THE EFFECT OF WELDING ON THE PROPERTIES OF NEW AUSTENITIC STEELS FOR USE IN BOILERS WITH HIGHER STEAM PARAMETERS

Lukáš POMIKÁLEK [a], Zdeněk KUBOŇ [b], Jiří VATRAL [b]

[a] *VÍTKOVICE POWER ENGINEERING a.s., Ostrava, Czech Republic, EU,*
lukas.pomikalek@vitkovice.cz jiri.vatral@vitkovice.cz
[b] MATERIAL AND METALLURGICAL RESEARCH Ltd.*, Ostrava, Czech Republic, EU,*
creep.lab@mmvyzkum.cz

Abstract

The project MPO FR-TI3/458 "Material solutions for industrial equipment working with ultra-preheated steam", is focused on the assessment and prediction of long-term creep life of heterogeneous and homogeneous weld joints of the selected materials that can be used for superheaters and re-heaters of newly built or refurbished power plant boilers. The acquisition of detailed and reliable information, especially about the behaviour of weld joints exposed to high temperatures and pressure during long-term operation is of vital importance.

Examined heterogeneous and homogeneous weld joints were made from austenitic heat resistant steels HR3C, SUPER 304H and Tp347HFG and also from martensitic steel P92.

In order to ensure optimal and reproducible welding conditions, it was necessary to set the parameters of automated orbital GTAW welding, including thermal regime during welding - preheating, interpass and reheating temperatures as well as postweld heat treatment (PWHT). Information about the properties and behaviour of the welds were obtained by testing (WPQR) made in compliance with standard EN 15614-1. The presented work thus builds on the results of previous activities published last year and now it presents the results of welds and tests performed on heterogeneous weld joint of steels Tp347 HFG and Super 304H. Besides the principal results it shows also the results of additional testing of materials made after different regime of PWHT. Moreover, we present the preliminary results of long-term creep tests, which are still continuing.

Keywords: Welding, heat treatment, heterogeneous joint, creep test

1. INTRODUCTION

It should be noted that there is relatively enough information about the properties of modern types of austenitic steels for end-stage super-heaters USC boilers (HR3C, Super 304H and Tp347 HFG). On the other hand, we can´t obtain more detailed information about the influence of welding (or other technological operations) on the properties of steel and weld joint itself. If such information exists, then it is only a summary and comparison of results of creep or corrosion in welds and base material, without more detailed information on the welding process and vice versa as stated in [1].

In our previous work [1] were presented the first results of short-term tests on selected homogeneous and heterogeneous welding joints of these steels with and without postweld heat treatment (for connections using material P92 is then only possible variation with PWHT). There was also given a detailed description of the basic materials, filler materials and summarized welding and PWHT issues. Therefore in the individual chapters are given only elementary information now.

In the year 2013 there was new heterogeneous weld joint between Tp347 HFG and Super 304H included into researched welds. In addition, tubes and welded joints were subjected to additional tests, such as determination of the δ-ferrite grain size determination, or micro purity, which results are presented here.

In this time, long-term corrosion and creep tests are under way. Partial results of creep tests of steel Tp347 HFG including its homogenous weld joints are also already listed.

2. TESTED MATERIALS

From the literature [2-10] were drawn information about the behavior studied materials and were examined their mechanical properties, creep, corrosion resistance on both the flue gas side as well as on the steam side (however, not be subject to further monitoring) and microstructure. The input information for the selection of additional materials, design of welded joints and perform PWHT were taken from above mentioned literature.

As revealed by research of expert literature which exist to the topic is used to these nodes mainly austenitic materials as Super 304H, Tp347 HFG and HR3C. The martensitic steel P92 is used to manufacture sleeves chambers or adapters in connection with these materials. All three austenitic materials are issued by the German data sheets [7-9] these steels are not yet normalized in Europe and only type Tp347 HFG and HR3C are listed in ASTM A213.

Production and testing was carried out on seamless pipes with dimensions of 38 x 6.3 mm.

3. WELDING AND POSTWELD HEAT TREATMENT

3.1 Welding method, technology and welding position, filler material

Welding was performed using the 141 (GTAW, respectively TIG) - non-consumable electrode in a protective atmosphere of inert gas; protective and forming gas was Ar 4.6. It was used automated welding technology on the company's equipment Polysoude called orbital welding (position PK). The weld was performed a total of three weld beads and heat input for individual connections and layers was in the range of 1100-1600 J/mm excluding the effectiveness of the method. Interpass temperature was 150 °C.

