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Microstructure and Properties of Dissimilar Welded Joints Made of Steels used in the Power Industry

Abstract: The article presents the microstructure and properties of dissimilar welded joints of pipes made of the 304HCu (X10CrNiCuNb18-9-3) and P92 (X10CrWMoVNb9-2) steels in the as welded state and after PWHT. The test-related TIG welding was carried out using two filler metals in the form of the Thermanit 304HCu and the EPRI P87 filler metal wires. The tests revealed the significant influence of heat treatment time extension on the decrease in the hardness of the martensitic steel and its HAZ as well as an on the increase in the hardness of the austenitic steel, its HAZ and of the weld made using the Thermanit 304HCu filler metal. The microscopic observations revealed the presence of a carburised zone on the fusion line between the P92 steel and the weld made using the Thermanit 304HCu filler metal wire.

Keywords: dissimilar welded joints, 304HCu steel, P92 steel, welding properties

Introduction

The power unit of a conventional power plant, to put it simply, is composed of two integral units, i.e. a boiler and a turbine (connected by means of pipelines). Due to a diversified temperature in the boiler, depending on temperature, it is necessary to use materials varying in properties and microstructure. This entails the necessity of making dissimilar joints, potentially the most critical areas in the boiler structure. The proper selection of filler metals must take into consideration many factors which may significantly affect joint properties and in particular creep strength in time. The tests have indicated two basic factors – differences in the thermal expansion of materials and diffusion processes taking place in the welded joint fusion line area. This article focuses on the microstructure and properties of dissimilar joints made of martensitic and austenitic structure steels [1, 2].

Table 1. Chemical composition of P92 and 304HCu steels [3, 4]

Steel	C	Si	Mn	Cr	Ni	Nb	Cu	Mo	W	V	Al
P92	0.07-0.13	<0.5	0.3-0.6	8.5-9.5	<0.4	0.04-0.09	-	0.3-0.6	1.5-2.0	<0.04	0.03-0.07
304HCu	0.07-0.13	<0.3	<1.0	17.0-19.0	7.5-10.5	0.30-0.60	2.5-3.5	-	-	-	0.003-0.03

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Tests

The tests involved the use of test pieces sampled from dissimilar girth butt joints made of the 304HCu steel (X10CrNiCuNb18-9-3, 1.4907) and P92 (X10CrWMoVNb9-2, 1.4901) steel pipes having the chemical composition presented in Table 1. The pipe external diameter was 42.5 mm and the wall thickness amounted to 6.8 mm. Both steels can be used in the production of pressure vessels following the Directive 97/23/wE [3, 4].

The 304HCu steel is classified in group 8.1 according to CR ISO 15608, and in group 7 according to the AD 2000 specification. The specifications of AD 2000 and TRD provide the temperature of 750°C as the maximum during operation [3]. The P92 steel is classified in group 6.4 according to CR ISO 15608, and in group 4.2 according to the AD 2000 specification. The AD 2000 specification provides the temperature of 650°C as the maximum during P92 steel operation [4].

The filler metals used during TIG welding were the Thermanit 304HCu and EPRI P87 filler metals with the chemical composition presented in Table 2.

Table 2. Chemical composition of the Thermanit 304HCu and EPRI P87 filler metals [5, 6]

Filler	C	Si	Mn	Cr	Ni	Nb	Cu	Mo	N
Thermanit 304HCu	0.1	0.40	3.20	18.0	16.0	0.4	3	0.8	0.2
EPRI P87	0.1	0.15	1.55	8.5	47.7	1.1	-	2.0	-

The welding was followed by non-destructive visual inspection, destructive macro- and microscopic examination as well as Vickers hardness tests under a load of 98.1 N (HV10). The tests were performed on the test pieces in the as welded state and after heat treatment at 760°C for 30 min, 2 hours, 8 hours and 24 hours.

The non-destructive visual testing did not reveal any welding imperfections. The joints represented the quality level B according to PN-EN ISO 5817 [7]. The exemplary view of the welded joints from the face side is presented in Figure 1.

