Research

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The Effect of Post-Weld Heat Treatment Temperature on the Structure and Hardness of Joints Made in Steel 10CrMoVNb9-1

Abstract: The article discusses the effect of annealing temperature applied during heat treatment as well as the suitability of preheating before the welding of butt joints in pipes (having a diameter of 33.7 mm and a wall thickness of 4.5 mm) made of steel X10CrMoVNb9-1 (P91). In the article, the structure and properties of a joint subjected to heat treatment performed in accordance with manufacturing standards concerning power unit elements are compared with those of a joint not subjected to heat treatment. The welding process discussed in the paper was based on the TIG method and involved the use of filler metal Thermanit MTS 3 (W Cr Mo 91). The material of steel X10CrMoVNb9-1 after welding and not subjected to heat treatment is both very hard and brittle. Because of the fact that the power engineering steel of the above-presented characteristics cannot be exposed to the effect of a high-pressure and high-temperature medium (due to possible crack formation), the welding of such steel should be followed by appropriate post-weld heat treatment.

Keywords: P91 steel, weld joint, heat treatment

DOI: 10.17729/ebis.2020.2/1

Introduction

The use of welding methods in the construction of power generation equipment considerably facilitates the implementation of design concepts characterised by high complexity and efficiency. The increased number of welded joints in power generation devices significantly affects their unitary power. Modern boilers contain tens of thousands of welded joints exposed to conditions characterised by very wide ranges of temperature. Recent decades have seen relentless efforts undertaken to obtain the highest possible efficiency of power units. This objective is primarily achieved by using increasingly high steam parameters, i.e. pressure and temperature. Presently, it is possible to construct power units characterised by the so-called ultra-supercritical parameters, i.e. a temperature

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of approximately 610°C and a pressure of 325 bar. Increased fresh steam parameters and, consequently, increased operating parameters of power generation equipment necessitate the development of steel grades capable of operation at higher temperature (as previously used steel grades are not characterised by sufficient mechanical properties). In cases of power engineering applications based on "dated" unalloyed steels, the wall of power engineering equipment must be very thick, significantly increasing the weight of such equipment [1]. The material-related reduction of wall thicknesses (in pipelines) is presented in Figure 1 [9].

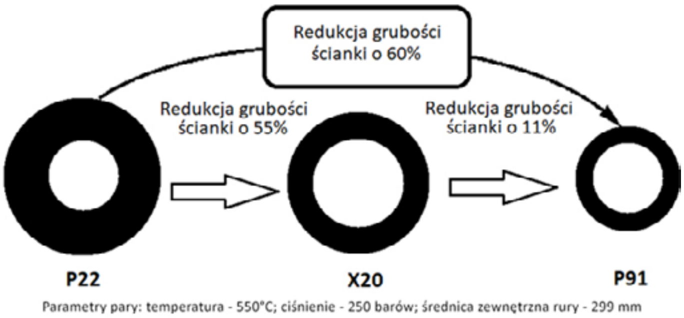

Fig. 1. Reduction of wall thickness demonstrated through comparison relation to steel P22, X20 and P91 [9]

As the chemical composition of alloy steels intended for operation at higher temperature includes many agents increasing hardenability, the weldability of such steels is, to some extent, more limited than that of unalloyed steels. The welding of alloy steels requires the strict control of welding parameters, the obtainment of the appropriate temperature of the base material during preheating and, frequently, the performance of post-weld heat treatment [6]. The heat treatment of the welded joint is performed to reduce welding stresses and obtain required plastic properties in the weld and heat affected zone. Heat treatment tends to be very complicated and, depending on various contents of alloying agents and microagents, may include tempering, normalising and annealing. Usually, heat treatment is performed for several hours at various temperatures and requires the strict control of cooling rates. The exceeding of recommended temperatures during heat treatment may trigger the solution of precipitates in the material and result in the loss of its both mechanical and plastic properties. Each specific steel grade requires the development of dedicated post-weld heat treatment conditions [6].