For welding was used wire with diameter 0.8 mm wound on the "endless" coil made of UTP A 6170 Co (according to EN ISO 18274: S Ni 6617 (NiCr22Co12Mo9); according to AWS A5.14-05: ERNiCrCoMo-1; Wr.-Nr. 2.4627).

3.2 Welding combinations

In earlier stages were performed a total of 14 combinations of welded joints - (homogeneous weld joints of each materials, dissimilar joints between Super304H and HR3C, Tp347HFG and HR3C always in two versions with and without PWHT and heterogeneous connections between each austenitic steel and steel P92 with PWHT. [1] Two additional new weld joints were qualified see **Table 1**.

Table 1 Production of weld joints

No	1. material	2. material	Filler metal	Temperature PWHT
1	Super 304H	Tp347 HFG	UTP A 6170Co	
3	Super 304H	Tp347 HFG	UTP A 6170Co	1130 °C

3.3 Post weld heat treatment

After welding, has been carried out solution annealing in a furnace with an inert atmosphere with a holding time of 15 minutes at a temperature of 1130 °C followed by cooling in water. Subsequently, the same weld joints were prepared without heat treatment. The aim of the production and testing of welded joints of identical austenitic materials differing applications or lack of solution annealing after welding was to examine the differences in the properties depending on the use of PWHT. These differences are also observed even creep and corrosion testing.

4. RESULTS OF SHORT-TERM TESTING

4.1 Hardness measurement

Heterogeneous weld between steels Tp347 HFG and Super 304H without PWHT had a quite uniform hardness, which was slightly higher in the material Super 304H. It corresponds to the normalized values of the material. The hardness decreased across the weld joint after heat treatment with the exception of the two areas HAZ, wherein the hardness values were at the same level as without PWHT. Heat treatment had no significant effect on the hardness of the weld joint, as shown by measuring the micro-hardness profile across the weld joint. See **Fig. 1**.

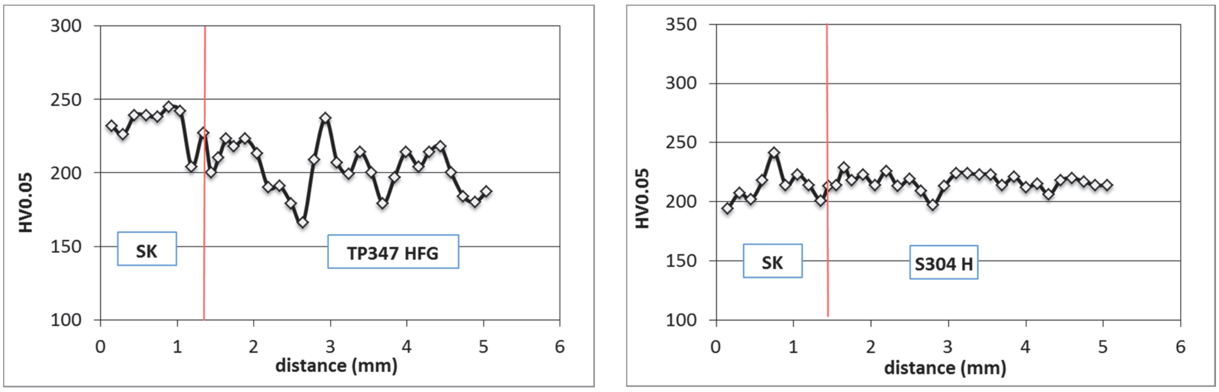

Fig. 1 Micro hardness profile of heterogeneous weld joint of Tp347 HFG and Super 304H steels after postweld heat treatment

4.2 Tensile and Charpy-V impact tests

The test bars were ruptured in all cases in the base material outside of the weld. Effect of PWHT is minimal (there was a slight reduction of yield strength). For all these joints, the results of tensile tests are indicative (though a necessary condition for issuance of WPQR). Tested steels belong to a group of creep-resistant steels, i.e. steels operating at high temperatures. For these steels the important value is the creep rupture strength (R_{mT}), which is determined by creep tests.

The values of impact energy did not change significantly after heat treatment. A small degrease was observed in the weld metal depending on specimen location in the tube (in position PA and PE).

4.3 Macrostructure and microstructure

Macrostructure of welded joints in terms of integrity and quality of the welded joint is satisfactory. Example macrostructures and microstructures of the individual areas of the weld joint are shown in **Fig. 2**.

