A challenging weld repair of Grade 91 tubing by avoiding PWHT

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Abstract

Grade 91 pipes and tubes have become a standard material for the design of new and refurbishment of existing Power Plants. Several major failures have been encountered after fabrication of these new Creep Strength Enhanced (CSE) steels and are mainly attributable to improper practices. Another critical situation however is arising when it comes to repair welding. Gas backing and the required PWHT are a time consuming factor in the total weld repair schedule. While PWHT is a prerequisite for obtaining the correct microstructure, power generators will tend to avoid this thermal treatment in order to reduce down-time of the power plant.

In a collaborative research program, the BWI and Laborelec undertook the challenge to investigate the feasibility of a Cold Weld Repair methodology in order to weld repair T91 tubes without the use of gas backing and PWHT. The feasibility study so far demonstrated that a repair method based on the selection of an undermatched consumable and a controlled deposition procedure can result in an acceptable microstructure and hence inherent properties.

The results of the research program are very promising for temporary repair welding of T91 tubes within the containment of the boiler.

Keywords

T91, welding, cold repair

1. Introduction

Advanced CSE 9-12% Cr steels are state-of-the-art in modern power plants operating at 600°/620°C, aiming at increased efficiencies while reducing CO_2 emission. Also during refurbishments of existing power plants the use of 9% Cr steels is evaluated in order to increase creep strengths and thereby life of high temperature components.

However when failures occur, users are facing a double challenge when it comes to repair welding. From the perspective of weld quality and erosion in steam turbine blades, GTAW is the preferred welding process for welding root passes and thin-walled tube. Unfortunately, 9%Cr steels require gas backing to avoid root pass oxidation and a PWHT is required for 9%Cr steels in order to create the correct tempered martensitic microstructure and its inherent properties.

Purging and backing procedures are always a concern when repair welding. Usually a time-consuming total purging procedure is needed or (water soluble) purging dams need to be installed. Anyway, the root quality remains problematic and cannot be guaranteed in general.

PWHT is responsible for a great deal of the repair timeline. For a T91 tube repair, a minimum of 9h direct heat treatment time must be considered without taking into account the set-up and programming of all necessary equipment. Recent experiences published also show that several premature failures are due to improper heat treatment procedures [7, 8, 9, 10, 11].

It were these two concerns and the reduction of down-time during repair that initiated the idea to investigate the feasibility of a repair methodology without the use of argon backing and PWHT for applications in a temperature range of 540°-580°C.

During welding of air hardening T91 steel, the transformation temperatures must be kept in mind and special precautions have to be taken to avoid hard, brittle microstructures and cracking problems in the HAZ and weld metal.

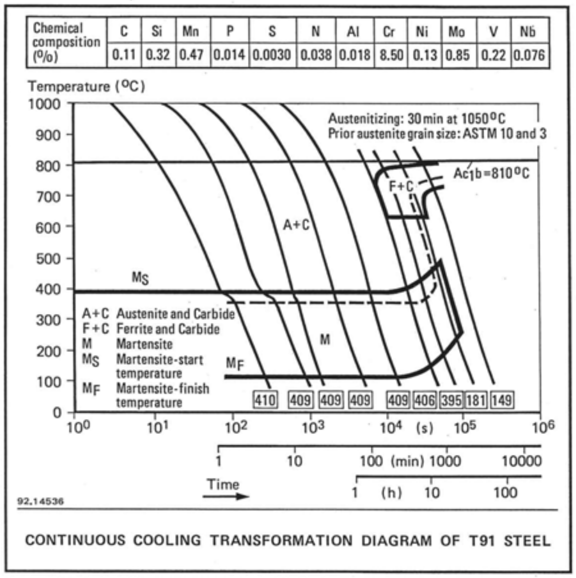

Figure 1: CCT Diagram of T91 steel [1]