Individual tests

The tests aimed to assess the effect of annealing temperature during heat treatment and the justifiability of preheating before the welding of butt joints of pipes (having a diameter of 33.7 mm and a wall thickness of 4.5 mm) made in steel X10CrMoVNb9-1 (P91, Table 1). The tests also aimed to compare the structure and properties of the joint after heat treatment performed in accordance with manufacturing standards (Fig. 2) for power unit elements with the structure and properties of the joint not subjected to heat treatment.

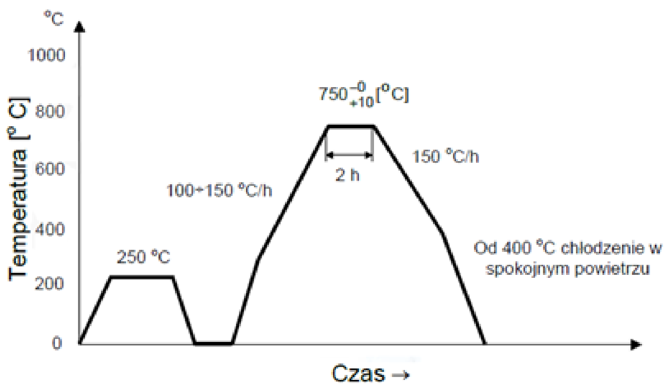

Fig. 2. Course of temperature changes during welding and heat treatment in relation to steel T/P91 [6]

Table 1. Chemical composition of steel X10CrMoVNb9-1 consistent with manufacturer's conformity certificate 3.1

Heat	Chemical composition, %							
986411	C	Si	Mn	P	S	Al	Cr	Ni
	0.120	0.270	0.450	0.015	0.001	0.008	8.710	0.140
	Mo	V	Cu	Ti	Nb	N	Zr	-
		0.220	0.100	0.001	0.070	0.049	0.003	

Welding process

The TIG welding process involved the use of filler metal Thermanit MTS 3 (W Cr Mo 91), the chemical composition of which is presented in Table 2. The welding process also involved the strict control of process parameters (in order to make them consistent with the joint-related welding procedure specification (WPS)) as well as measurements of interpass temperature and preheating temperature (carried out using a contact thermometer). The welding parameters are presented in Table 3. The maximum permissible interpass temperature amounted to 350°C, whereas the preheating temperature was 200°C. The process of preheating was performed using a gas torch.

Table 2. Chemical composition of filler metal Thermanit MTS 3

Chemical composition of weld deposit, %							
C	Si	Mn	Cr	Mo	Ni	Nb	V
0.1	0.3	0.5	9	1	0.5	0.06	0.2

Heat treatment

After the completion of the welding process, the joints were cooled to a temperature below 80°C and after an hour were subjected to heat treatment. The heat treatment (Fig. 3) was performed using a multi-channel electric-resistance annealing machine (CHINO). The values of temperature during annealing were recorded by means of a recording unit receiving information from thermocouples welded to the workpieces. Areas of measurements were covered with plates made of ceramic cloth, whereas the entire welded specimens were additionally insulated to prevent heat losses. The welding process and heat treatment were performed in accordance with the following schedule:

- joint no. 1 – subjected to preheating up to a temperature of 200°C and not subjected to annealing,
- joint no. 2 – subjected to preheating up to a temperature of 200°C and subjected to annealing at a temperature of 700°C for 60 minutes,
- joint no. 3 – subjected to preheating up to a temperature of 200°C and subjected to annealing at a temperature of 750°C for 60 minutes, i.e. in accordance with guidelines contained in PN-EN 12952-5 and PN-EN 13480-4,
- joint no. 4 – subjected to preheating up to a temperature of 200°C and subjected to annealing at a temperature of 800°C for 60 minutes,
- joint no. 5 – not subjected to preheating and subjected to annealing at a temperature of 750°C for 60 minutes.

