UPUTE ZA ZAVARIVANJE I PREGLED ČELIKA ZA OPREMU ENERGETSKIH POSTROJENJA TE MOGUĆNOSTI KORIŠTENJA SIMULACIJA U ZUT-U ZA UNAPRJEĐENJE KVALITETE ZAVARA

INSTRUCTION OF WELDING AND REVIEW OF STEELS FOR POWER PLANT EQUIPMENT AND POSSIBILITY OF USING HAZ SIMULATION IN ORDER IMPROVE WELD JOINT QUALITY

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Ključne riječi: 9 % Cr čelici, 9-12 % Cr čelici, energetska postrojenja, toplinska obrada, zona utjecaja topline, tvrdoća, žilavost

Key words: 9 % Cr steels, 9-12 % Cr steels, power plant, post weld heat treatment, heat affected zone, hardness, toughness

Sažetak: U radu je predstavljen pregled čelika za opremu energetskih postrojenje, počevši od C-Mn čelika, a završavajući sa 9-12 % Cr čelicima, uključujući i neke CCT dijagrame. Prestavljene su osnovne instrukcije za zavarivanje novih CrMo i novih 9-12 % Cr čelika, te njihova obavezna naknadna toplinska obrada. Moguće je pojavljivanje nekih problema u ZUT-u tijekom eksploatacije, posebice pukotina tipa IV kod 9-12 % Cr čelika u finozrnatom ZUT-u. Na kraju rada je predstavljen način kako se simulacijom toplinskog ciklusa zavarivanja u ZUT-u može unaprijediti kvaliteta zavarenog spoja.

Abstract: In article is presented review of steels for power plant equipment starting with C-Mn steel and ending with new 9-12 % Cr steels including some CCT diagrams. There are presented some basic instruction for welding new CrMo and new 9-12 % Cr steels and their obligatory post weld heat treatment. Some problems also can appeared in HAZ during exploitation especially type IV cracking in 9-12 % Cr steel that appear in fine grain HAZ. Way how to use simulation of HAZ material in order to improve weld joint quality is presented at the end of article.

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1. INTRODUCTION

Electricity can be produced in hydroelectric stations, steam power stations, nuclear power stations and Renewable Power Station (solar photovoltaic, wind...). Great proportion of world electricity production is produced in steam power stations on fossil fuels. Last accident of the Fokushima nuclear power station in Japan was split world's expert public about reasonableness of nuclear power stations, because pollution was not lag far behind to pollution in Chernobyl's accident in Ukraine. Some governments like German think to gradual close down of the nuclear power stations. It is expected that proportion of the electricity which is produced in steam power stations will rise in near future, but only under condition that emissions of $C0_2$ will decrease and efficiency of the steam power stations will increase [1].That can be attained only by using better combustion of fossil fuels and by using higher steam's exploitation temperatures and steam's pressure. New grades of materials will needed to use to attain this goal and reduce of power plant components weight [2]. It is almost demand that new materials need to be resistant to creep, resistant to corrosion and they need to have high tensile strength and impact toughness and other mechanical properties at elevated temperatures. They need to be resistant to cracks, especially to cracks of type IV, which usually appear in heat affected zone (HAZ) near weld joints. All steam power plant components make by welding, because of their bigness and their complexity. Weld joints are usually the weakest link in power plant components. They need to be welded by using appropriate filler materials and optimal technology of welding and appropriate post weld heat treatment (PWHT)[3]. Power plant components are equipment which operates at pressure at elevated temperature, so they need to be produced according to the Pressure Equipment Directive PED and its harmonised standards when they were made in Europe. Only that way could be assure uninterrupted operation of power steam power stations during their lifetime which are approximately 30 to 40 years.

2. MATERIALS FOR STEAM POWER PLANTS COMPONENTS

Development of steels for steam power plants is shown in figure 1 according to 10^5 h creep rupture strength and operation temperatures. Chemical compositions of steels that are used for power plants components and equipment in steam power stations are shown in table 1 [2].

3. KARAKTERISTIKE I PROIZVODNJA RAZLIČITIH TIPOVA PRAHOM PUNJENIH ŽICA

Prahom punjene žice sastoje se iz metalnog plašta i punila. Poprečni presjek prahom punjene žice izrađene punjenjem cijevi prikazan je na slici 1. Električni luk kod MIG/MAG zavarivanja prahom punjenom žicom prikazan je na slici 2.

Funkcija metalnog plašta je, da stvara osnovni metal depozita, formira oblik žice i omogućuje prijelaz električne struje preko plašta.

Punilo može biti na bazi metala, minerala, dezoksidanata i dodataka a ima slične karakteristike kao plašt kod obloženih elektroda. Punilo omogućava čišćenje zavara, dezoksidaciju, legiranje, veću stabilnost električnog luka, tvorbu kapljica, putem troske sprječava oksidaciju zavara te usporava hlađenje metala šava.

Karakteristike prahom punjenih žica razlikuju se međusobno i po tehnologiji izrade. Postoji više postupaka, ali u principu su tri osnovna postupka izrade punjenih žica: bešavna prahom punjena cijev, izrada cijevi iz traka na stik i izrada cijevi preklapanjem, slika 3 [1].

