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Investigation of Heat Affected Zone of Steel P92 Using the Thermal Cycle Simulator

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Abstract**—**This work is focused on mechanical properties and microstructure of heat affected zone (HAZ) of steel P92. The thermal cycle simulator was used for modeling a fine grained zone of HAZ. Hardness and impact toughness were measured on simulated samples. Microstructural analysis using optical microscopy was performed on selected samples. Achieved results were compared with the values of a real welded joint. The thermal cycle simulator allows transferring the properties of very small HAZ to the sufficiently large sample where the tests of the mechanical properties can be performed. A satisfactory accordance was found when comparing the microstructure and mechanical properties of real welds and simulated samples.

Keywords**—**Heat affected zone, impact test, thermal cycle simulator and time of tempering.

I. Introduction

In power plant, great efficiency means a saving in fuel and less emissions of carbon dioxide in a given electricity output, which consequentially reduces the rate of the global environment damage. Increasing of the maximum operating pressure and temperature leads to improvement of steam turbine efficiency [1]. That is why there is tendency that operating parameters become much higher to promote efficiency [1]. Pressure exceeding 260 bar and temperature around 600 °C are called as super-critical parameters, pressure over 300 bar and temperature over 600 °C are called ultra-super-critical (USC) parameters [2].

Due to USC parameters, great attention is paid to the development of modified 9-12% Cr steels with creep resistant strength higher than 100 MPa (at 600 °C and 10^5 hours) [3]. Steel P92 is currently considered as one of the best modified chromium steel grades as far as creep resistant strength (CRS) is concerned.

Initial estimates of creep rupture strength of grade P92 were about 190 MPa at 600 °C for 100,000 hours. However, these results were based on short-term creep tests [4]. Detailed analysis of the extensive files of creep data then resulted in the gradual lowering of creep rupture strength [5] and the recent values based on long-term creep tests show that the CRS of this steel lies between 110 and 120 MPa [6], which is however still high value in comparison to other chromium modified steels.

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Critical parts of USC boilers are welded joints. Especially the HAZ appears to be the weakest point in terms of creep resistance. This significantly affects the operational reliability and service life of components in USC blocks. Therefore, this work is focused just on research of properties of HAZ of P92 steel.

II. Experimental Procedure

Analysis of mechanical properties of the HAZ was performed on 16 samples of steel P92 with dimensions 10x10x100 mm. Chemical composition of base material is indicated in Table I. Temperature cycles were simulated on prepared samples using the thermal cycle simulator, see Fig. 1.

Fig. 1 The thermal cycle simulator

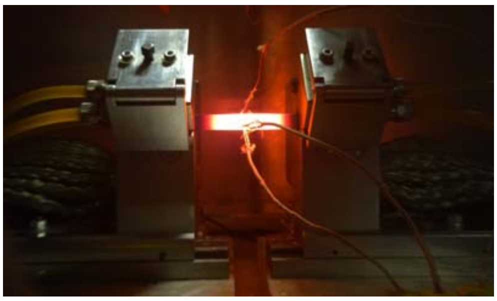

Fig. 2 Sample with thermocouples during heating

TABLE I
CHEMICAL COMPOSITION OF BASE MATERIAL – STEEL P92, WT%

C	Mn	Si	Cr	W	Mo
0.109	0.44	0.30	8.86	1.69	0.404
V	Nb	N	B	P	S
0.191	0.049	0.048	0.0033	0.016	0.0026

A heated up sample during the simulation of the temperature cycle is shown in Fig. 2. Experiments on a simulator were preceded by the measurement of temperature cycles of the single layer welded joint of steel P92. The measured temperature cycle during TIG welding of steel P92 and the corresponding simulated temperature cycle are compared in Fig. 3.

The simulated treatment consisted of:

- Thermal cycle simulation of TIG welding modelling fine grained zone with max. temperature of 1060 °C.
- Tempering at 760 °C with a holding time for 1 hour, 3 hours and 4 hours.