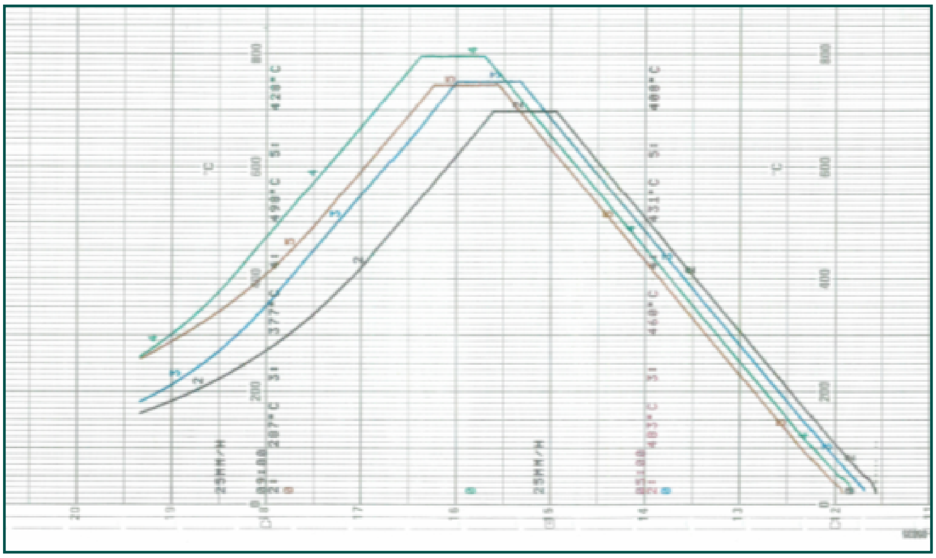

Fig. 3. Diagram of the heat treatment process

Table 3. Welding parameters of related WPS

Run	Welding process	Filler metal size, mm	Current, A	Voltage, V	Current type /polarity	Welding rate, mm/s	Heat input, kJ/mm
1	141	2.4	85-125	11-14	DC „-„	0.51-1.10	0.58-1.41
2 -n	141	2.4	90-150	11-15	DC „-„	0.53-1.13	0.58-1.51

Fig. 4. Welded joint no. 1

Fig. 5. Welded joint no. 3 after the dye penetrant test

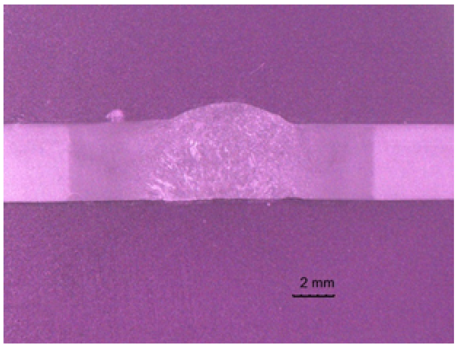

Fig. 6. Macrostructure of joint no. 1

After heat treatment, the joints were subjected to visual tests, penetrant tests, microscopic metallographic tests and hardness measurements.

Analysis of test results

Visual tests, performed in accordance with the PN-EN ISO 17637 standard, revealed that all of the joints represented quality level B in accordance with the PN-EN ISO 5817 standard (Fig. 4). The dye penetrant tests performed in accordance with the procedure described in PN-EN 3452-1 did not reveal any indications in the weld areas of the test joints. The only present indications were non-linear indications located in areas where thermocouples were welded to the specimen (to measure temperature during post-weld heat treatment) (Fig. 5). In view of the foregoing it can be assumed that all of the joints satisfied the requirements of acceptance level 1 in accordance with PN-EN ISO 23277. The macroscopic metallographic tests did not reveal the presence of any welding imperfections (Fig. 6).

The analysis of the hardness measurement results (Fig. 7) and microscopic test results (Fig. 8) revealed that joint no. 1 differed significantly from the remaining joints, which could be ascribed to the lack of post-weld heat treatment. The base material structure was that of tempered martensite with precipitates of carbides as well as vanadium and niobium carbonitrides. The base material tempered martensite was characterised by a hardness of approximately 220 HV. In the weld and heat affected zone (HAZ) of joint no. 1, the hardness of the martensite in the heat affected zone was restricted within the range of approximately 430 HV to 460 HV, whereas the hardness of the martensite in the weld area was restricted within the range of 420 HV to 425 HV. The base materials of the remaining specimens were characterised by very similar hardness restricted within the range of 210 HV to 230 HV as well as by a similar structure containing tempered martensite, areas of bainite as well as inclusions of carbides and other elements deriving from the chemical composition of steel X10CrMoVNb9-1.

