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INFLUENCE OF THE ANNEALING TIME AFTER WELDING ON THE MECHANICAL PROPERTIES OF WELDED JOINT OF T91 STEEL

The paper presents the results of research on the influence of the time of annealing after welding at the temperature of 750°C on the mechanical properties of a homogeneous welded joint of T91 steel. The welded joints were annealed at 750°C for 0.5; 1.0; 1.5 and 2.0 hours. The research scope included the basic study, i.e. the measurement of hardness, the test of impact energy, the static tensile test, bending test, as well as the accelerated creep test. The results of the tests of mechanical properties indicate the possibility of using shorter annealing times for thin-walled welded joints, and thus the possibility of savings as a result of flexible heat treatments.

Keywords: T91 steel, post welded heat treatment, mechanical properties

1. Introduction

Modern steels for work at elevated temperature, called creep-resisting steels of new generation, as well as the nickel-based alloys – of the Inconel type enable constructing power units of supercritical and ultra-supercritical parameters of steam, but also they are used when performing the modernization works on pressure elements of power units of subcritical parameters, serviced so far [1, 2]. These installations enable not only a considerable growth of the thermal efficiency of power units, but also, combined with other appliances, a radical reduction of the emission of CO_2, SO_2, NO_X [3]. The currently used creep-resisting steels and alloys include the ones that have been used for around 20 years, as well as the new ones or those planned to be introduced [2]. The first group includes P91 steel introduced into the power industry in the 1990s, mostly as the material for hot-rolled pipes without a seam. From then on, the steel can be subject to observations and investigations in terms of service [4].

Regardless of the tests on modern alloys and their joints implemented already, there is still an ongoing search for the new welding technologies and an improvement of the existing ones [5, 6, 7]. It is known that obtaining high strength properties of joints involves controlling the amount of heat supplied during welding and applying the proper heat treatment before, during, and after welding [8, 9, 10].

Previous publications, inter alia [1, 3, 6, 8, 11, 12], mostly cover homogeneous and heterogeneous pipe joints with T91 steel, particularly the thick-walled ones whose weld thermal cycles significantly differ from those used during the welding of pipes of small diameters and thickness of walls. It is significant because the extent to which the conditions of welding determine the changes in the joints morphology, including the precipitation processes, and in consequence obtaining different mechanical properties of joints (including impact energy), is greater than in the case of heat treatment [6, 8, 9].

The research described in this work is a complement of previous works, inter alia [1, 3, 5, 11÷15], with the joints made on the thin-walled pipes, and indicate a relatively easy possibility of receiving full welded joints by way of combining proper welding technologies and postweld heat treatment.

2. Examined material

The material for research was welded joints of the diameter amounting to 63.5 mm and the wall thickness of 4.5 mm, made of X10CrMoVNb9-1 (T91) steel of the chemical composition presented in table 1.

TABLE 1

Chemical composition of X10CrMoVNb9-1 (T91) steel, % mass

C	Mn	Si	P	S	Cr	Mo	V	Nb	N
0.15	0.50	0.41	0.017	0.005	8.39	0.95	0.17	0.07	0.051

The analysis of chemical composition of T91 steel showed a slight excess of the maximum amount of carbon (including the allowable deviation of 0.01%C set by the standard [16]) compared with the requirements of PN-EN 10216 – 2 [16] standard, which could result in a greater difficulty in obtaining the joints, and particularly welds of the required plasticity and impact energy.