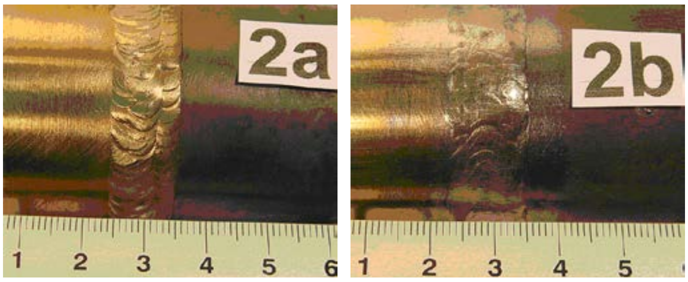

Fig. 1. Weld face view of the joint made of the P92 and 304HCu steels welded with the Thermanit 304HCu (2a) and EPRI P87 (2b) wires

The macroscopic examination of both welds revealed the properly made runs without visible internal welding imperfections. Figure 2 presents the exemplary macrostructure of the joint welded with the Thermanit 304HCu wire (etching with Adler's reagent).

Due to the different structure of the parent metals of dissimilar joints it was necessary to use various reagents to reveal the structure during microscopic tests. The electrolytic etching in the 10% aqueous solution of CrO_3 revealed the microstructure of 304HCu and that of the welds, whereas the chemical etching using Villella's reagent with 1g of picric acid enabled the observation of the P92 steel microstructure. The examinations were conducted using a Leica-DMLM light microscope.

Figures 3 and 4 present the austenitic structure of the Thermanit 304HCu and EPRI P87 welds. Due to the same crystallographic lattice in both cases it was possible to observe the epitaxial crystallisation of the weld from the 304HCu steel side (Fig. 5 and 6).

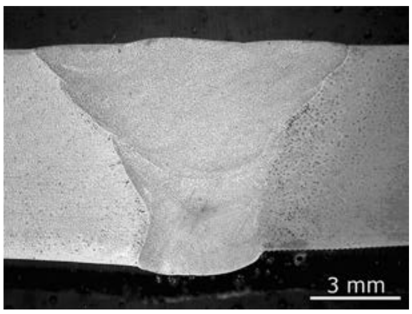

Fig. 2. Macrostructure of the P92 and 304HCu steel joint welded with the Thermanit 304HCu filler metal wire

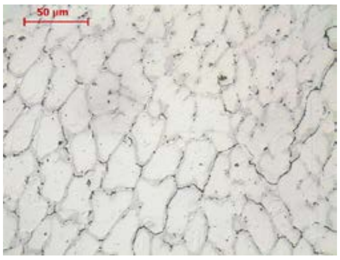

Fig. 3. Weld microstructure (Thermanit 304HCu wire)

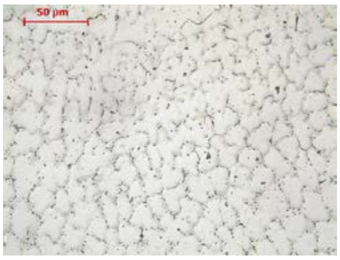

Fig. 4. Weld microstructure (EPRI P87 wire)

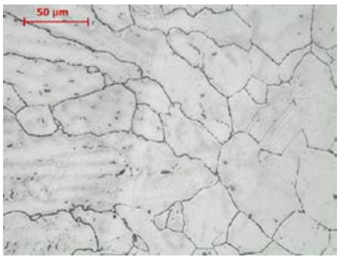

Fig. 5. Fusion line between the 304HCu steel and the Thermanit 304HCu weld; the visible presence of epitaxial crystallisation

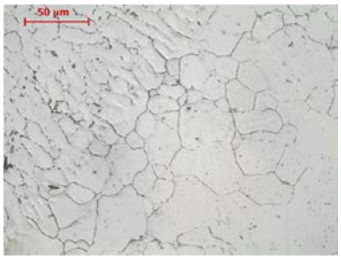

Fig. 6. Fusion line between the 304HCu steel and the EPRI P87 weld; the visible presence of epitaxial crystallisation