For welding thin-walled tubes, preheating at minimum 150°C is acceptable and the maximum interpass temperature is limited to about 300°C. After each weld pass, the weld metal cools down below the martensite start temperature (M_s) of around 380°C (depending on chemical composition), partially transforms to martensite and will be tempered to some extent by the subsequent weld layers. Once the weld is completed, it must cool down slowly to a temperature below 100°C (below the martensite finish temperature M_f) for allowing the complete martensitic transformation before a PWHT is carried out. For medium wall thicknesses and dry atmospheres, cooling down to room temperature is possible. If the martensite transformation was incomplete, remaining austenite transforms only after PWHT, which implies that hard and brittle regions of untempered martensite will be present in the joint. A PWHT is mandatory for tempering the hard, brittle untempered martensite, for relieving the residual stresses and for avoiding the risk of hydrogen stress corrosion cracking. The PWHT temperature must be kept below the lower transformation temperature A_{c1}, to avoid the formation of new austenite which transforms to (hard) untempered martensite on cooling. Depending on chemical composition, A_{c1} can be as low as 785°C, with most of the values between 800°C and 830°C [1]. The optimum PWHT was found to be at 750°-760°C with a minimum holding time of 30 minutes for thin-walled tubes.

2. Service exposed T91 tubes

Within this project EON (UK) delivered T91 finned boiler tubes with an outside diameter of 50,8 mm and a wall thickness of 7 mm. Service life was 56 000 hours. The design pressure was 132 bar. The actual operating pressure was lower. An average value for full load operation had been estimated as 110,4 bar at an average temperature of 553°C. An average value for part load operation had been estimated as 80,1 bar at an estimated average temperature of 569°C.

TABLE 1 : CHEMICAL COMPOSITION, T91 TUBES

C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	N	Al
0,115	0,44	0,35	0,024	0,006	8,77	0,99	0,10	0,190	0,088	0,042	0,008

TABLE 2: MECHANICAL PROPERTIES AT RT, T91 TUBES

$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)	Hardness (HV10)	$KV_{400/5}$ (J)
516	696	24	224 - 232	69 / 71 / 73

3. Development of a cold weld procedure

3.1. Filler metal selection

Within this project, undermatching T24 filler metal from Böhler Thyssen was used. The benefit in using this filler metal is that, due to its low carbon content, it can be welded without PWHT with low as welded hardness and high toughness for the weld metal.

TABLE 3: CHEMICAL COMPOSITION, ALL WELD METAL UNION I P24, Ø 2,4 MM [2]

C	Si	Mn	Cr	Mo	V	N	B	Ti	Nb
0,061	0,23	0,49	2,29	1,0	0,24	0,014	0,002	0,034	0,007

TABLE 4: MECHANICAL PROPERTIES AT 20 °C, ALL WELD METAL UNION I P24, Ø 2,4 MM [2]

PWHT	$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)	Hardness (HV10)	Impact (J)
-	664	803	19,1	322	298 / 298 / 298

The use of this undermatched filler metal also minimises the difference in creep properties between the weld metal and service exposed base material (Figure 2). Due to steam side oxidation rate the service temperature of the 2,25% Cr filler metal is limited to 580 °C [2].