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In the as-received state, the examined steel was characterized by a microstructure typical for this grade of steel, that is tempered martensite with retained lath structure and numerous precipitations observed not only on the boundaries of grains of prior austenite, but also on the boundaries of laths and inside martensite laths (Fig. 1).
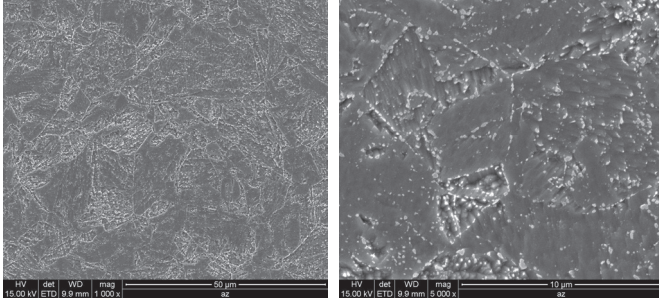

Fig. 1. Microstructure of T91 steel in the as-received state – native material

3. Methodology of research

The joints were made by bonding the pipes by method 141 (TIG), using a wire of the ER90S-B9 type as an additional material (W CrMo91 according to ISO 21952 [17]). The diameter of the wire was 2.5 mm, and the welding parameters were as follows: current intensity 100 A, of electrode negative, and voltage 15 V. Preheating was not used, and the welding was performed continuously.

Obtained joints were subject to diverse heat treatment of the following parameters of temperature and time:
- joint marked with No. 1 – holding time of 0.5 hours/ temperature 750°C;
- joint marked with No. 2 – holding time of 1.0 hours/ temperature 750°C;
- joint marked with No. 3 – holding time of 1.5 hours/ temperature750°C;
- joint marked with No. 4 – holding time of 2.0 hours/ temperature 750°C.

The aim of these treatments was to verify if short times of annealing at the temperature of 750°C are sufficient to obtain joints with the properties that meet any output service requirements with reference to standards, both the material ones and those qualifying the technology. The welded joint without any heat treatment was also investigated.

The tests of welded joints included: macro– and microscopic tests, static test of tension, hardness measurement, bend test, impact energy test and short-term creep test. The macro– and microscopic tests were carried out on metallographic specimens etched with ferrous chloride. The microscopic tests were performed using a scanning electron microscope Inspect F. The static test of tension was carried out by means of a testing machine Zwick/Roell Z100 on the A-type test samples – without a narrowing in the weld. The measurement of the joint hardness was made by the Vickers method, using the indenter load of 10 kG (98.1N) and the hardness tester Future – Tech FV-700. Bend tests with tension of the face and root of the weld were performed using an arbor with its diameter amounting to 18.9 mm. Impact energy of the joints was determined on non-standard test samples of the width reduced to 2.5 mm. Mechanical properties of the joints were tested according to the recommendations of relevant standards. Creep tests were carried out in the single-specimen creep-testing machines with temperature accuracy during the test ±10°C, in the range of 550-700°C. Shortening the time of tests was achieved by performing the tests in the range of temperatures higher than the expected service, i.e.: 620, 640, 660 and 680°C, and with the stress during the test amounting to 100 MPa. Such a way of running creep tests was verified on the basis of long-term creep tests, and the results of the tests were the subject of numerous publications e. g. [18, 19].

4. Research results

Microstructural tests

The tests of microstructure revealed no presence of microcracks and confirmed the correct structure of particular phases of the welded joint of T91 steel without any significant welding nonconformities for all variants assumed in the experiment. An example of macroscopic image of welded joint is presented in Fig. 2.
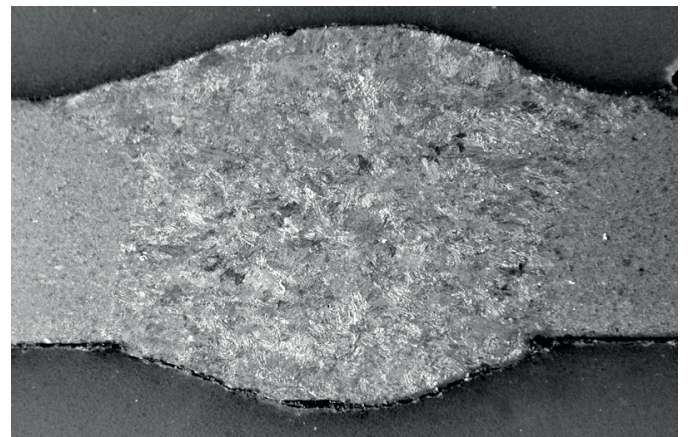