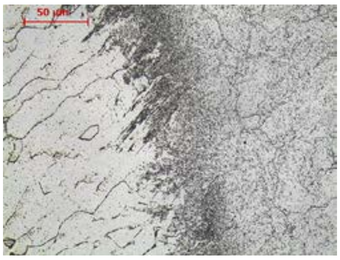

Fig. 7. Fusion line between the P92 steel and the Thermanit 304HCu weld after heat treatment 760°C/24h; the visible zone of carbon diffusion from the steel to the weld

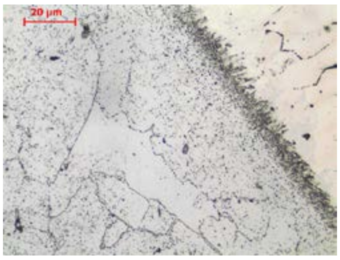

Fig. 8. Fusion line between the P92 steel and the Thermanit 304HCu weld after heat treatment 760°C/2h; the visible zone of carbon diffusion from the steel to the weld and the presence of ferrite δ in the HAZ coarse-grained area

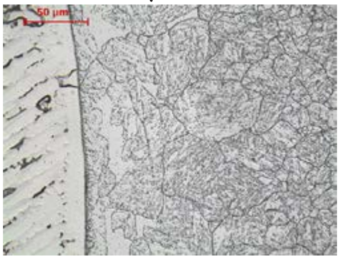

Fig. 9. Fusion line between the P92 steel and the Thermanit 304HCu weld after heat treatment 760°C/8h; the visible presence of ferrite δ in the HAZ coarse-grained area

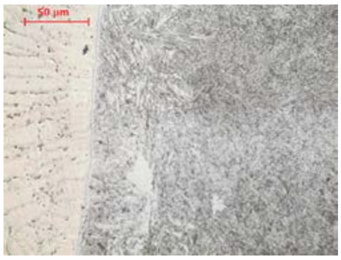

Fig. 10. Fusion line between the P92 steel and the EPRI P87 weld; the visible presence of ferrite δ in the HAZ coarse-grained area

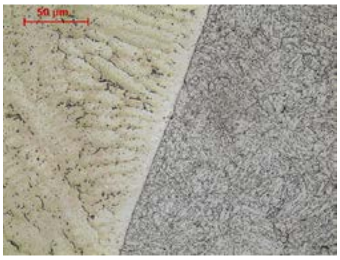

Fig. 11. Fusion line between the P92 steel and the EPRI P87 weld after heat treatment 760°C/8h; no traces of carbon diffusion

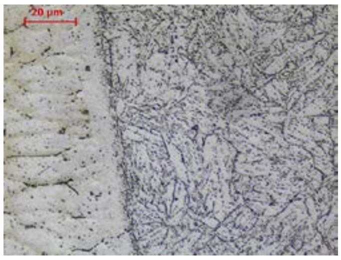

Fig. 12. Fusion line between the P92 steel and the EPRI P87 weld after heat treatment 760°C/24h; no traces of carbon diffusion

In the case of the joints welded with the Thermanit 304HCu filler metal along with the heat treatment time extension it was possible to observe the progressive diffusion of carbon from the higher carbon potential areas (P92) to those with a lower carbon potential (the weld made with Thermanit 304HCu). The consequence of this process was the formation of a hard carburised layer on the fusion line (Fig. 7 and 8). Near the fusion line, in the coarse-grained HAZ area of the P92 steel it was also possible to observe ferrite δ grains (Fig. 8 and 9). As opposed to the joints welded with the Thermanit 304HCu filler metal wire, in the case of the EPRI P87 filler metal wire no carburised layer in the as welded state (Fig. 10) or after heat treatment 760°C/24h was observed, which indicates that carbon diffusion did not take place (Fig. 11 and 12).

The hardness measurements were performed using a Zwick-Roell ZHU 187.5 hardness testing machine, following the instructions of PN-EN ISO 9015-1 [8], in two lines, on the face and on the root side, 1.5 mm away from the test piece surface. Three imprints were made in each of the joint zones.

Figures 13÷16 present the hardness measurement results for the welded joints made of the P92 and 304HCu steels using the 304HCu and EPRI P87 filler metals in the as welded and PWHT state 760°C/2h. Figures 17 and 18 present the changes of the maximum hardness value in the individual welded joint zones in the function of heat treatment time at 760°C.