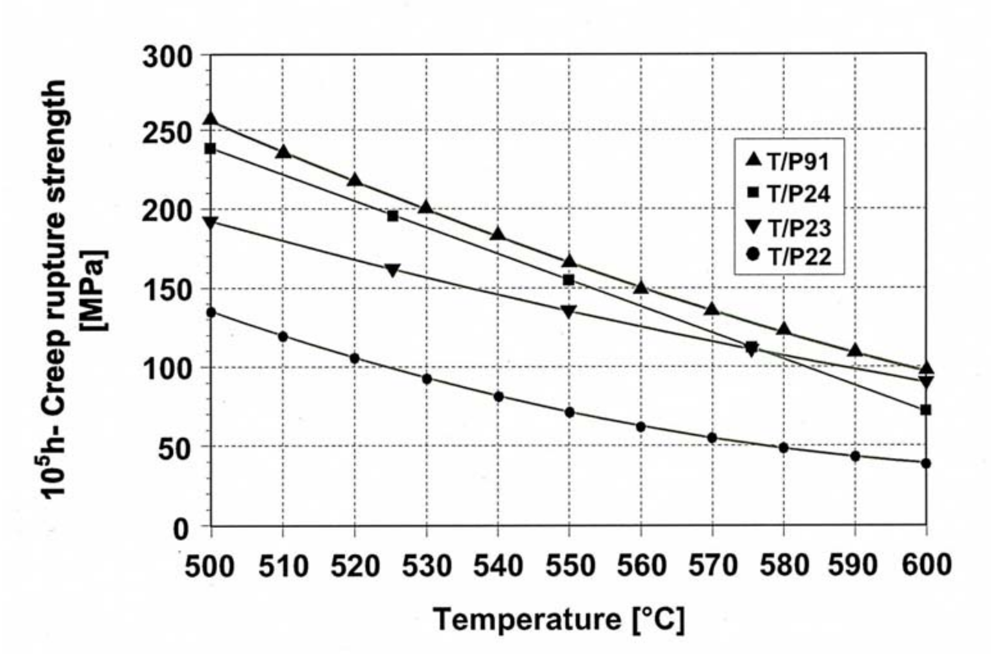

Figure 2: Creep strength of boiler steels

Weldability tests revealed that gas backing is necessary when using T24 filler metal to weld T91 tubes. Excessive oxidation of the root bead was clearly visible after welding.

Figure 3: Oxidation of the root bead (dia. 50.8*7mm)

Therefore it was decided to apply a standard 2,25% Cr filler metal (Union I CrMo910 matching to T/P22) for the root which can be welded without the use of gas backing. A modified 2,25% Cr filler metal (Union I P24) is used for the filling/capping layers.

TABLE 5: CHEMICAL COMPOSITION, ALL WELD METAL UNION I CRMO910, Ø 2,4 MM [2]

C	Si	Mn	Cr	Mo
0,070	0,60	1,00	2,55	1,00

3.2. Determining welding parameters

Weld simulations on T91 base material were performed using a Gleeble to determine the most optimum welding parameters and to look at the influence of the preheat/interpass temperature, multiple layer welding and a controlled deposition procedure (two-layer refinement and temperbeads) on the hardness and impact toughness in the HAZ. The target was a maximum hardness of 350 HV10 and a toughness of 20 J at RT for subsize specimen (thickness 5 mm) corresponding to 40 J for full size specimen. Simulations were carried out with a cooling time $t_{8/5}$ of 35, 50 and 150 seconds, corresponding respectively to preheating at 100°, 175° and 300 °C and a heat input of 10 kJ/cm according to Rykalin 2-D, for a T91 tube with wall thickness 7 mm. Interpass temperatures (T_i) of respectively 100°, 250° and 325 °C were applied.

The following could be concluded from the weld simulations:

- Increasing the preheat/interpass temperature has no significant effect on the hardness in he HAZ of martensitic 9% Cr material after heating into the austenite region. The impact toughness in the HAZ is lowered by applying higher preheat and interpass temperatures.

TABLE 6: INFLUENCE OF PREHEAT/INTERPASS TEMPERATURE

T_{p1} (°C)	T_i (°C)	T_{p2} (°C)	$t_{8/5}$ (s)	$KCV_{400/5}$ (J)	Hardness (HV10)
Coarse Grained HAZ					
1350	250	-	50	30 / 25 / 31	421
1350	325	-	150	17 / 16 / 17	423
SuperCritical Grain Refined HAZ					
1350	250	1050	50	-	438
1350	325	1050	150	-	436
InterCritical HAZ					
1350	250	850	50	-	417
1350	325	850	150	-	421

- Simulation of multiple welding layers (up to four layers) with the application of a temperbead (T_p=750°C) revealed that keeping a higher interpass temperature results in high hardness, which can’t be further reduced.

TABLE 7: INFLUENCE OF INTERPASS TEMPERATURE AND TEMPERBEADS

T_{p1} (°C)	T_{p2} (°C)	T_{p3} (°C)	T_{p4} (°C)	$t_{8/5}$ (s)	Hardness (HV10)
T_i: 250 °C					
1350	750	-	-	50	404
1350	1050	750	-	50	399
1350	850	750	-	50	371
1350	1050	850	750	50	374
T_i: 325 °C					
1350	750	-	-	150	394
1350	1050	750	-	150	391
1350	850	750	-	150	393
1350	1050	850	750	150	390

Keeping a higher interpass temperature during martensitic welding of 9% Cr steels will result in less transformation of austenite into martensite. Only a small volume fraction will be tempered by the next weld layer. This will result in a harder as-welded girth weld. After every weld run, the joint must cool down to 100 °C (i.e. below the martensite finish temperature M_f) allowing the complete transformation to martensite and increasing the effect of tempering of the underlying runs by successive weld beads.