Fig. 2. Macrostructure of welded joint after 1.5 hour of annealing at the temperature of 750°C

The microstructure of heat-affected zone (HAZ) (Fig. 3, 4) was a microstructure of high-tempered martensite, of diverse morphology and amount of precipitated carbide particles. In places, the amount of carbides precipitated on the boundaries of prior austenite grain was so large that they formed the so-called continuous grid of precipitates. The relative amount and size of precipitates was the biggest in the joint subject to 2-hour annealing at the temperature of 750°C.
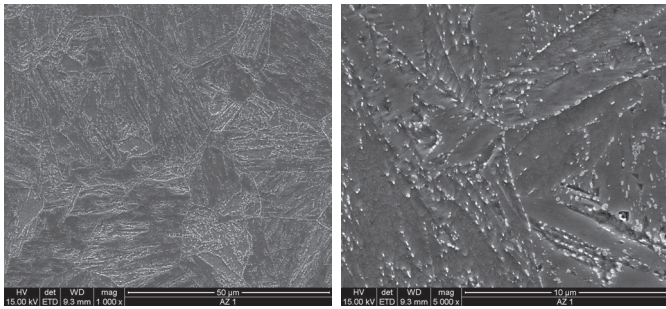
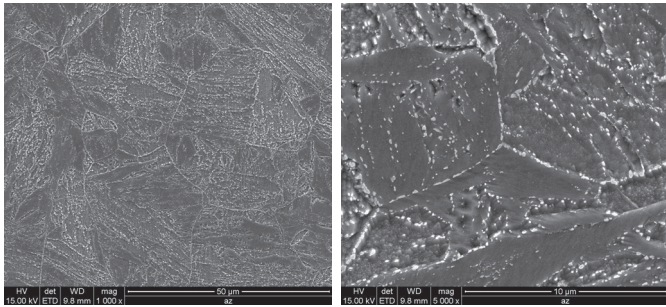Fig. 3. Microstructure in the HAZ after 0.5 hour of annealing at 750°C

Fig. 4. Microstructure in the HAZ after 2 hours of annealing at the 750°C

5. Mechanical properties of the joints

The tests of mechanical properties of the joints constitute one of the basic criteria of assessment of their quality and the heat treatment after welding. This knowledge also allows comparing the properties of the obtained material with the base material. The minimum required properties of T91 steel determined at room temperature are presented in Table 2.

TABLE 2

Required mechanical properties of T91 steel in the as-received state [16]

YS	TS	El.	KV
MPa	MPa	%	J
min. 450	min. 630	min. 17	min. 27

The results obtained in the tensile test (Fig. 5) prove the lack of change in the static tensile strength as a result of the applied heat treatments, which is consistent with the declared parameters of T91 steel [16]. The rupture of the samples always occurred in the native material regardless of the heat treatment parameters. Also in the case of the welded joint without heat treatment, the rupture occurred in the native material. The performed tests of tensile strength of the welded joints showed that, irrespective of the applied parameters of heat treatment, the strength of the joints was higher than the value required for the native material, i.e. 630 MPa. Whereas the properties of the native material of T91 steel were at the following level: YS = 492 MPa, TS = 673 MPa, El. = 22%, RA = 58%. The properties of the native material were higher than the required minimum for this grade of steel – see Table 2.
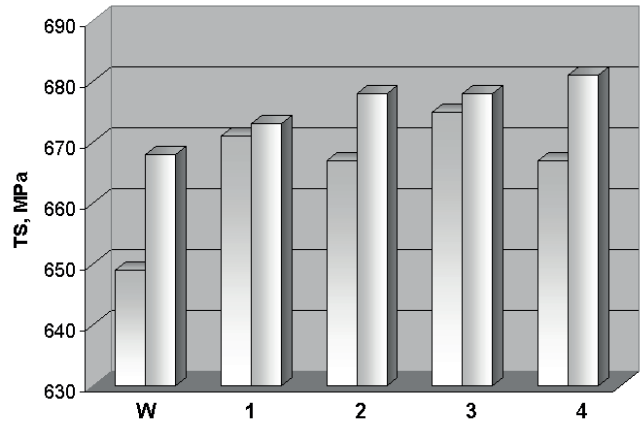