The highest hardness was observed in the P92 steel HAZ in the as welded state. The heat treatment 760°C/2h made it possible to reduce hardness below 312 HV10. The HAZ hardness in the 304HCu steel and in the welds made with the Thermanit 304HCu and EPRI P87 filler metals in the as welded and PWHT state 760°C/2h did not exceed 260 HV10. The increase in annealing time was accompanied by the significant hardness decrease in the P92 steel HAZ

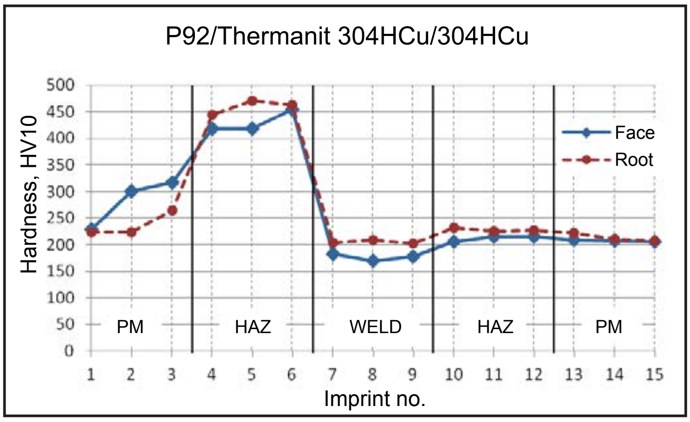

Fig. 13. Hardness of butt joint of the P92 and 304HCu steel pipes welded with the Thermanit 304HCu filler metal wire in the as welded state

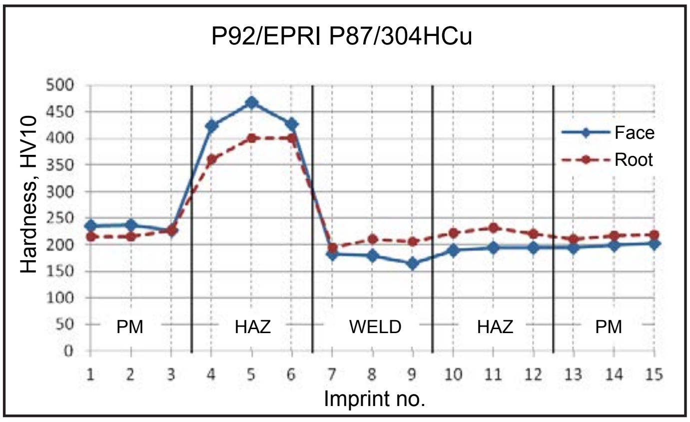

Fig. 14. Hardness of butt joint of the P92 and 304HCu steel pipes welded with the EPRI P87 filler metal wire in the as welded state

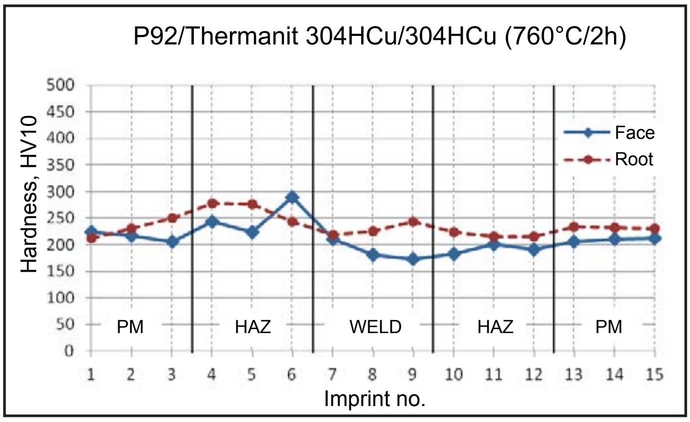

Fig. 15. Hardness of butt joint of the P92 and 304HCu steel pipes welded with the Thermanit 304HCu filler metal wire in the as welded state and after HT 760°C/2h