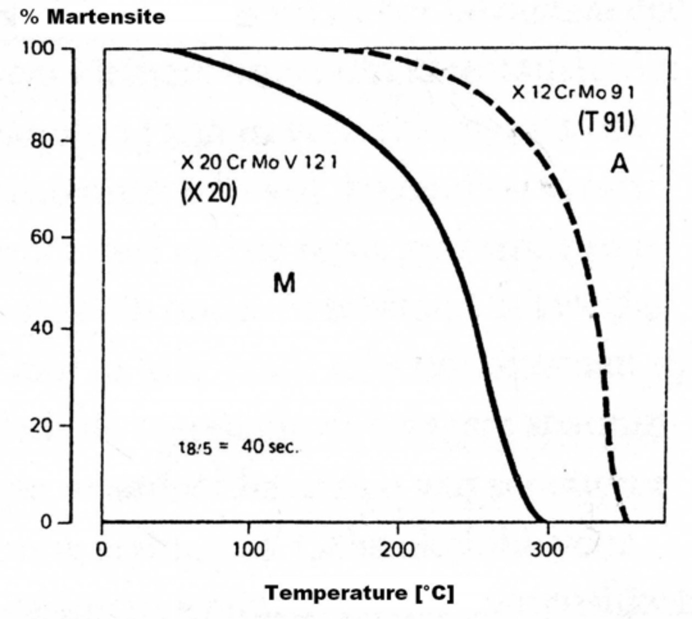

Figure 4: Transformation diagram T91 [3]

- Using a preheat/interpass temperature of max. 100°C and the application of a two-layer refinement technique followed by a temperbead results in a softer microstructure with an acceptable toughness.

TABLE 8:
INFLUENCE OF WELDING PARAMETERS ON IMPACT TOUGHNESS AND HARDNESS IN WELD SIMULATIONS

T_{p1} (°C)	T_i (°C)	T_{p2} (°C)	T_{p3} (°C)	$t_{8/5}$ (s)	$KCV_{400/5}$ (J)	Hardness (HV10)
1350	-	-	-	35	67 / 53 / 56	426
1350	< 100	1050	-	35	80 / 87 / 78	437
1350	< 100	1050	750	35	32 / 31 / 30	385

By application of two-layer refinement, the Coarse Grained HAZ should transform to the SuperCritical Grain Refined HAZ to obtain grain refinement. A third weld run, a temperbead, is needed to reduce the hardness. This heat treatment corresponds more or less to a normalising (1040°C-1080°C) and tempering (750°C-780°C) heat treatment, which gives to the base material the required microstructure i.e. tempered martensite with optimum grain size.

Main conclusions of the weld simulations are:

Applying multiple-layer welding with a preheat/interpass temperature of 100 °C and a controlled deposition is necessary to reduce the hardness substantially and to obtain an acceptable impact toughness in the HAZ. It will be difficult to obtain a girth weld with an as-welded hardness of 350 HV10, especially in the sub-surface HAZ near the cap layer. An acceptable toughness in the HAZ can be reached when low preheat and interpass temperatures are applied.

By reducing the preheat and interpass temperature to 100°C, the temperature falls within the sensitive temperature range for cold cracking, also called hydrogen cracking, to occur. However, three conditions must be present simultaneously: a sensitive microstructure, a sufficient level of hydrogen and a high level of stress. Hard, brittle martensite which promote crack formation is present, but the direct control of hydrogen level is the most important method for avoiding hydrogen cracking. As the hydrogen level is reduced from high to very low, higher hardness levels can be tolerated in the HAZ. A low hydrogen technology should be applied. Therefore the TIG welding process must be used, which is regarded as giving ultra-low hydrogen levels. It is also important to maintain control of steel cleanliness, for example corrosion products (i.e. rust). Material stresses (transformation from austenite to martensite), system stresses (high restraint) and welding stresses are present but will be limited when welding thinwalled, tube to tube connections.