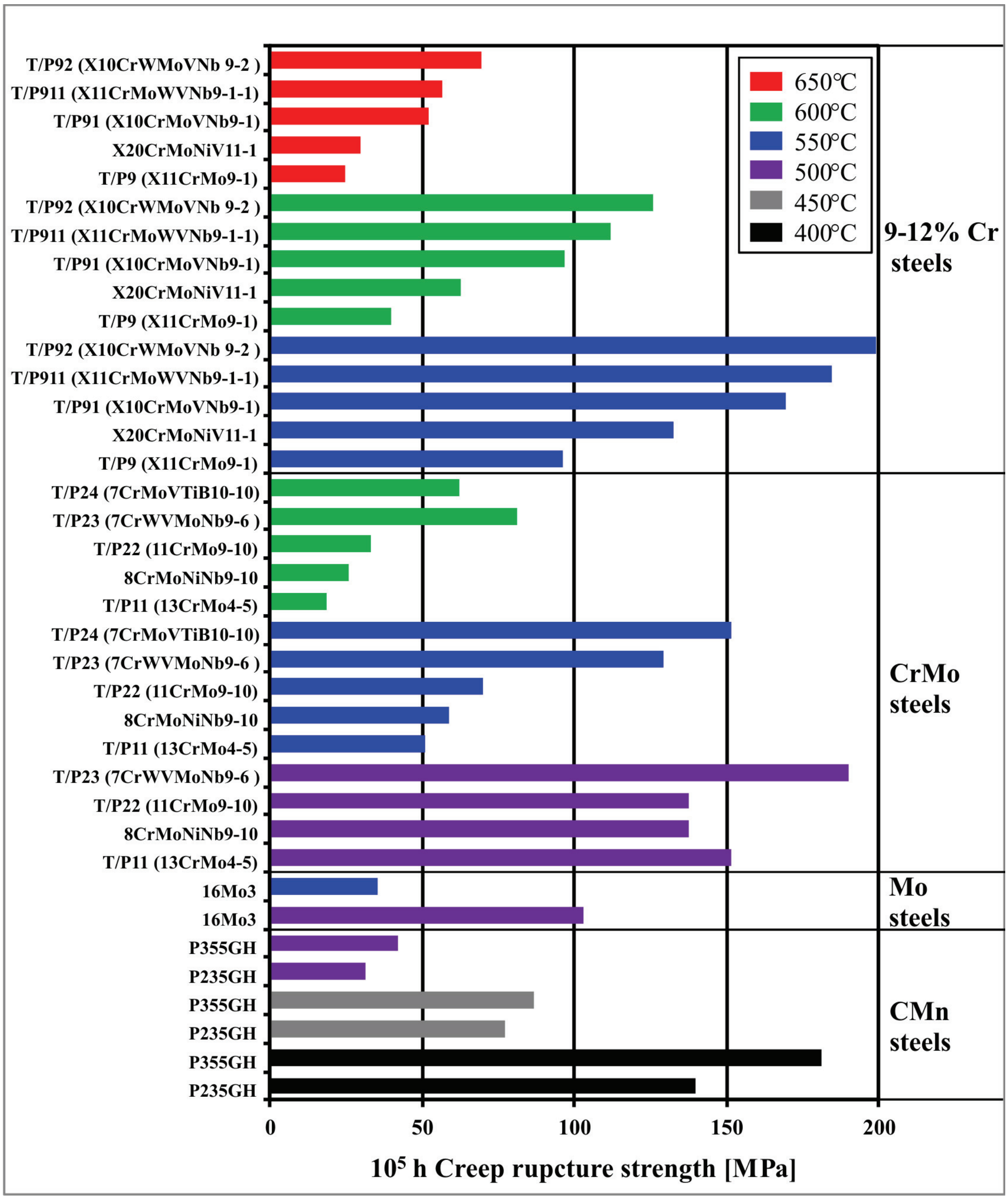


Figure 1. 10^5 creep rupture strength for several materials at different temperatures

2.1. CMn steels

P235 GH has ferrite perlite microstructure. Contents of carbon and manganese influence on better strength properties. Addition of niobium refines crystal grains and increase yield stress at steel P355. Rupture strength is not increased by niobium, but it is increased by addition of manganese CCT diagram for P355 GH steel is shown in figure 2.

Table 1. Chemical composition of the steels for power plant components in weight % [2]

Material		C	Si	Mn	P	S	Ni	Cr	Mo	W	Ti/Cu	V	Nb	Al	N	B
P235 GH	> ≤	0,16	0.35	0.40 0.80	–	–	0.30	0.30	0.08	–	Cu 0.30	–	–	0.02	–	–
P355 GH	> ≤	0,22	0,15 0,35	1,00 1,50	–	–	–	–	–	–	–	–	0,02 0,10	0,06	–	–
16Mo3	> ≤	0,12 0,20	0,15 0,35	0,40 0,80	–	–	–	–	0,25 0,35	–	–	–	–	0,04	–	–
T/P11	> ≤	0,10 0,17	0,10 0,35	0,40 0,70	–	–	–	0,70 1,10	0,45 0,65	–	–	–	–	0,04	–	–
8CrMoNiNb9-10		0,10	0,15 0,40	0,40 0,80	–	–	0,30 0,80	2,00 2,50	0,90 1,10	–	–	–	10× %Cr	0,04	–	–
T/P22	> ≤	0,15	0,50	0,30 0,60	0,025	0,025	–	1,90 2,60	0,87 1,13	–	–	–	–	–	–	–
T/P23	> ≤	0,04 0,10	0,50	0,10 0,60	0,030	0,010	–	1,90 2,60	0,05 0,30	1,45 1,75	–	0,20 0,30	0,02 0,08	0,03	0,03	0,0005 0,0060
T/P24	> ≤	0,05 0,10	0,15 0,45	0,30 0,70	0,020	0,010	–	2,20 2,60	0,90 1,10	–	Ti 0,05 0,10	0,20 0,30	–	0,02	0,01	0,0015 0,0070
X20CrMoV11-1		0,17 0,23	0,15 0,50	1,00	0,025	0,020	0,30 0,80	10,00 12,50	0,80 1,20	–	–	0,25 0,35	–	0,04	–	–
T/P91	> ≤	0,08 0,12	0,20 0,50	0,30 0,60	0,020	0,010	0,04	8,00 9,50	0,85 1,05	–	–	0,18 0,25	0,06 0,10	0,04	0,03 0,07	–
T/P92	> ≤	0,07 0,13	0,50	0,30 0,60	0,020	0,010	0,04	8,50 9,50	0,30 0,60	1,50 2,00	–	0,15 0,25	0,04 0,09	0,04	0,03 0,07	0,0010 0,0060
T/P122	> ≤	0,07 0,13	0,50	0,70	0,020	–	0,50	10,00 12,50	0,25 0,60	1,50 2,50	Cu 0,30 1,70	0,15 0,30	0,04 0,10	0,04	0,04 0,10	0,0050