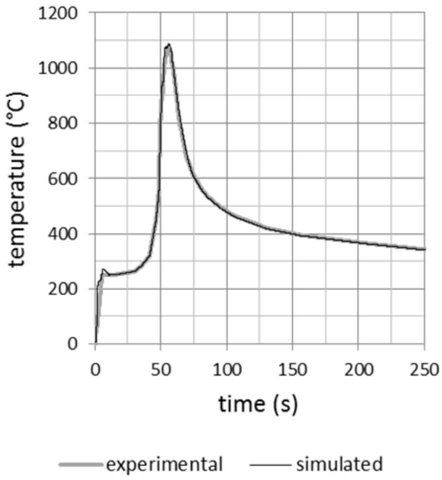

Fig. 3 Real and simulated welding thermal cycle

III. Results

Hardness, impact toughness measurement and microstructural analysis were carried out on simulated samples. Measurements were performed at + 20 °C.

Standard EN 10216-2 specifies the minimum value of the impact energy 27 J at + 20 °C in the transverse direction [6]. The experimental results confirmed that this material cannot fulfil this request after the simulation of welding cycle itself, without subsequent tempering. Average values of impact energy are graphically depicted in Fig. 4 showing a similar trend of the impact energy values in simulated samples and real welds. A significant difference is observed in the initial state without PWHT. In a real weld, the impact values are significantly higher (41 J versus 13 J). However, it should be emphasized that the test result is highly dependent on the location of the notch. In a real welded joint, it is nearly impossible to place a notch accurately in the fine grained zone of HAZ. Individual HAZs are of very small dimensions, they are hardly distinguishable, and moreover they can intersect each other.

The location of the notch in the HAZ of simulated sample is always with a great certainty. Therefore, the results measured on the simulated sample are more relevant than measurement on real welded joint.

Evaluation of properties of modeled HAZs was accompanied also by hardness measurements. Five HV 10 measurements were performed randomly in the HAZ of each simulated sample from thermal cycle simulator. The results of individual measurements and their average values for each sample are presented in Table II. In graphical form, the results are shown in Fig. 5.

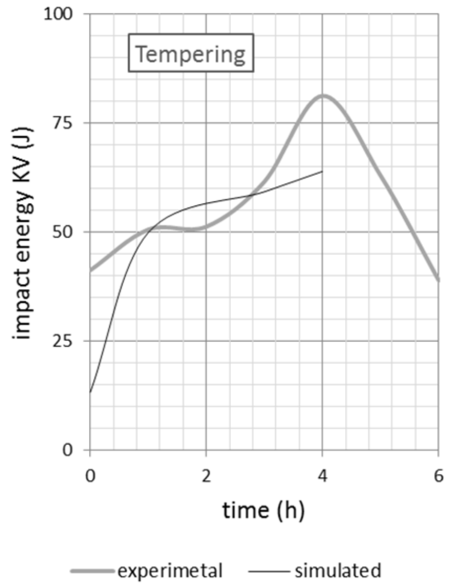

Fig. 4 Comparison of impact energy values of real and simulated weld joint samples

TABLE II
Results of Hardness Test of Simulated HAZ

Sample No.	Simulated heat regime	Hardness HV 10					
		1	2	3	4	5	Average value
1	1060 °C/30 s	431	464	441	446	431	443
5	1060 °C/30 s + 760 °C/1 hour	227	228	224	229	227	227
9	1060 °C/30 s + 760 °C/3 hours	209	218	214	219	224	217
14	1060 °C/30 s + 760 °C/4 hours	201	195	204	213	208	204

The results of the hardness measurements show that tempering reduces the initial hardness level of about 450 HV to the values between 200 and 230 HV. With increasing time of tempering, hardness decreases, although this decrease is very slight.

Fig. 5 shows a comparison of the hardness in HAZ between the real weld joint welded by TIG and samples with simulated thermal cycles (fine grained zone). The measured results show good agreement.

The microstructural analysis using optical microscope was also carried out on the samples for hardness measurement. Metallographic sections were prepared in the plane perpendicular to the long axis of the sample.

The microstructure of the sample heated up to 1060 °C without tempering (sample 1) is shown in Figs. 6 and 7. It consists of lath martensite with a high proportion of small, generally globular or elongated particles of δ-ferrite. The formation of δ-ferrite was facilitated around the coarse particles of carbides, presented in particular at the original austenite grain boundaries. These carbides were partially dissolved during austenitization and the surrounding matrix was enriched by the ferrite forming elements (Cr, Mo), which lead to the δ-ferrite stabilizing around these particles.