4. Procedure for cold weld repair

After fine-tuning, the following weld procedure was developed:

- remove all oxidation/corrosion products at the inside/outside of the tube by grinding/brushing;
- machine a bevel as shown in figure 5 below. The advantage of a modified joint design is that it leads to a more controlled deposition;

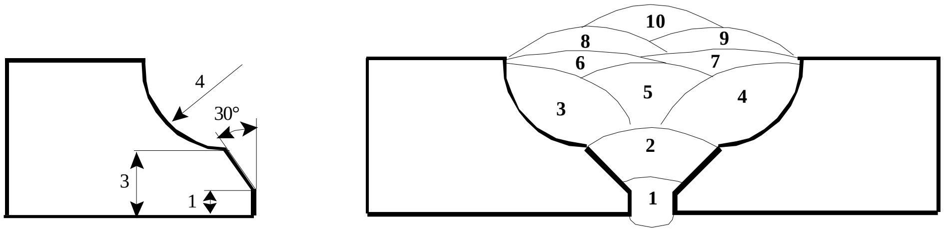

Figure 5: Joint design and weld build up

- use GTAW welding;
- preheat and interpass temperature are 100 °C and must be kept as constant as possible;
- use standard 2,25% Cr filler metal (Union I CrMo 910) for the root layer (without gas backing);
- use modified 2,25% Cr filler metal (Union I P24) for the filling/capping layers;
- use a weld sequence as shown in the figure 5 above;
- use a ‘half bead’ technique for the filling layers, by grinding away the coarse grained weld metal after each weld run;
- use a temper bead to achieve some degree of tempering at the sub-surface HAZ near the cap layer;
- cool down under insulation;
- no Post Weld Heat Treatment is applied.

With this weld procedure, an as-welded hardness below 385 HV10 and high toughness in the weld metal (81J/81J/91J) could be achieved when welding clamped tubes (high restraint) in PC position.

TABLE 9: AS-WELDED HARDNESS OF A JOINT WELDED IN PC POSITION

HV10	HAZ			WM			HAZ		
FACE	206	355	383	343	336	358	352	344	294
MID	320	349	335	368	347	357	333	314	275
ROOT	313	292	333	381	383	374	354	263	274

The impact of a controlled deposition procedure is demonstrated by a joint welded in PF position, where hardnesses below 350 HV10 as well above 400 HV10 are measured in the same weld.

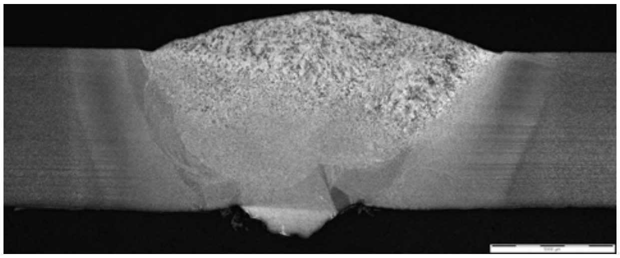

Figure 6: Macro of a joint welded in PF position

TABLE 10: AS-WELDED HARDNESS OF A JOINT WELDED IN PF POSITION

HV10	HAZ			WM			HAZ		
FACE	219	298	315	333	314	327	413	405	301

The sub-surface hardness in the HAZ near the cap layer could be reduced significantly by applying an adequate temperbead technique. This requires a weld bead to be deposited at a fixed and closely controlled distance from the weld toe. This bead tempers the hard HAZ on the parent steel of the final weld run and leaves its own HAZ in less hardenable weld metal. If required, the temper bead can be ground off on completion.

The impact toughness in the HAZ was high, around 100 J. It was remarked that the fracture pattern tends to deviate out of the hard HAZ in to the soft parent metal. Tensile specimens broke outside the weld metal and face/root bends showed no cracks.

5. Cold weld repaired T91 tubes in service

Because there is still a risk that cold weld repairs with a too high hardness are put into service, an evaluation is made of the behaviour of such joints and possible damage mechanisms during service.