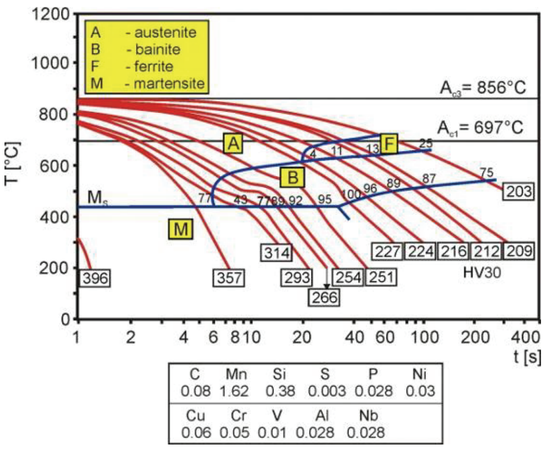


Figure 2: CCT diagram for P355 GH

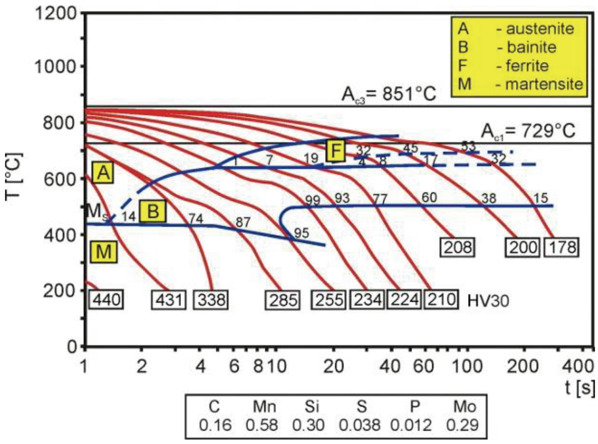


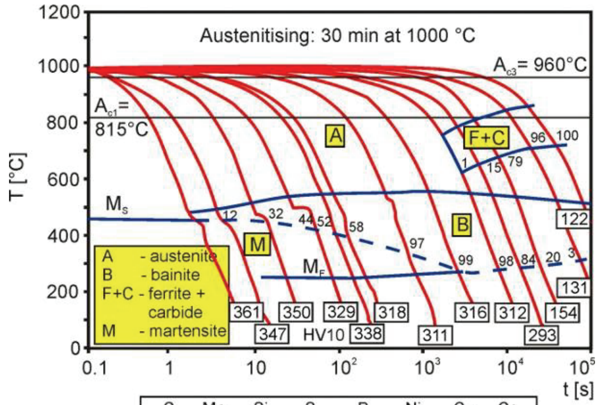
Figure 3: CCT diagram for 16Mo3 steel

2.2. Mo steels

Mo steels were alloyed by about 0,3 % of molybdenum, which increase creep rupture strength. Typical materials from this grade of steels are 16Mo3 and 9NiCuMoNb5-6-4 (WB36) steels. CCT diagram for 16Mo3 steels is show in figure 3.

2.3. CrMo steels

CrMo steels were used for power plant components and equipment for many years. They enabled to attain exploitation temperature above 500 °C for first time and they were resistant to creep enough. Mainly they are alloyed by Mo and Cr which enables better creep rupture strengths than classical Mo steel. Mo and Cr form chromium carbides which are stable above 500 °C. Higher Cr content enables also higher exploitation temperatures and higher corrosion resistant. New steels are developed by using classical 10CrMo9-10 (T/P22) steel as a base. Those steels are 7CrWVMoNb9-6 (T/P23) which were developed in Japan and i 7CrMoVTiB10-10 (T/P24) which was developed in Germany. T/P23 steel is alloyed by wolfram, vanadium, molybdenum and niobium and T/P24 steel is alloyed by vanadium, titanium, and boron to attain better creep resistance of the steels. Low content of carbon enables lower hardness and microstructure is mainly bainitic. Thin T/P23 and T/P24 steels can to operate even without PWHT after welding. Those steel is preferable in components and equipment where water is inside medium. Figure 4 shows CCT diagram for T/P24 steel [2].