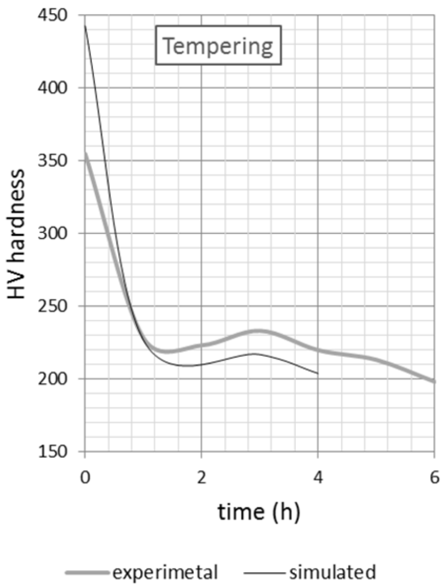

Fig. 5 Comparison of hardness values of real and simulated weld joint samples

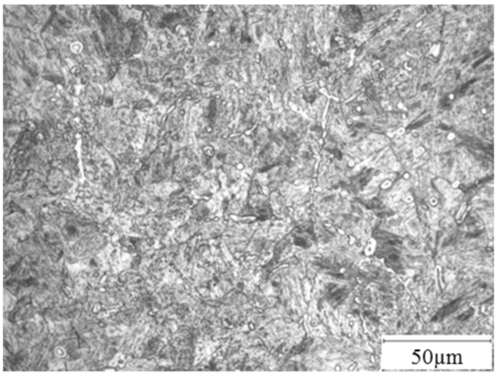

Fig. 6 Microstructure of the sample (1060 °C/30 s without tempering)

After tempering at 760 °C for 1 hour (sample 5), the microstructure consisted of heavily tempered martensite and particles of secondary precipitates along original grain boundaries of austenite and inside large particles of δ-ferrite, see Figs. 8 and 9. Finer and dispersed particles were observed also inside grains.

The special situation developed around the original particles of $M_{23}C_6$ carbides that were not dissolved during austenitization. Clouds of fine carbides appeared inside particles of δ-ferrite due to lowering of carbon solubility during tempering. At the same time, some larger particles formed at the martensite-δ-ferrite interface. These particles have exhausted the adjacent areas of carbon and carbide-forming elements (Fig. 9).

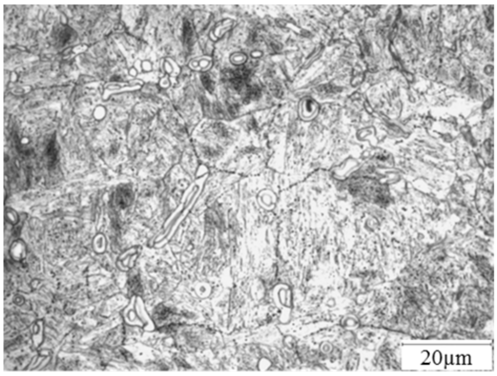

Fig. 7 Detail of microstructure of the sample 1 (1060 °C/30 s without tempering)

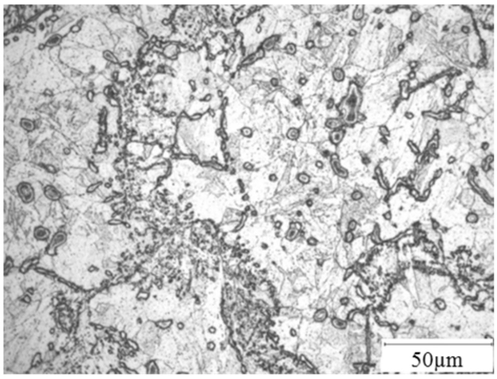

Fig. 8 Microstructure of the sample 5 (1060 °C/30 s+760 °C/1 h)