A hard HAZ is sensitive to hydrogen induced stress corrosion cracking (SCC) in a humid environment. Little information is available in literature, but some results are reported on the stress corrosion susceptibility of T91 in chloride-containing waters (content of chloride 50 ppm and 500 ppm) [4]. To determine the critical hardness, T91 was tempered at different temperatures. The specimens were loaded with a stress of 90% $R_{p0,2}$ during 3139 h, if no fracture occurred before. It was shown that T91 is resistant to stress corrosion cracking in waters containing 50 ppm of chloride. After addition of 500 ppm chloride, fracture was observed in specimens with hardness above 400 HV10. The critical hardness is considered to be 400 HV10, if a corrosive medium is present. EPRI on the other hand reported a critical hardness of 270 HV10 [5]. They developed a screening method for two SCC damage mechanisms (hydrogen embrittlement and active path corrosion) by immersion corrosion tests on modified C-Ring specimens. However, they could not reproduce SCC in self-restrained weld specimens from Grade 91 material. They argued that welded specimens are not suitable for screening tests because of variations in the condition of the HAZ microstructure in the multi-pass weld due to the tempering effect of the sequential beads. This latter confirms that by applying a modified welding technique using multiple-layer welding SCC can be avoided. So, in combination with the elimination of an aqueous corrosive environment, by keeping the welds dry and free of contaminants, SCC can be eliminated.

Reheat cracking, also called stress relief cracking, is defined as an intergranular cracking phenomena occuring in the HAZ or in the weld metal of a welded joint, being initiated during PWHT or during high temperature service. A susceptible microstructure is a coarse prior austenite grain size with strong grain interiors that resist plastic deformation and weak grain boundaries. During a PWHT the residual stresses caused by welding will relax on the coarse prior austenite grains and there may be a risk of cracking if the material is susceptible. Cracks can be found during non destructive examination after the heat treatment. When a cold repair is carried out, the initial thermal exposure occurs in service. Hence, cold repair requires a welding procedure which does not produce a crack susceptible coarse grained HAZ or weld metal. At the Research Center of the Belgian Welding Institute, a lot of experience has been gathered with the isothermal slow strain rate tensile test. In this test, cylindrical specimens are given a weld simulation cycle with peak temperature 1350 °C to simulate the CG-HAZ. After cooling to room temperature, the specimen is heated to and held at the temperature of interest. As soon as this temperature is obtained, the specimen is slowly strained to fracture at a tensile velocity of 0,5 mm/min. After fracture, the specimen’s reduction in area is measured to assess the ductility. The reduction in area is an indication of the susceptibility to reheat cracking. For reductions of more than 20% the material is not susceptible. Research showed that T22, T24 and T91 have reductions in area above 20% indicating that they are not susceptible to reheat cracking in as welded condition at service temperatures from 540 °C to 580 °C.

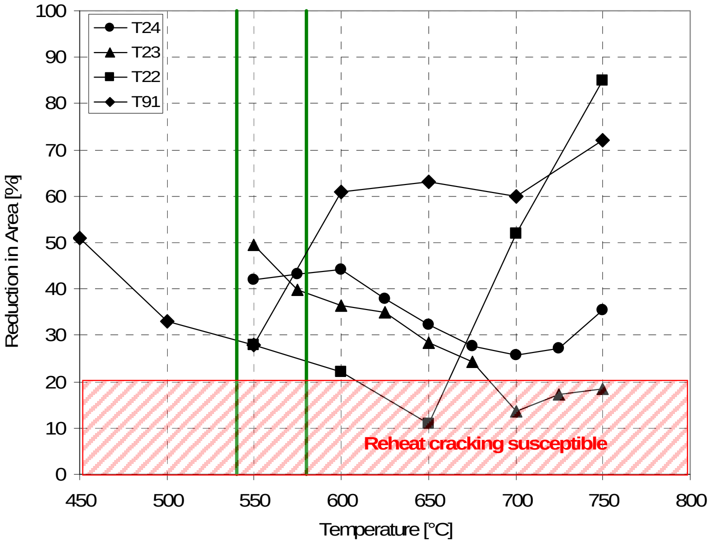

Figure 7: Reheat cracking susceptibility of boiler tubes

Within this project, the influence of the service temperature on the hardness was examined. T91 tubes were TIG welded in PC position without gas backing and without PWHT using standard 2,25% Cr filler metal for the root and Union I P24 for the subsequent layer. The joint was not fully filled (only two layers). Sub-surface hardness measurements near the root layer were made on test specimens removed transversely from the welded joint. Ageing tests at 560°C were started to examine how long it takes for the hardness to reduce to an acceptable level. The specimens were taken out of the furnace after 6, 12, 24, 50, 100, 500 and 1000 hours. The initial maximal hardness was around 440 HV10 in the HAZ and around 380 HV10 in the weld metal. After ageing the maximum hardness in the HAZ reduced to around 400HV10 after 24 hours, 380 HV10 after 50 hours and 350 HV10 after 500 hours. The weld metal was more temper resistant and the hardness was reduced to values below 350 HV10 after 500 hours. The HAZ and the weld metal softens and stresses relax, so the risk reduces as the weld ages in service.