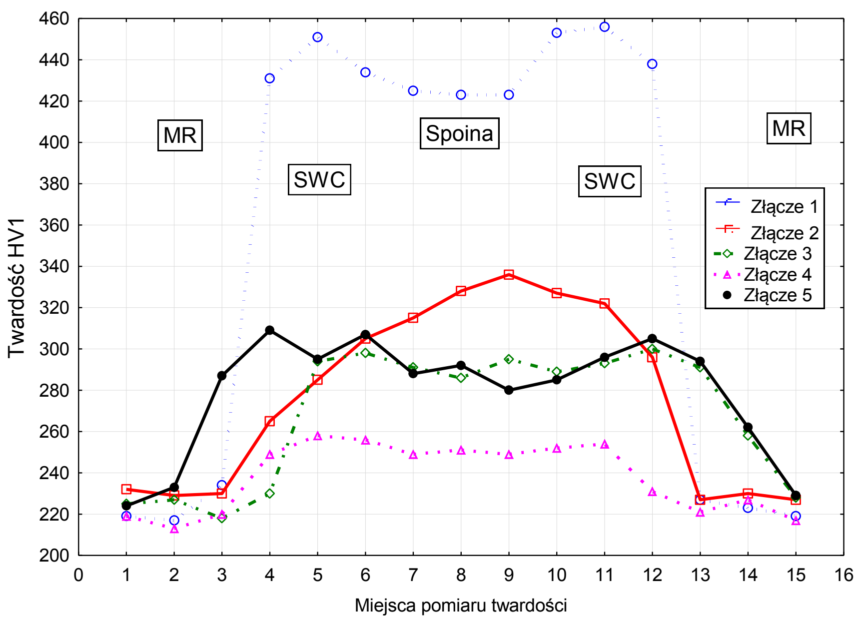

Fig. 7. Hardness distribution in the welded joints

The highest hardness was measured in joint no. 2, i.e. the joint subjected to post-weld heat treatment performed at a temperature of 700°C. In the heat affected zone the hardness of the material was restricted within the range of approximately 290 HV to 315 HV, whereas the hardness in the weld was restricted within the range of 320 HV to 340 HV. Slightly lower hardness was characteristic of joints no. 3 and 5, i.e. the joints subjected to post-weld heat treatment performed at a temperature 750°C. Although specimen no. 5 was not preheated to a temperature of 200°C, the hardness values of the joint in relation to the HAZ and weld were very similar to those of joint no. 3 (heated with a gas flame). In both cases, the hardness in the HAZ and weld was restricted within the range of approximately 285 HV to 300 HV and did not differ significantly in relation to the above-named zones. The lowest hardness was found in joint no. 4, i.e. the joint subjected to post-weld heat treatment at a temperature of 800°C. Similar to the joints subjected to post-weld heat treatment at a temperature of 750°C, no significant differences in hardness as regards the HAZ and the weld were recorded. The hardness in the above-named zones was restricted within the range of