C	Mn	Si	S	P	Ni	Cu	Cr
0.08	0.53	0.21	0.004	0.004	0.18	0.09	2.44
Mo	V	Al	Ti	B	N	Nb	
0.95	0.26	0.004	0.053	0.004	0.0072	0.002	

Figure 4: CCTdiagramfor T/P24 steel [2]

2.3.1. Welding of T23 Steel

Welded joints on T23 steels can be welded by using appropriate consumable materials without preheating and with preheating till 175 °C depending on wall thickness and complexity of welded structure [4]. PWHT in some cases is not needed, if the hardness is enough low, below of 350 HV10 (figure 5). The difference of the hardness on welded joints made by preheating and without preheating is small. Welding of boiler screen (heat exchanger in figure 6) can be performed by bends of T11 or T22 material and 2,25 % Cr 1% Mo consumable material. Welding can be made by using SAW welding process with or without preheating. Maximal allowable hardness is 350 HV10.

2.3.2. Welding of T24 steel

Welding can be performed without using preheating or using preheating of 200 °C depend on wall thickness and complexity of welded structure [4]. PWHT after welding is not necessary if hardness stays below 350 HV10 (figure 5). Influence of preheating to hardness is small. Welding of boiler screen (heat exchanger in figure 6) can be performed by bends of T22 material and 2,25 % Cr 1% Mo consumable material without PWHT if hardness in HAZ is below 350 HV10. In the case of T24 bends material is possible to use 1 Cr 0,5 Mo/2,25 Cr 1 Mo or T24 consumable material [3]. After welding, PWHT is not needed if hardness stays below 350 HV10.

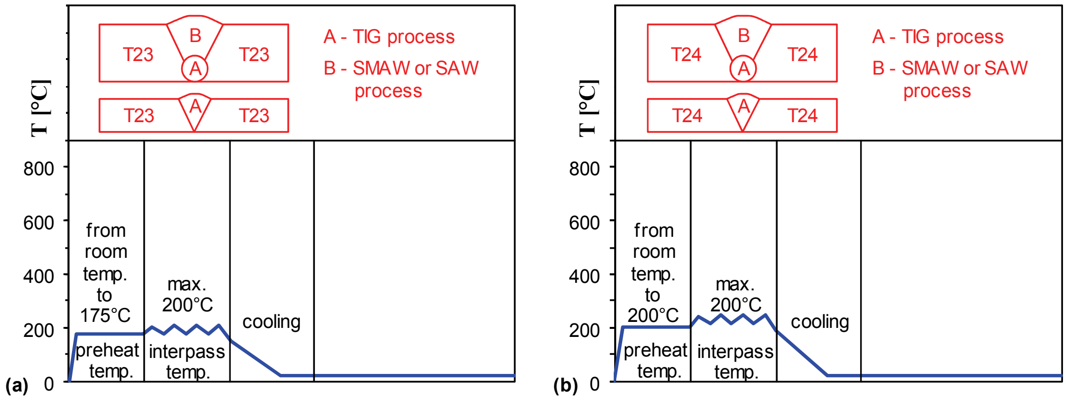


Figure 5: Welding T23 to T/P23 (a), welding T24 to T24 (b)

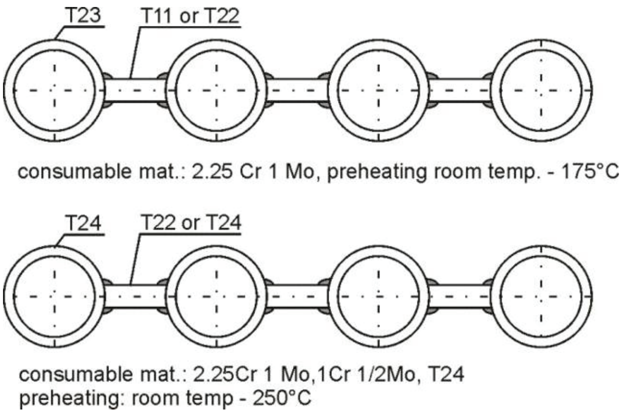
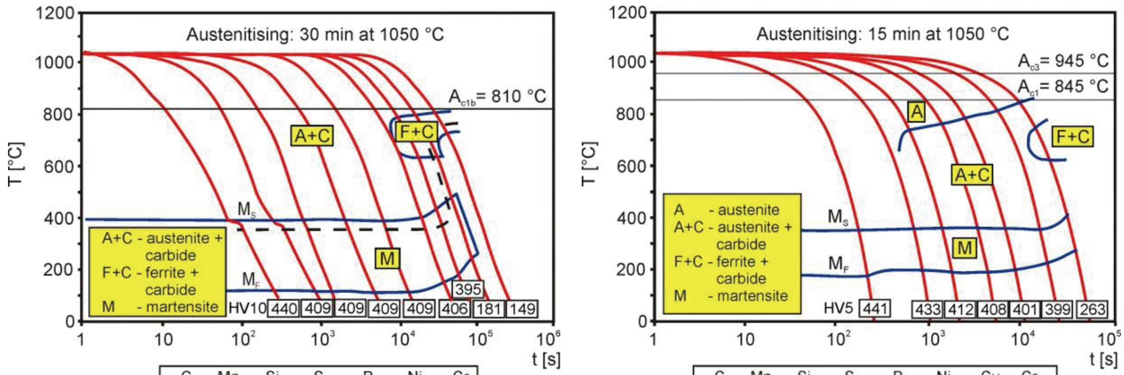