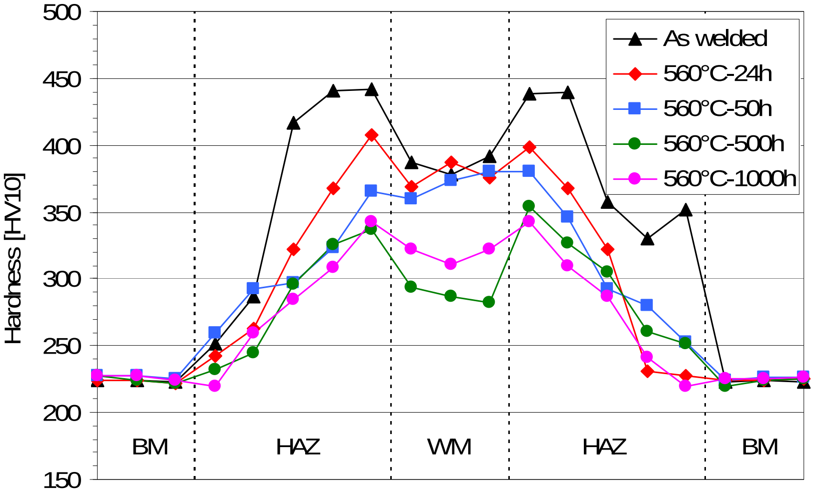

Figure 8: Influence of service temperature on hardness

Due to the difference in chromium contents between the materials involved, carbon diffuses during exposure at service temperatures, from the lower Cr-alloyed weld metal (2,25% Cr) into the neighbouring higher Cr-alloyed base material (9% Cr). As a result, a carbon-depleted zone evolves in the weld metal and a carbon-enriched zone (so called carbon band) in the T91 base material. The extensions of these zones depend on exposure time and temperature. In comparison with dissimilar metal welds P22/P91 the special carbide forming elements V, Nb and Ti in the modified 2,25% Cr weld metals either prevent or reduce the degree of carbon diffusion [6].

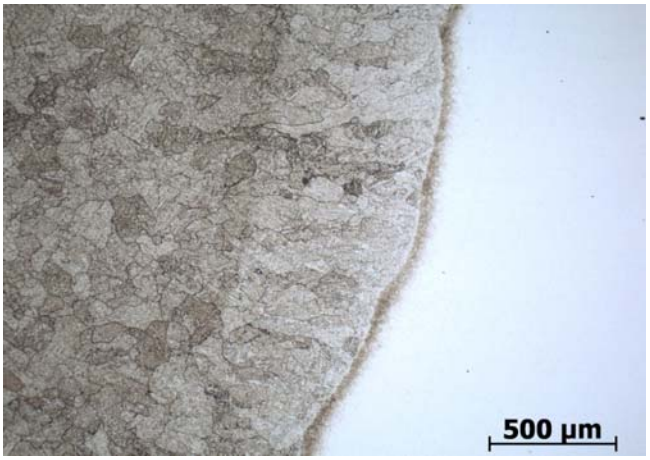

Figure 9: Carbon diffusion in T91 joint with modified T24 filler metal (560°C during 1000 hours)

Carbon diffusion could influence the impact toughness of the weld metal near the fusion line and creep strength of the cold welded joined. Isothermal creep tests at 580 °C on cold weld repaired tubes were started. The specimens at high stress levels broke, all but one, in the SubCritical-HAZ with hardness values below 350 HV10 across the joint. The specimen at a stress level of 150 MPa broke in the T24 filler metal. Test results can be found in figure 10 and are compared with creep results on tubes repair welded according to a standard weld procedure with matching filler metal followed by a PWHT (750°C - 30 minutes). Creep tests at lower stresses are subject to further investigation.