In the framework of qualifications was also ordered determination of the δ-ferrite in the weld metal and heat affected zone. A certain proportion of δ-ferrite in the steel is beneficial to reduce the susceptibility of the weld metal cracks in the heat, but on the other hand, δ-ferrite reduces the corrosion resistance and promotes the formation of brittle sigma phase at elevated operating temperatures. Knowledge of the content of δ-ferrite is thus necessary information to assess the quality of the weld joint and prediction of the properties of the weld metal and heat affected zone. The microstructure of the base material Super 304H and Tp347 HFG is composed of austenite and carbides excluded inside and partially along the grain boundaries. The microstructure of weld metal is formed austenite and δ-ferrite. The amount δ-ferrite in weld metal is an average of 5 %. The microstructure of both heat-affected zones consists of the austenite and carbides excluded mainly in grains with a rare occurrence of δ-ferrite. After application PWHT grain size of the base material was increased about 1-2 degrees. Locally close to the surface was even greater increase in grain size, a significant increase of grains was then observed in the HAZ, especially in material Super 304H (up to a distance of 3 mm from the fusion zone towards the base material) as shown in **Fig. 2**. This increase was similar to that observed in all previously produced welded joints of steel Super 304H [1]. Determining the causes of grain growth in such a large area is subject of the current investigation. With regard to the positive impact of fine-grained structure on the corrosion resistance of austenitic steels in conditions of high steam parameters can be expected that this will have a negative impact on the corrosion resistance of these steels in the operating conditions.

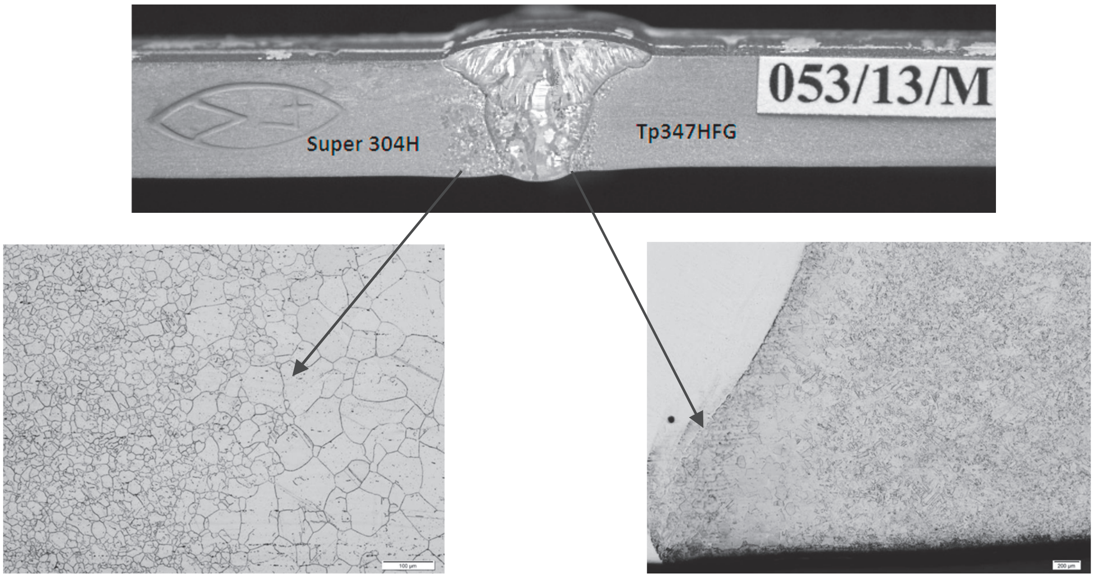

Fig. 2 Heterogeneous weld joint of Tp347 HFG and Super 304H steels after PWHT including detailed view of HAZ with coarsened austenite grains on both sides of the joint

4.4 Determination of content of non-metallic inclusions

The content of non-metallic inclusions supplied pipes were determined according to GOST 1778 by S1 and ČSN EN ISO 4967 method A. According to ČSN EN ISO 4967, there were no occurrences of inclusions A, B, C types and type D just fine max level 1. According to GOST 1778 method Š1 were no occurrences of oxide inclusions, a rare type of SN, NT and NA and to max 1.7 grades. They have been tried all delivered heats and significant difference was found between the micro purity.

5. RESULTS OF CREEP TESTS

Creep tests were performed according to the ČSN EN ISO 204 [11] and test specimens with circular cross-section and threaded heads were used with the gauge length 25 mm for basic material and 50 mm for weld joints. The diameter of the individual creep test specimen varied from 3.8 to 5.1 mm according to the applied stress. The results of the individual creep tests including testing parameters are shown in **Table 2**, where time to rupture of still running test specimens is stated in parenthesis.