Figure 6: Welding parameters for pipe-line-walls

2.4.9-12% Crsteels

If content of Cr and Mo increase above 7 %, microstructure became mainly martensitic. Microstructure consist fine lath martensite which is stabilised by $M_{23}C_6$ precipitations. T/P91 steel is alloyed by molybdenum, vanadium and niobium. It has better creep rupture resistance and strength at elevated temperatures according to classical X20CrMoNiV11-1 steel even that Cr content is lower. T/P911 is almost the same like T/P91 steel except that T/P911 steel consist also approximately 1 % of wolfram. Similar T/P92 and T/P122 steels are alloyed also by wolfram (1,5-2,5 %) to prevent formation of delta ferrite. Less content of molybdenum is replaced by higher content of wolfram, but proportions of Mo + ½ W remain the same for both steels (T/P91 and T/P92). Wolfram is used for increase the strength of material. During exploitation wolfram precipitate in new Laves phase which is not usual imminently after welding. This is one reason why at those grade of steels impact toughness decrease during the exploitation. All 9-12% steels are alloyedby boron in order to reduce growth speed of carbides. Steels P122 is additionally alloyed by copper and it has good resistance to corrosion. Copper content in steel enable to reduce A_{C1b} temperature little above 800 °C, so PWHT can be performed at lower temperature with but using longer time. Softening in HAZ at T/P122 steel after welding is even higher according to other steels in this group. 9-12 % steels are used in normalised condition followed by appropriate heat treatment where optimal proportion of yield stress, ultimate strength and impact fracture are achieved. On figure 7 is shown CCT diagrams for T/P91 and T/P92 steels [2].



C	Mn	Si	S	P	Ni	Cr
0.11	0.32	0.47	0.003	0.014	0.13	8.5
Mo	**V**	**Al**	**Ti**	**N**	**Nb**	
0.85	0.22	0.018	0.004	0.038	0.076	

C	Mn	Si	S	P	Ni	Cu	Cr
0.11	0.45	0.22	0.007	0.015	0.26	0.07	9.11
Mo	**V**	**Al**	**Ti**	**B**	**N**	**Nb**	**W**
0.47	0.21	0.006	0.004	0.003	0.045	0.065	1.77

Figure 7: CCT diagrams for T/P91 steel (left) and T/P92 steel (right) [2]

2.4.1. Welding of T/P91

Welding technology for T/P91 is similar for martensitic 9 – 12 % Cr steels. In figure 8 is shown typical heating cycle before, during and after welding. Preheating temperature is around 200 °C in order to avoid hydrogen cold cracking. Welding interpass temperature should be kept bellow 300 °C. After welding, is essential to slowly cool down below 80 °C – 100 °C for thin material and to room temperature for thick material in order to complete transformation into martensite. PWHT after welding is obligatory. PWHT temperature is between 750 – 770 °C [5].

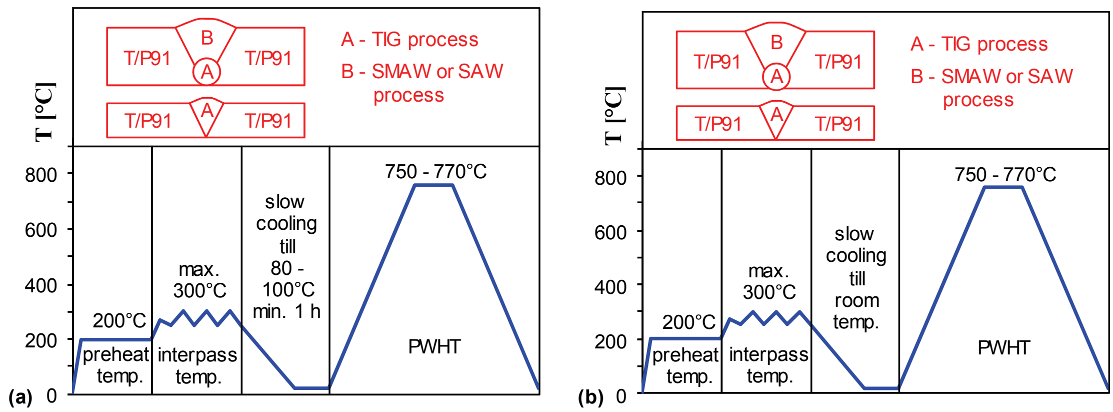


Figure 8: Welding T/P91 to T/P91; thick material (a), thin material (b)

The welding parameters maybe varied depending on type of welding structure. Butt welds and welds in tubes that usually contain low residual stresses can be welded below 200 °C depending on wall thickness. Till wall thickness 80 mm they can be allowed to cool down to room temperature. Otherwise heavy tick wall forgings or castings should never be welded below 200 °C and cooling after welding must be limited to a minimum temperature 80 °C in order to avoid cracking. Satisfactory impact toughness which is mainly problem in weld material can be achieved by multiple-bead welding technique.

2.4.2. Welding of P92

Welding technology from welding T/P91 steel can be translated to T/P92 steel. Figure 9 shows typical heating cycle before, during and after welding. Preheating temperature is around 200 °C and welding interpass temperatures have to be below 250 °C. After welding, it is essential to cool down slowly below to 100 °C, in order to allow complete transformation into martensite (see figure 5). PWHT after welding is obligatory. PWHT temperature is between 750 – 770 °C. Duration of PWHT depends on thickness of material and complexity of welded structures. During PWHT material has to handle with care to avoid damage. Typical heating rate is 100-150 °C/h and typical cooling rate 150 °C/h [6].