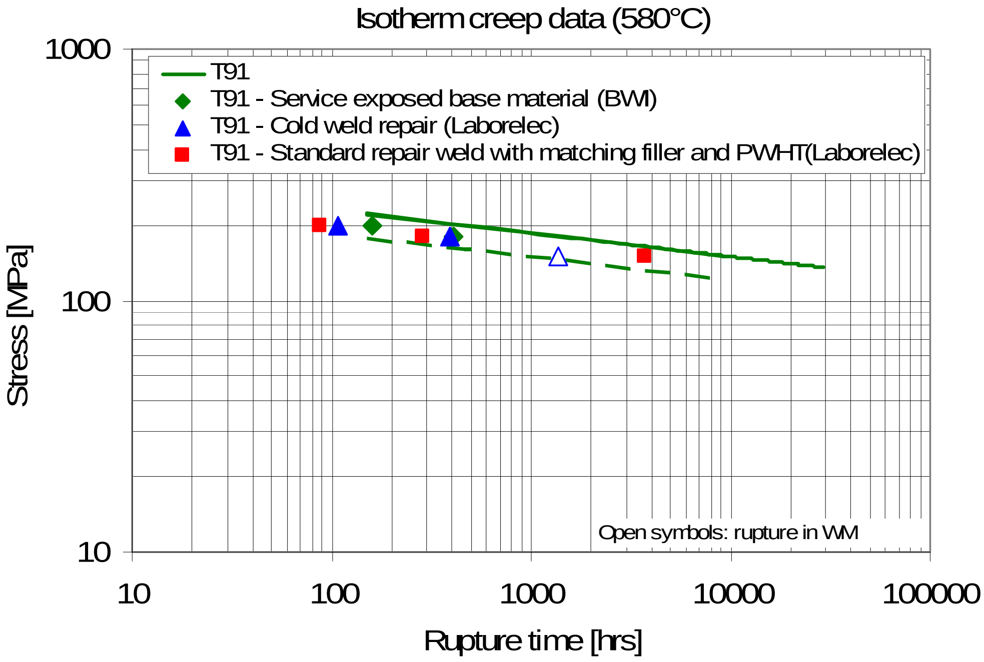

Figure 10: Creep strength of cold weld repaired T91 tubes

6. Conclusions

Within this project a cold weld repair procedure without gas backing is developed for thinwalled T91 tubes, for applications in boilers, where the safety risk is limited. Hardness values below 380HV10 without PWHT could be obtained under optimized conditions, but a controlled deposition welding technique requires careful planning and welder training well ahead to the actual repair. Monitoring during repair welding is necessary. Creep tests at lower stresses to guarantee a life extension of 3 to 4 years for T91 tubes by cold weld repair and service exposed repairs are subject to further investigation.

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References

1. Vallourec & Mannesmann Tubes "The T/P91 Book" 1999
2. J.C. Vaillant, B.Vandenberghe, B. Hahn, H. Heuser, C. Jochum "T/P23, 24, 911 and 92: New Grades for Advanced Coal-Fired Power Plants – Properties and experience" ECCC Creep Conference September 2005, London
3. J. Quist "Het lassen van een kruipvast martensitisch Cr-staal met 9-12%" Lastechniek oktober 1997
4. Dr. W. Bendick, "Development and qualification of a W-bearing modified 9%Cr steel for use in the boiler and piping system of advanced high efficiency, low emission power plants" COST501-Round III
5. K. Coleman "Stress Corrosion Cracking of Grade 91 materials" EPRI Tech Update 1013360, March 2007
6. H. Heuser, C. Jochum, W. Bendick, B. Hahn "Welding of dissimilar joints of new power plant steels" IIW International Conference July 2008, Graz
7. R. Swanekamp "Maintenance Workshop Tackles the Challenges of P91/T91 and HRSG Layup" – Power Engineering/January 2004
8. P. de Smet, H. van Wortel "Controlling Heat Treatment of Welded P91" – AWS Welding Journal/June 2006
9. R. Swanekamp "Handling Nine-Chrome Steel in HRSGs" – Power Engineering/February 2006
10. K. Coleman, W.F. Newell Jr. "P91 and beyond" – AWS Welding Journal/August 2007
11. J.F. Henry "Growing experience with P91/T91 forcing essential code changes" – Combined Cycle Journal/Q1 2005