Fig. 5. Tensile strength of the joint: w – after welding and after heat treatment: 1 – 0.5 h, 2 – 1.0 h; 3 – 1.5 h; 4 – 2.0 h

The tests of bending of the joints proved that in each case (that is, when stretching the face an the root of the weld), the obtained bending angles amounted to 180°, without scratches and cracks on the surfaces being stretched. Thus for all the applied versions of heat treatment after welding and for the joint without treatment, the tests results were positive. However, the joint without heat treatment showed lower deformability in the weld zone.

Hardness pattern in the joint cross-section for various heat treatment variants after welding is shown in Fig. 6.
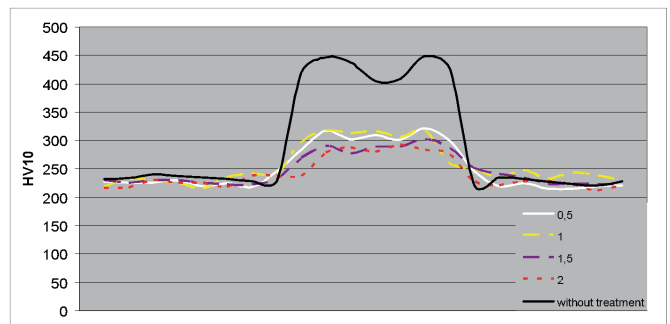

Fig. 6. Changes in hardness HV10 in the cross-section of the joint depending on the parameters of heat treatment after welding

The joint without heat treatment was characterized by unacceptably high hardness at a level of around 450 HV10, definitely exceeding the allowed value of 350 HV. The hardness value of 350 HV is a conventional limiting value above which the joints show the cold cracking susceptibility. The heat treatment of joints, regardless of the annealing time, influenced the decrease in the level of maximum hardness, and resulted in the attenuation of hardness gradients in the joint cross-section (Fig. 6). It results from the operation of tempering of the weld and the accompanying process of matrix softening [8, 9]. Moreover, a relatively small, expected, and acceptable growth of hardness was observed in the weld and in its zone after each of the applied heat treatments. Obtained results prove the

necessity of performing postweld heat treatment of joints made of thin-walled T91 steel, as well as the sufficiency of the minimum application of holding time – 0.5 h.

Performed tests of impact energy of the investigated joints showed low and insufficient (at a level of 7 J) impact energy of the weld without treatment, whereas the crack resistance of the HAZ was high (Table 3).

TABLE 3

Results of tests of impact energy of welded pipe joints

Test sample marking	KV 300/2.5 J	KCV 300/2.5 J/cm²	KVc*
As-received state - MR	25	127	101
After welding_s	7	35	28
After welding_p	24	120	96
1s	17	87	69
2s	17	87	69
3s	19	93	75
4s	19	93	77
1p	22	112	89
2p	19	90	77
3p	18	92	73
4p	31	153	123

* – the value of impact energy calculated from the relation $KV_c = (10 \times KV_p)/w$; KV_p – the value of impact energy obtained on non-standard test sample; J, w – width of non-standard test sample; mm [16], s – notch cut in the weld, p – notch cut in the HAZ

The tests of impact energy of the heat-treated joints after direct calculation – in proportion to the surface areas, gave the results on a high level, both for the welds (impact energy in the range of 87 ÷ 93 J/cm²) and for the HAZ (90 ÷ 153 J/cm²). The values of impact energy determined for the weld and HAZ of the welded joint do not differ much from the impact energy of the native material, which amounted to 127 J/cm².