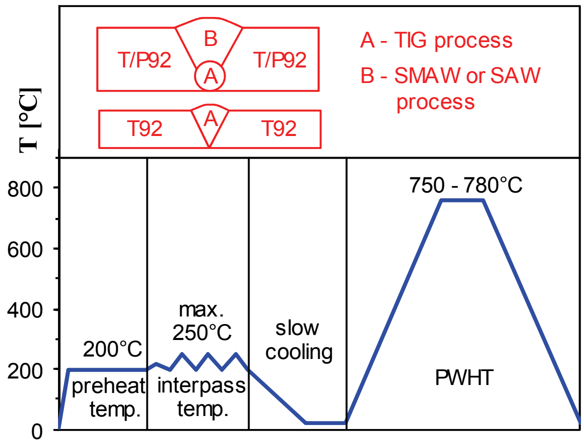


Figure 9: Welding T/P92 to T/P92

The welding parameters maybe varied depending on type of welding structure. Butt welds and welds in tubes that usually contain low residual stresses can be welded below 200 °C depending on wall thickness. Till wall thickness 50 mm they can be allowed to cool down to room temperature. Otherwise heavy tick wall forgings or castings should never be welded below 200 °C and cooling after welding must be limited to a minimum temperature 80 °C in order to avoid cracking. Satisfactory impact toughness which is mainly problem in weld material can be achieved by multiple-bead welding technique.

9-12 % Cr steels during long exploitation might have some problems in weld joints with type IV cracking, which can appeared in fine grain heat affected zone (HAZ). During exploitation, more and more Laves phase appeared in HAZ and weld material. That reduce impact toughness of material and some crack can be appeared in fine grain HAZ so welding have to be optimised to prevent this.

3. INVESTIGATION ON SIMULATION OF HAZ MATERIAL

HAZ region in welded joint is narrow and materials in the HAZ are heterogeneous. Many different microstructures arise in HAZ under the influence of weld thermal cycle. Mechanical properties in HAZ are hard to determine except hardness, because particular HAZ region is very narrow. In order to analyse particular part of HAZ simulation of HAZ material was used. Fine grain HAZ was analysed, because this HAZ region is the most problematic due to creep in practice. Uninfluenced base material was used for simulation. It was exposed to influence of weld thermal cycle, which is the same like influence of the weld thermal cycle for particular part of HAZ in real weld. It was exposed to influence of weld thermal cycle, which is the same like influence of the weld thermal cycle for particular part of HAZ in real weld. For simulation are needed some real data like heating speed, maximal temperature, holding time at maximal temperature and cooling speed, especially cooling time between 800 and 500 °C ($\Delta t_{8/5}$) [7-9]. Influence of weld thermal cycle and dilatation curve are recorded during the simulation. Dilatation curve show how material is expanded during heating and how it is contracted during cooling. Particular HAZ region is that way wider, and it enables to machine different specimens for mechanical testing. Suitability of the simulated HAZ material microstructure is checked by hardness measurements on simulated and real HAZ. If results of hardness measurement were the same, the simulated HAZ microstructure can be used for further analysis.

The example of fine grain HAZ analysis on steel P91 will be shown in continuation. This region of welded joins is the most sensitive for appearance of the type IV cracks on welded construction for power plants. Type IV cracking is appeared on material which is exposed to elevated temperature for long time and it gradually lost its toughness.

Cooling time $\Delta t_{8/5}$ is measured during the vertical SAW welding of pipe (diameter 296 mm and thickness 22 mm), by sinking of the Ni-CrNi thermocouple into weld pool. It was 20 s. Similar shown calculated results from welding parameters taking into account thickness of the materials in equations 1 and 2. First equation is used to calculate limit thickness for 2D or 3D heat transfer.

$$s_{limit} = \sqrt{\frac{q_1 \cdot N_3}{2 \cdot \rho \cdot c} \cdot \left(\frac{1}{500 - T_0} + \frac{1}{800 - T_0} \right)}. \qquad (1)$$

Where q_1 is heat input, N_3 is shape of welded join, ρ is density of material (kg/m^3), c specific heat (J/kgK) and T_0 is preheating temperature (K). Calculated s_{limit} is 26 mm what is above of the thickness of material (22 mm), so 2D heat transfer can take into account. Therefore cooling time $\Delta t8/5$ is calculated by using equation 2.

$$\Delta t_{\frac{8}{5}} = \frac{q_1^2 \cdot N_2}{4 \cdot \pi \cdot \lambda \cdot \rho \cdot c \cdot s^2} \cdot \left[\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{800 - T_0} \right)^2 \right]. \qquad (2)$$

Where is N_2 the shape of the weld joint, λ is thermal conductivity in W/(m·K), ρ is density of material (kg/m^3), c specific heat (J/kgK), s is thickness of material (m), T_0 is preheating temperature (K). Calculated $\Delta t_{8/5}$ was 20,4 °C.

That way, the following input data were usedfor simulation:
preheatingT_0 = 200 °C,

- preheatingT_0 = 200 °C,
- heating speed 150 °C/s,
- maximal temperature, T_{max} = 975°C
- holding time 0,5 s at T_{max}
- cooling time between 800 and 500 °C, $\Delta t8/5$ = 20 s,
- duration of the simulation, t_{finish} =300 s.

Figure 10 is shown simulation of fine grain HAZ material on specimen 11 × 11 × 55 mm.