The results of creep tests were summarized in the form of stress dependence on Larson-Miller parameter $\mathbf{P_{LM}}$ defined as: [12]

$$P_{LM} = T\,(C_{LM} + \log t_r) \tag{1}$$

where σ means stress in v MPa, $\boldsymbol{T}$ is the absolute temperature in Kelvin, $\boldsymbol{t_r}$ represents time to rupture in hours and $\mathbf{C_{LM}}$ is the Larson-Miller constant having here the value of 19.4, which is the optimized value of the Larson-Miller constant calculated by the least square method from the creep data given in the material datasheet of Tp347 HFG steel [10].

Table 2 Results of creep tests

BM	Temperature (°C)	Stress (MPa)	Time (h)	Elongation (%)	R.A. (%)
after welding	**650**	**240**	**295**	**20.2**	**52.1**
	650	**215**	**438**	**34.8**	**62.3**
	650	**180**	**3454**	**22.4**	**59.2**
	650	**160**	**3275**	**35.7**	**62.7**
	700	170			
	700	150	400		
	700	**120**	**291**	**49.4**	**77.6**
	700	100	(2000)		
after PWHT	**650**	**240**	**157**	**32.8**	**57.0**
	650	**215**	**2032**	**21.8**	**49.8**
	650	**180**	**2620**	**28.3**	**61.4**
	650	**160**	**6173**	**23.6**	**55.6**
	700	**170**	**140**	**50.2**	**77.5**
	700	**150**	**309**	**50.2**	**77.5**
	700	120	(1650)		
	700	100	(1750)		

Weld	Temperature (°C)	Stress (MPa)	Time (h)	R.A. (%)
after welding	**650**	**240**	**278**	**61.1**
	650	**215**	**146**	**62.8**
	650	**180**	**3079**	**59.2**
	650	160	(4800)	
	700	170		
	700	150	(200)	
	700	**120**	**908**	**70.1**
	700	100	(2450)	
after PWHT	**650**	**240**	**323**	**55.4**
	650	**215**	**186**	**65.5**
	650	**180**	**1635**	**54.6**
	650	160	(2600)	
	700	170	(50)	
	700	150	(100)	
	700	**120**	**1461**	**68.2**
	700	100	(6500)	

Although the number of finished creep tests is so far limited and does not enable us to calculate creep rupture strength of the individual testing series, it is possible to compare the experimental results of creep tests with the standardized mean creep rupture strength value stated in the material datasheet [10]. Such a comparison is illustrated in **Fig. 3**, where creep data of both basic material and weldment are processed according to Larson-Miller procedure and compared with the mean standardized curve valid for the steel Tp347 HFG. The first results give the good prospects about the creep resistance of the tested super heater tubes and their weld joints as can be seen in comparison with the curve representing the mean values of creep rupture strength stated in the material specification [10]. Regardless to the fact whether the weld joint was post weld heat treated or not, the results of the individual creep tests lie close to this mean standardized curve and in its lower 20 % tolerance limit, which confirms good creep properties of both super heater tubes as well as their weld joints.

The promising long-term creep resistance of the tested steel will probably have to be corrected, as it was shown that in this steel make (and probably also in the other modern austenitic creep resistant steels) there is a great risk of sigma phase appearance after long-term creep exposure close to 100 000 hours [13]. This phase is very hard and has low plasticity and precipitates typically o grain boundaries, which can significantly lower toughness of the steel and increase of the risk of brittle failure even during the operation.