Short-term creep tests

The creep tests were carried out for the welded joints no. 2 and 4, i.e. annealed after welding for 1.0 and 2.0 hours at the temperature of 750°C. The results of creep tests are presented graphically as a relation: $\log t_r = f(T_b)$, with the use of stress of the test $\sigma_b = const$ (Fig. 7). The time to rupture with reference to the temperature and stress of the test is given in Table 4. All test samples in the creep tests ruptured around 4-5 mm from the weld line in the base material of T91 steel.

TABLE 4

The results of short-term creep tests of welded joints with the use of test stress $\sigma_b = 100$ MPa

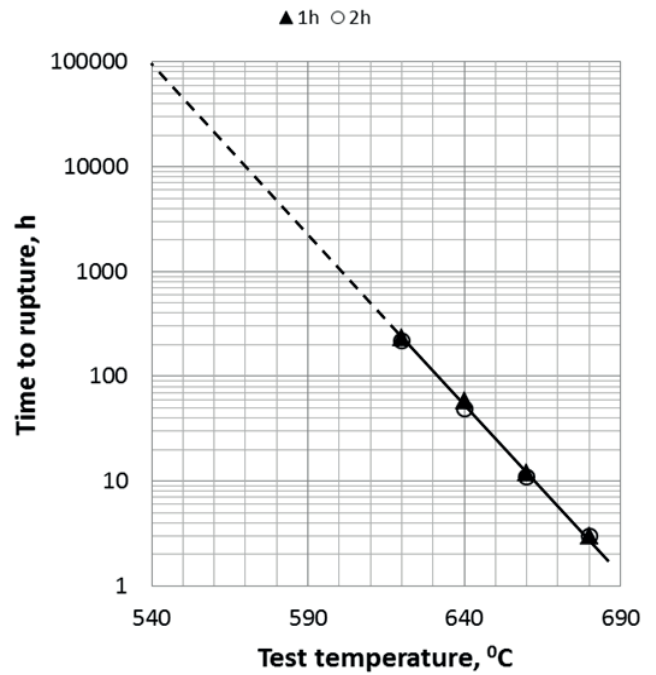| Parameters of heat treatment after welding	Temperature of testing T_b, °C			
	620	640	660	680
	Time to rupture t_r, h			
750°C/1h	234	58	12	3
750°C/2h	219	49	11	3

Fig. 7. Results of short-term creep tests of welded joints after heat treatment 750°C/1h and 750°C/2h

Extrapolation of the results of creep tests towards the temperature close to the temperature of service allows determining the time to rupture of the examined welded joints depending on the applied variant of heat treatment after welding (Table 5). The obtained results of the tests show the lack of difference in time to rupture for the performed variants of annealing times 1.0 and 2.0 hours.

TABLE 5

Determined time to rupture of homogeneous welded joints of T91 steel depending on the applied heat treatment after welding

Assumed service stress σ_r, MPa	Assumed temperature of further service T_r, °C	Determined time to rupture, h	
		Treatment variant: 750°C/1h	Treatment variant: 750°C/2h
100	540	**~100 000**	**~ 100 000**

6. Statements and conclusions

- In the case of welding of the pipes of small diameters and wall thickness, preheating before welding does not have any significant influence on the mechanical properties of the welded joint made of T91 steel;
- The time of annealing after welding at the temperature of 750°C shorter than two hours ensures achieving the required mechanical properties of the joint;
- Shortening the time of annealing after welding should contribute to the moderating of the degradation processes of the HAZ areas which in consequence leads to joints cracking by the mechanism of type IV;
- Simplified heat treatment of the joints can bring direct and indirect economic effects;

- The determined service life of the welded joints of T91 steel, regardless of the performed heat treatment variants, is at a similar level.

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