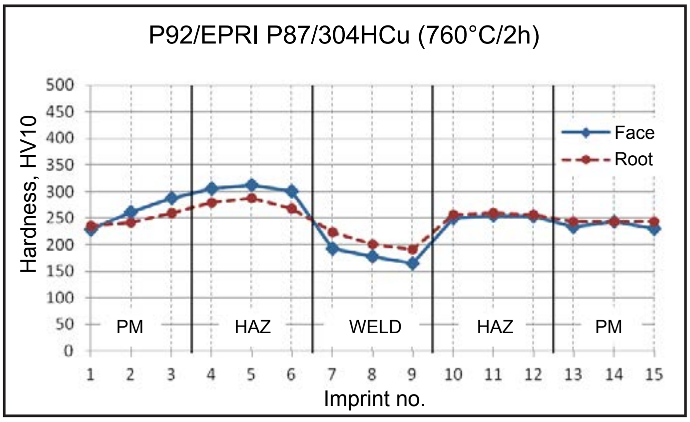

Fig. 16. Hardness of butt joint of the P92 and 304HCu steel pipes welded with the EPRI P87 filler metal wire in the as welded state and after HT 760°C/2h

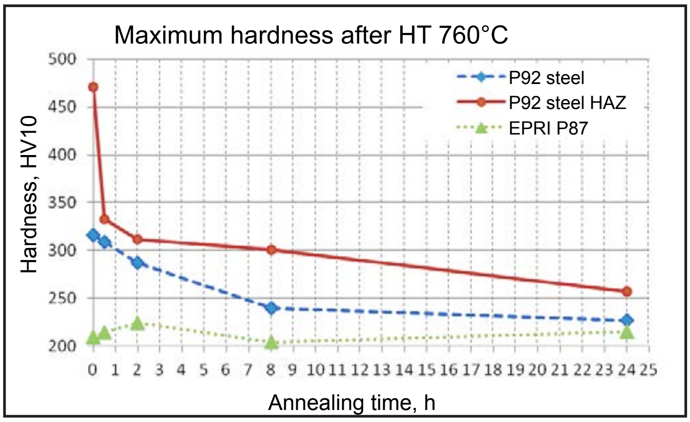

Fig. 17. Change of the maximum hardness values of the P92 steel, the P92 steel HAZ and of the weld made using the EPRI P87 filler metal in the function of heat treatment time at 760°C

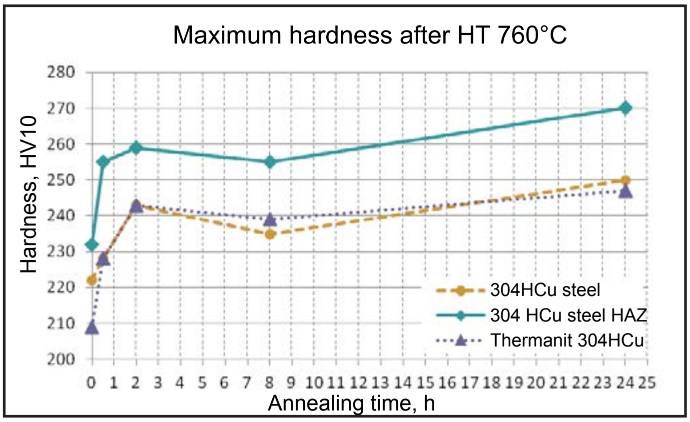

Fig. 18. Change of the maximum hardness values of the 304HCu steel, the 304HCu steel HAZ and of the weld made using the 304HCu filler metal in the function of heat treatment time at 760°C

attributable to the tempering process. A similar effect was visible in the P92 steel, yet to a lesser extent. Unlike in the P92 steel, in the 304HCu steel and its HAZ as well as in the weld made with the Thermanit 304HCu filler metal the increase in annealing time was accompanied by a hardness increase, caused by precipitation processes. In the case of the weld made using the EPRI P87 filler metal the annealing time extension was not accompanied by a hardness increase.