Influence of weld Thermal cycle to fine grain HAZ and dilatation curve were recorded during simulation of fine gran HAZ. Hardness and Charpy toughness were measured on the simulated specimen before and after PWHT. Instrumented Charpy pendulum was used for Charpy tests.

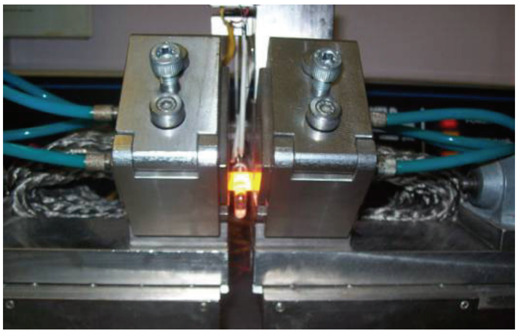


Figure 10: Simulation of fine grain HAZ materuial

4. RESULTS AND DISCUSION

Influence of weld thermal cycle and dilatation curve is shown in figure 11. Start of transformation of austenite into martenzit (M_S) is 405 °C and finish (M_F) is 325 °C.

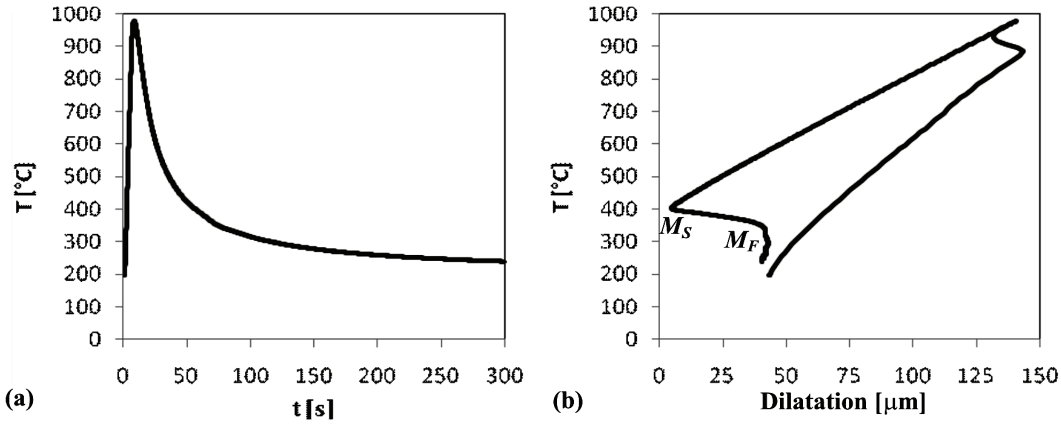


Figure 11: Influence of weld thermal cycle (a) and dilatation curve (b);
M_S - martensite start and M_F - martensite finish

4.1. Microstructure

Microstructure of base material is tempered martensitic. Most of carbides type $M_{23}C_6$ are on grain boundary (figure 12).

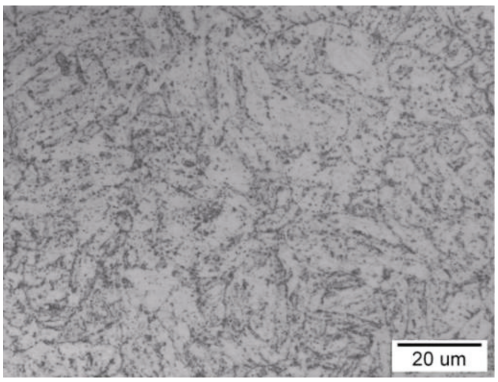


Figure 12: Microstructure of base material (light microscope 1000×)

Microstructure of fine grain HAZ in as welded condition after simulation is shown in figure 13 (a). The microstructure is build up from untempered lath martensite. Martensite is tempered after using PWHT at 760 °C for 2h. Microstructure in PWHT condition is shown in figure 13 (b). The most $M_{23}C_6$ carbides are on grain boundary.

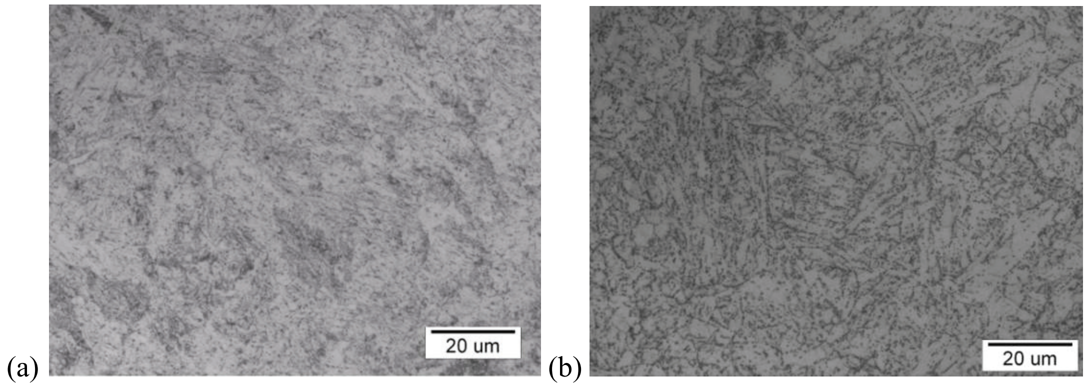


Figure 13: Microstructure of fine grain HAZ (light microscope 1000×);
before PWHT (a), after PWHT (b)

Distribution of $M_{23}C_6$ carbides is shown in figure 14 from scanning microscope at magnification 10000×. Mostly $Cr_{23}C_6$ carbides are on grain boundary, where density is very high more than 70 %. Some of them are also present in subgrains. Inside of grain are mostly present V-carbides, Nb carbides and Mo carbide. $M_{23}C_6$ carbides at grain boundary enable better creep resistance of the microstructure. PWHT is used to precipitate carbides that were dissolved during welding especially to the grain boundary.