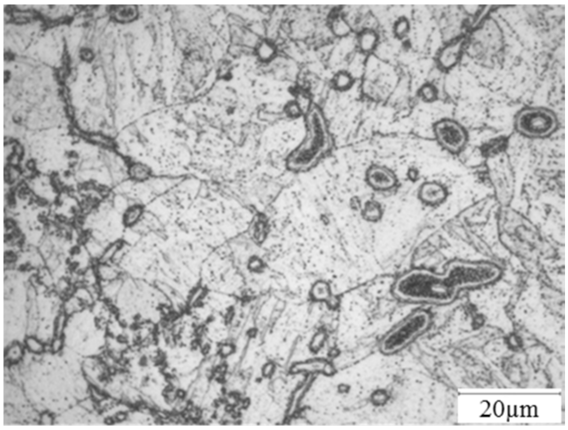

Fig. 9 Detail of microstructure of the sample 5 (1060 °C/30 s+760 °C/1 h)

The microstructure of samples after three and four hours at tempering temperature did not change significantly (see Figs. 10 and 11).

With increasing holding time, the only detectable change was gradual disappearing of fine precipitates inside particles of δ-ferrite that probably dissolved at the expense of larger particles on the δ-ferrite - martensite interface.

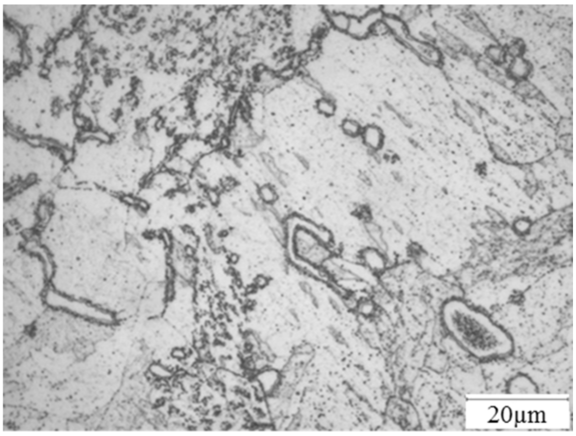

Fig. 10 Detail of microstructure of the sample 9
(1060 °C/30 s+760 °C/3 h)

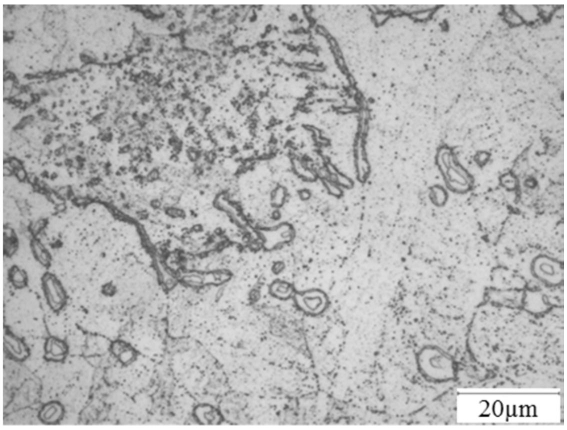

Fig. 11 Detail of microstructure of the sample 14
(1060 °C/30 s+760 °C/4 h)

IV. Conclusions

This work includes a comparison of mechanical properties and microstructure of HAZ of P92 real welded joints made by TIG method and samples with simulated temperature cycles. Achieved results show relatively good agreement. Use of the thermal cycle simulator brings a highly accurate, repeatable result and seems to be promising method how to investigate properties and microstructure of the HAZ.

The as-welded state, i.e. without tempering is not acceptable for very low level of impact energy and high hardness. Extending the tempering time from one to four hours has fairly little influence on hardness values. Hardness decreases from approx. 230 HV to about 205 HV. Prolonged time of tempering seems to be significant for increasing the impact toughness values.

The most striking feature of the microstructure of analyzed samples is an atypical network of δ-ferrite particles, which were found especially along the original austenitic grain boundaries. Inside these areas carbide particles were observed. This quite clearly indicates the fact that the time of austenitizing during temperature cycle at 1060 °C is not sufficient to dissolve all carbides present on grain boundaries. The favourable conditions for the nucleation of δ-ferrite then result from the increased concentrations of ferrite-forming elements, mainly chromium and molybdenum, in the immediate vicinity of these undissolved carbide particles.

Acknowledgment

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