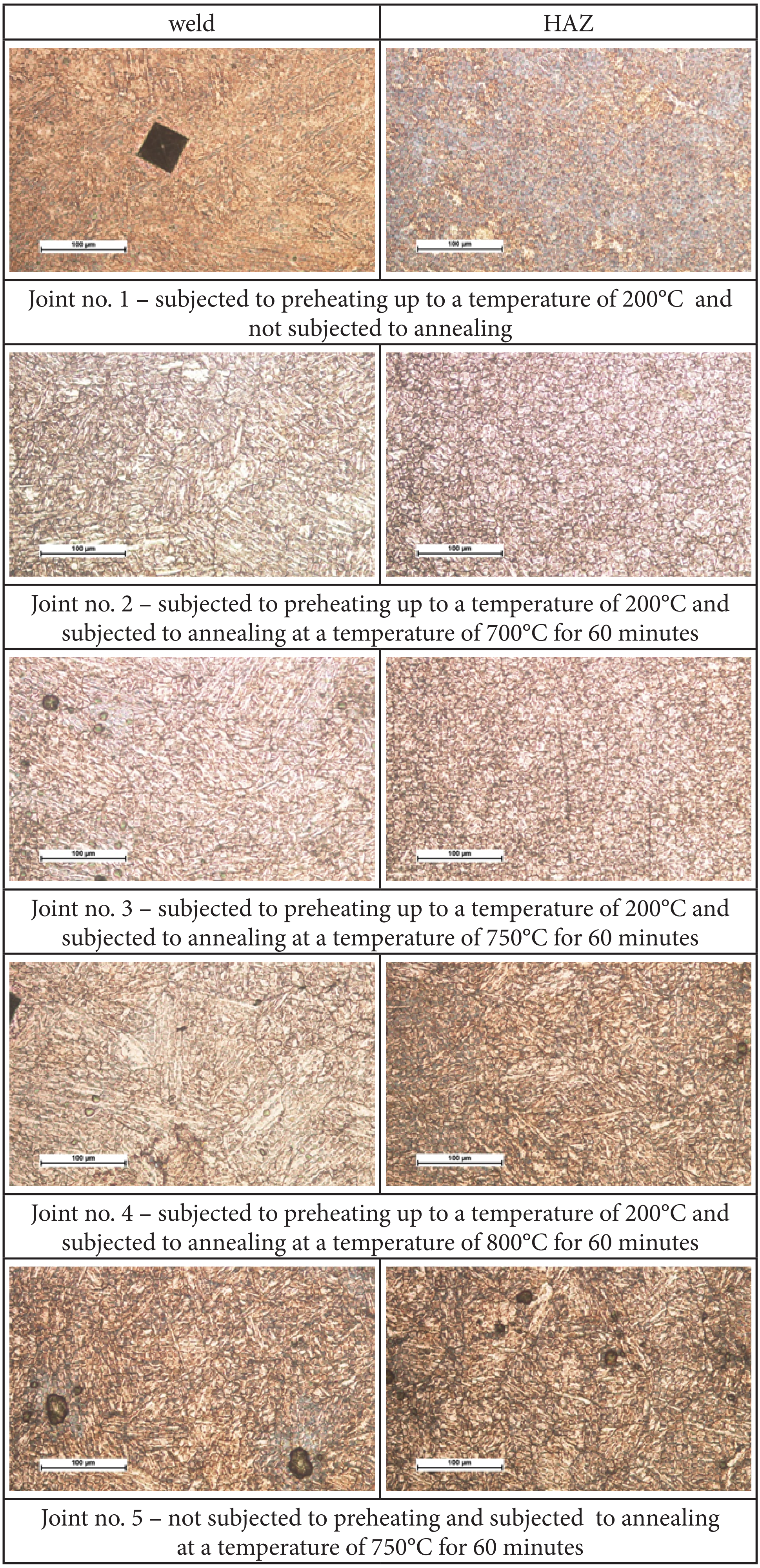

Fig. 8. Microstructure of the welded joints

250 HV to 260 HV, which only slightly differed from the values measured in the base material of joint no. 4.

Summary

The tests revealed significant differences between the joint subjected to treatment performed in accordance with related manufacturing standards and the joint not subjected to heat treatment. The aforesaid differences are already revealed during visual tests as welded pipes subjected to heat treatment often lose their anticorrosive layer and welds are more mat. Knowing this, inspectors responsible for the acceptance of boiler systems can, without performing any additional tests, easily assess whether the process of heat treatment has been performed properly. Primary differences are concerned with structural changes and hardness. The material of steel X10CrMoVNb9-1 after welding without being subjected to post-weld heat treatment is very hard and brittle. Power engineering steel in such a state and exposed to a medium characterised by both high temperature and pressure may develop cracks. For this reason, steel X10CrMoVNb9-1 requires post-weld heat treatment performed in accordance with a generally acceptable technology. The post-weld heat treatment of joints made in steel X10CrMoVNb9-1 results in the disappearance of the division of the joint into three zones. The foregoing is the effect of normalisation applied to equalise the structure and properties of each of the zones. Preheating up to a temperature of 200°C did not affect the structure and hardness of the welded joint of the pipes having a diameter of 33.7 mm and a wall thickness of 4.5 mm.

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