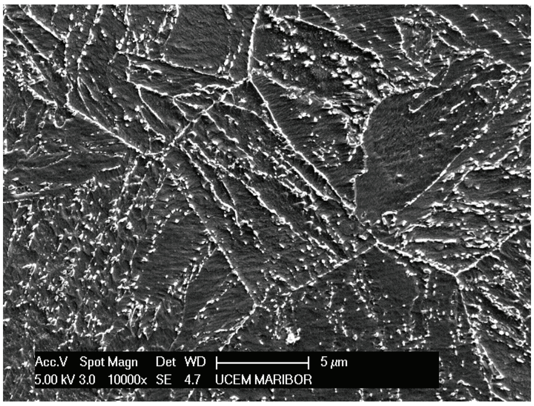


Figure 14: Distribution of carbides in fine grain HAZ (scanning microscope 10000×)

4.2. Results of hardness measurement

On figure 15 are presented results of hardness measurement on base material and fine grain HAZ material before and after PWHT. Hardness in fine grain HAZ after PWHT is reduced almost for twice according to condition before PWHT and is below of allowable harness 250 HV10.

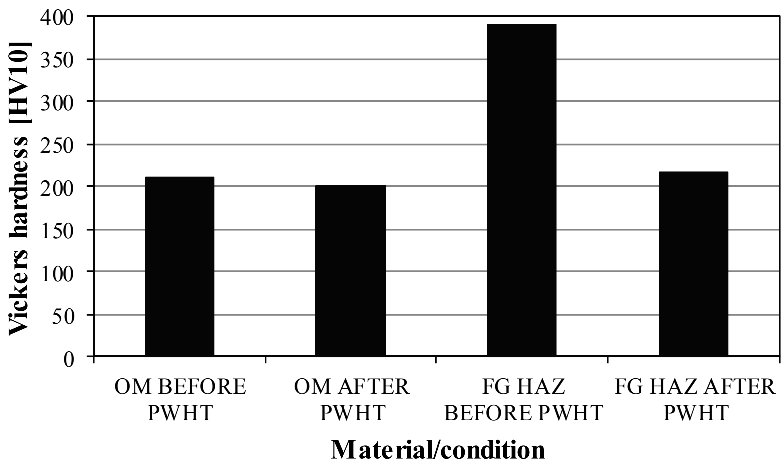


Figure 15: Results of Vickers hardness measurement before and after PWHT

4.3. Results of instrumented Charpy tests

Tests were made on instrumented Charpy pendulum RPK300, by using vuhicharpy software. Curve force versus time curve was recorded during the Charpy tests and curve energy versus time was calculated and recorded. Results of Charpy test in PWHT condition is presented in figure 16.

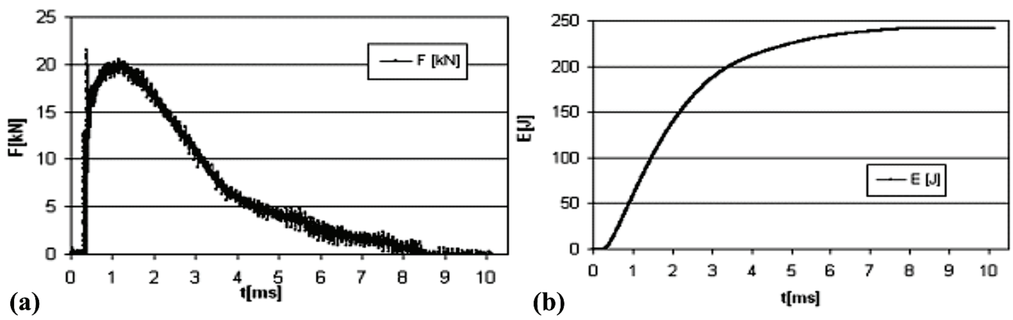


Figure16: Results of Charpy tests in PWHT condition; curve F-t(a) and curve E -t (b)

HAZ simulation enables investigation on particular HAZ material, which is not possible in real welds, because HAZ region is narrow. Therefore, it is very useful tool for optimisation of welding parameters and welding technology.

5. CONCLUSION

New grade CrMo steels like T23 and T24 are normally used for waterwall. If hardness after welding is lower than 350 HV10, in some cases PWHT is not necessary.

9 - 12 % Cr steels like P91 is used pipelines and tubes for temperature till 600 – 625 °C and is already use in practise for in last decade. Steel P92 is already started to use in practise and is used for temperature till 650 °C for power plant equipment. After the welding is obligatory PWHT.

Higher operation temperatures enables better efficiency of power plant so now is doing a lot of investigation on WM12 steel which will be used in future.

Ni alloys can be used for higher operation temperatures too (about 700 to 720 °C), but they are expensive. In America are some attempts to use it, because efficiently of power plant will increase for approximately 3 %.

HAZ simulation can be used for optimisation of welding technology and it enables some mechanical testing which are not possible on real welded joints.

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