1} was hold to the temperature 300°C and then specimen was cooled to the ambient temperature on the free air. The rest of the weld was already freely cooled down in air from the temperature of 100°C. Thanks to that, for the next examinations we obtain specimens after each bead welding (alternatively both beads in each layer) and also specimen after welding and heat treatment as well.

4 METALLOGRAPHIC EVALUATION AND HARDNESS MEASUREMENT

Weld was in the relevant places which corresponded to the individual layers cut up and metalographically evaluated as is shown at Figure 3. The determined geometrical dimensions, which were necessary to define Goldak´s heat source model, are shown in the Table 3. For numerical computation were used coefficients values of KX = KY = KZ = 3. [Yaghi 2009]

In order to obtain geometrical dimensions of thermally non-treated and thermally treated specimens, hardness HV 10 was measured. The distance between centers of the individual sticks was 1 mm.

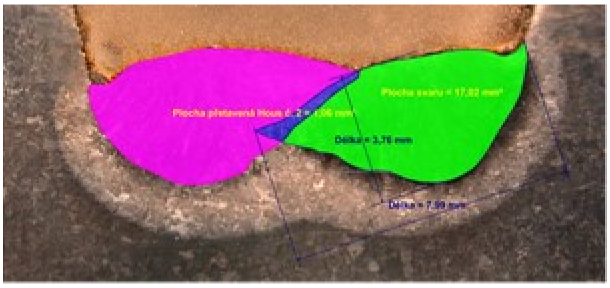

Figure 3. Metallographic and geometrical evaluation of Run 1

Table 5. Metalographically determined geometrical dimensions to define Goldak´s model

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
g	3.76	3.86	3.48	3.67	3.43	4.02	3.58
W	7.99	7.63	7.25	7.32	7.77	9.83	7.60
A	18.1	19.3	17.9	19.6	17.9	26.2	20.4

Remarks: g – weld penetration depth [mm], W – welding pool width [mm], A – total area of weld [mm^2]

Hardness was measured from the parent material across HAZ to filler metal and then again across HAZ always to the parent material. All rows of sticks was on the individual scratch patterns made always in the same place so that was possible to monitor influence of individual runs thermal cycles on the change of hardness in relevant places. There could have been described influence of such thermal treatment on the final hardness of structure by hardness measurement in the tempered part of weld. Totally were measured 6 rows of sticks. Row 1 was placed across not HAZ and row 2 goes through HAZ on a lower edge of runs 1 and 2 as is shown for first four beads at Figure 4. Row 3 goes through the first weld metal layer and then every subsequent row had offset by 2 mm. Figure 5 shows measured hardness course for Row 3 for each welded beads and also after post-weld heat treatment.

Figure 4. Rows of hardness measuring sticks for first two weld layers

Numerically calculated structural analysis which was carried out on the basis of temperature fields calculations by means of Goldak´s model detected martensite structure with low portion of bainite – mainly in HAZ [Slovacek 2012]. For hardness calculation after welding were used equations (4), (5) and (6). Equation (4) was used for hardness calculation of the martensitic phase and for hardness calculation of the bainitic phase was used equitation (2). For hardness calculation after tempering of the martensite, equitation's (6) and (7) were used [Kik 2013]. Symbol v_r stands cooling rate [°C.s^{-1}], p is tempering parameter given by tempering temperature T_p [°C], change of activation energy is stand ΔH [J.kg^{-1}], tempering time is tp [s] and R [J.mol^{-1}.K^{-1}] is gas constant.

$$HVM = 127 + 949\,C + 27\,Si + 11\,Mn + 8\,Ni + \\ + 16\,Cr + 21Log10(V_r) \qquad (4)$$

$$\mathrm{HVB} = -323 + 185\,\mathrm{C} + 330\,\mathrm{Si} + 153\,\mathrm{Mn} + 65\,\mathrm{Ni} + 144\,\mathrm{Cr} + 191\,\mathrm{Mo} + \mathrm{Log10}(V_r) * (89 + 53\,\mathrm{C} - 55\,\mathrm{Si} - 22\,\mathrm{Mn} - 10\,\mathrm{Ni} - 20\,\mathrm{Cr} - 33\,\mathrm{Mo}) \tag{5}$$

$$\mathrm{HVTemp} = -74 - 434\mathrm{C} - 368\,\mathrm{Si} + 15\,\mathrm{Mn} + 37\,\mathrm{Ni} + 17\,\mathrm{Cr} - 335\,\mathrm{Mo} - 2235\,\mathrm{V} + (103/p) * (260 + 616\,\mathrm{C} + 321\,\mathrm{Si} - 21\,\mathrm{Mn} - 35\,\mathrm{Ni} - 11\,\mathrm{Cr} + 352\,\mathrm{Mo} + 2345\,\mathrm{V}) \tag{6}$$

$$p = \left(\frac{1}{T_p} - \frac{R}{\Delta H} \cdot \ln t_p\right)^{-1} \tag{7}$$

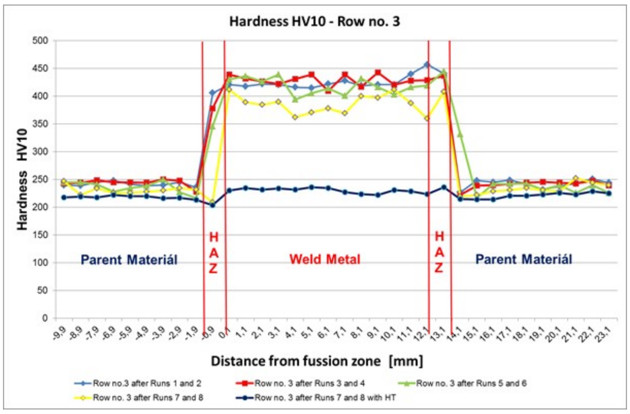

Figure 4. Hardness course of Row 3 placed in the level of lower edge of groove for individual weld layers and after post-weld heat treatment

5 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 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 do 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 no. At multilayer welds is questionable mainly hardness calculation after application individual weld runs. The described way of carrying out experiment eliminates such disadvantages into great extent and makes possible to optimize hardness computational model both by verification cooling rate in the relevant places by Eq. 4 and Eq. 5 and by change of tempering parameter 'p' in the case of tempering. From obtained metallographic scratch patterns it is also possible to verify results of structural analysis and suitability of used structural model. As a great advantage there is also constantness of boundary conditions during the duration of whole experiment.

Results of welding numerical simulations presented in this work, found that it is possible to use equations (4) and (5) for hardness calculations of X10CrWMoVNb 9-2 steel, even that the chemical composition just above the range of their applications range.

Maximal differences between numerical simulation results and real test in hardness measurements was not higher than 8%. From the tempering equation (6) there was not achieved satisfying results. Calculated hardness values after tempering were up to 58 HV lower than measured. This inaccuracy can be of course partially modified by changing tempering parameters but still the results are significantly different. At present, for 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 (5) 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. This equation taking into consideration mainly structure hardness before tempering, influence of tempering temperature and heating time [Richter 2013].

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