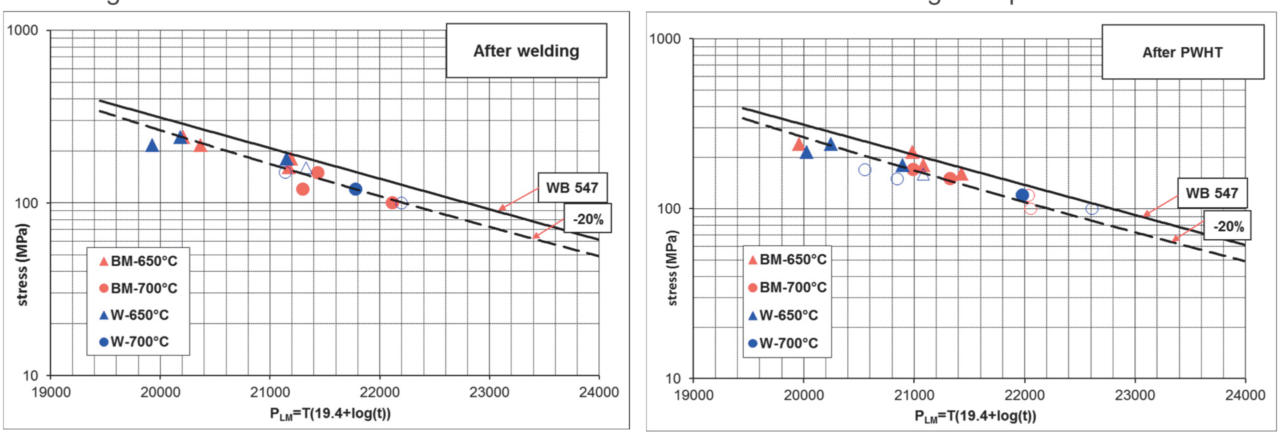

Fig. 3 Stress dependence of creep rupture strength of basic material and weld joint of steel Tp47 HFG tested on welds with and without PWHT

CONCLUSIONS

These results prove that the welds made were made in the quality required by standard ČSN EN ISO 15614-1 and additional rules (AD2000 Merkblatt HP2 / 1 and PED (97/23/EC)). Results of short-term tests have shown that the process of welding and heat treatment causes structural changes (precipitation hardening phase and coarsening of grains in the range of overheating), but changes in mechanical properties are not significant.

Similarly as in the other modern creep resistant austenitic steels the results of creep testing programme obtained on basic material and weldment of steel Tp347 HFG confirmed (however the results are still only preliminary) the promising creep resistance of both basic material and weldments. Although the results of short-term as well as creep tests have not shown the difference between material delivered in as-welded state or after PWHT, it seems that it should be better to leave out heat treatment after welding as it encourages excessive grain growth, which is unfavourable from the oxidation resistance point of view.

The results (to date 2013 year) but still do not provide enough information to predict the heat resistance or corrosion resistance (on the flue gas side) examined the specific weld joints in various corrosive environments, either with or without heat treatment. This is the subject of a long-term goal of ongoing research within the project. The results are interpretable only for repeatability of these specific combinations of primary and filler materials, welding or heat treatment method.

ACKNOWLEDGEMENTS

This project was supported by the Ministry of Industry and Trade of the Czech Republic within the R&D project FR-TI3/458 (program TIP3)

REFERENCES

[1] POMIKÁLEK, L., HERMANOVÁ, Š., DOBROVODSKÁ, L. Effect of Welding on the Properties of HR3C, Super 304H, Tp347HFG and P92 Steels, In: *Metal 2013*, Brno, TANGER, s.r.o., Ostrava, 2013, 806-812.

[2] BYSTRIANSKÝ, J., KUČERA, P. Děje ovlivňující vznik oxidických vrstev s dobrými ochrannými vlastnostmi na ocelích v parovodním prostředí energetických okruhů, In: *Metal 2004, Hradec nad Moravicí,* 2004, TANGER, s.r.o. Ostaval, 125-131.

[3] RICHARDOT, D., VAILANT, J. C. Vallourec & Mannesmann Tubes. *The T92/P92 Book*. 2000, 68 s.

[4] SVOBODOVÁ, M. Aplikační omezení žáropevné oceli P92. Informační portál a časopis *All for power*. July, 2009.

[5] Sumitomo Metal Ind. *Properties after long time service exposure of Super 304H steel tubes in power plant*. September 1996.

[6] Sumitomo Metal Ind. *Fabrication of HR3C Steel Tubes.* February 2000.

[7] Sumitomo Metal Ind. *Fabrication of Super304H Steel Tubes*. May 2004.

[8] VdTÜV-Werkstoffblatt 550-Warmfester Walz- und Schmiedestahl X10CrNiCuNb18-9-3 (1.4907), 12/2010.

[9] VdTÜV-Werkstoffblatt 546-Warmfester Walz- und Schmiedestahl X6crNiNbN25-20 (1.4952), 03/2008.

[10] VdTÜV-Werkstoffblatt 547-Warmfester Walz- und Schmiedestahl X8CrNi19-11 (1.4952), 06/2007.

[11] ČSN EN ISO 204 (420351) Kovové materiály Zkoušení tečení jednoosým tahem, Zkušební metoda, ČNI. Praha. October 2009.

[12] LARSON, F. R., MILLER, J. *A* Time-Temperature Relationship for Rupture and Creep Stresses. *Trans. ASME*, 74, 1952, 765-775.

[13] KORCAKOVA, L., MONTGOMERY, M., JENSEN, H.T. Investigations of superheater materials from Nordjyllandsværket coal-fired plant after 100.000 hours service In: *Baltica IX-2013 Interbnational Conference on Fast tools for condition and life assessment of power plants*. Hesinki-Stockholm-Helsinki, 2013.