Taking into consideration the maximum hardness criterion of 350 HV10 referred to in PN-EN ISO 15614-1 [9], among others, it was possible to determine the sufficient temperature and time of annealing using the Hollomon-Jaffe equation [10]. This dependence is expressed by the following equation (1):

$$Hp = T\,(20 + \log t)\cdot 10^{-3} \qquad (1)$$

where T – annealing temperature (K), t – annealing time (h).

The determined value of the Hp parameter necessary for obtaining the maximum P92 steel HAZ hardness of 350 HV10 amounted to 18.28 (Fig. 19). This enabled the determination of the temperature range and annealing time necessary for achieving hardness below 350 HV10 (see Figure 20). However, it should be mentioned that, due to the lack of data necessary for such an analysis, the criterion of the minimum impact energy was not taken into consideration.

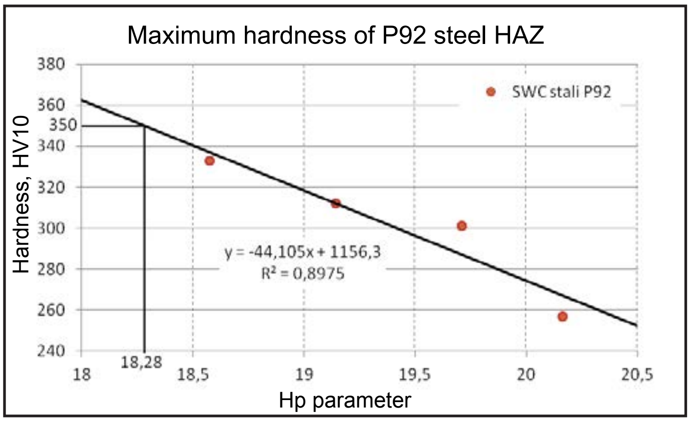

Fig. 19. Maximum hardness of the P92 steel HAZ depending on the Hp parameter

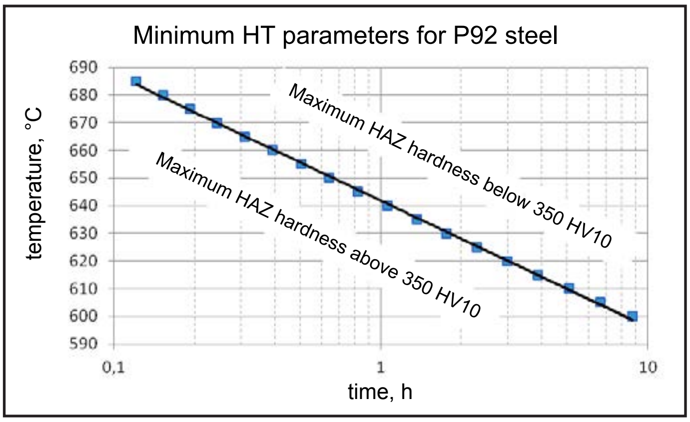

Fig. 20. Correlation between the annealing temperature and the hold time determined on the basis of the Hollomon-Jaffe dependence for the P92 steel HAZ

Summary

The tests have revealed that the welding technology applied enables the obtainment of joints representing quality level B according to PN-EN ISO 5817. The microscopic observations revealed that the welds made using the Thermanit 304HCu and EPRI P87 filler metal wires had an austenitic structure. The observations also revealed the presence of the carburised layer near the fusion line on the P92 steel side in the joint made with the Thermanit 304HCu wire; the width of the layer grew along with the annealing time extension. The carburised layer was not observed in the joint made with the EPRI P87 filler metal wire, which can be ascribed to the comparable chromium content in the P92 steel and EPRI P87 filler metal. The hardness measurement results revealed the high hardness of the P92 steel HAZ in the as welded state (above 450 HV10) and that it was possible to reduce hardness to the value <350 HV10 by using heat treatment at 760°C. The annealing time extension was accompanied by the decrease in the hardness of the P92 and of its HAZ as well as by the increase in the hardness of the 304HCu steel, its HAZ and in the weld made with the Thermanit 304HCu filler metal wire. The hardness increase was the result of precipitation processes. The hardness of the weld made with the EPRI P87 filler metal wire remained unchanged.

The tests were performed within the statutory work no. 11.11.110.299.

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