ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 18, No. 2. 2012

The Structure and Properties of 5 % Cr-0.5 % Mo Steel Welded Joints after Natural Ageing and Post-weld Heat Treatment

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crossref http://dx.doi.org/10.5755/j01.ms.18.2.1911

Received 20 September 2010; accepted 19 October 2011

The article deals with the ageing and heat treatment influence on operational reliability of 5 % Cr-0.5 % Mo steel welded joints and pipeline elements. Separate components of the pipelines in the refineries are manufactured from chrome-molybdenum 5 % Cr-0.5 % Mo alloy steel. Reduction of internal stresses in chrome-molybdenum steel welded joints can be provided only by thermal treatment. Other methods of stress relieving are not acceptable for these steels. Presented materials analyses the impact of heat treatment on the microstructure and operational reliability of this steel. The objects of research are heat-treated welded joints of piping elements operated at high temperature for an extensive period of time, where degradation of mechanical properties has been observed. When value of the heat treatment temperature or time are exceeded, the structure degradation process is taking place, carbides coagulate within the boundaries of ferrite grains, they form coarse carbide colonies combined into long chains. Mechanical properties – tensile strength and impact strength decrease. Detailed analysis of these objects and the interpretation of the received results allow to select the most appropriate heat treatment parameters for the investigated steel structures.
Keywords: chrome-molybdenum steel, welding joints, post-weld heat treatment, microstructure.

1. INTRODUCTION

Cr-Mo steels are widely used in petrochemical industries and power plant as pipelines materials used for high temperature (350 °C – 600 °C) and high pressure (15 MPa – 30 MPa). These steel systems are expected to sustain at least for 250,000 h [1]. This requires a depth knowledge of the influence of long term high temperature and pressure exposure on the steel microstructure and on the mechanical properties [2]. Therefore, in recent years there have been significant efforts in industries to determine the remaining life of the components approaching their design lives [3]. Separate components of the pipelines in the refineries are manufactured from chrome-molybdenum 5 % Cr-0.5 % Mo alloy steel. Reduction of internal stresses in chrome-molybdenum steel welded joints can be provided only by thermal treatment [4, 5]. Other methods of stress relieving are not acceptable for these steels. Non-heat-treated welded joints are not acceptable for service due to their excessive brittleness and hardness. Heat treatment parameters specified in the normative documents for the installation of these piping do not expressly define the time of exposure at the tempering temperature [6]. Minimal and maximal tempering temperature is specified in the standards, whereas only minimum exposure time is indicated there. In case of repairing or replacing of piping elements the heat treatment exposure time is deliberately exaggerated in order to ensure the required metal hardness value, because metal hardness value is the main criterion of heat treatment quality evaluation. Therefore, a complex research of the dependence of chrome-molybdenum steel welded joint mechanical properties and microstructure on heat treatment parameters is one of the accident prevention In this research the dependence of mechanical properties on heat treatment regime has been identified and causes of mechanical property changes were determined by means of up-to-date microstructure analysis. The analyses of the same-type steel pipes operated at high temperature for an extensive period of time were carried out and the results of these analyses were compared with the test results of the new (not exploited) steel welded joints.

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2. MATERIAL

The material for the present study is 5Cr-0.5Mo steel (ASTM A335) obtained from petrochemical industry in the form of a 15 mm thick tube with 219 mm diameter. The chemical composition of the as-received tube and weld metal is shown in Table 1. The specimens (Ø219×15) mm were welded and post-weld heat treated, applying different heat treatment parameters (Table 2). For the comparison of the results, a series of welded specimens from the same pipe, but without heat treatment, and specimens from the new, as-received material, which was in its virgin state and never has been put in service, were tested. Welding process parameters were identical for all the specimens. Type of welding wire – EN12070: W CrMo5 Si.

Table 1. Chemical composition of parent and weld metal

Material	Chemical composition, (wt.)%				
	C	Si	Mn	Cr	Mo
Parent metal (5 % Cr-0.5 % Mo steel)	0.09	0.34	0.36	4.63	0.48
Weld metal (BÖHLER CM5-IG)	0.08	0.4	0.5	5.8	0.6

Temperature (T) and time (t) parameter P was calculated for each heat treatment process according to Eq. (1) [6, 7]:

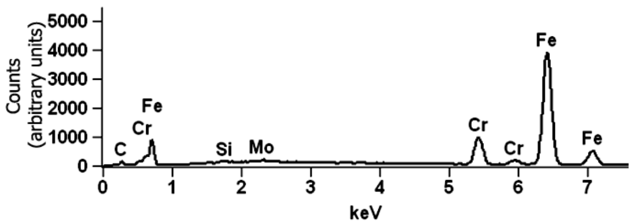
$$P = T\,(20 + \lg t)\cdot 10^{-3}. \qquad (1)$$

Table 2. Heat treatment parameters of specimens

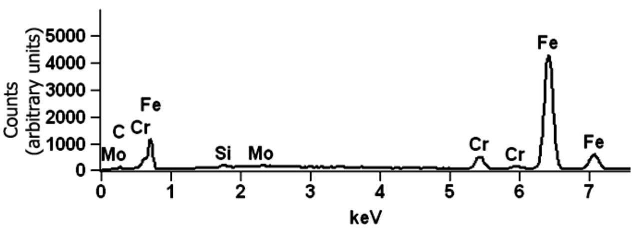
Spec. No.	Heating / cooling rate, °C/h	Temper., °C	Holding time, h	Parameter P
1	50 / 100	500	1	15.46
3	50 / 100	600	1	17.46
5	50 / 100	700	1	19.46
6	50 / 100	750	1	20.46
7	50 / 100	500	8	16.16
9	50 / 100	600	8	18.25
11	50 / 100	700	8	20.34
14	50 / 100	800	7	22.37

3. ANALYSIS METHODS

The mechanical properties (hardness, yield strength, impact strength) test and microstructure analysis of the specimens were performed. The standard specimens were cut from the tube components for the present study. Internal defects of weld zone were controlled by Radiographic inspection method. Butt weld transverse tensile tests were performed according LST EN 895, impact strength according LST EN ISO 15614-1. The tests were performed at room and 0°C temperature. Welded joints testing as well as in-service and new pipe metal microstructure testing performed using optical and electronic scanning microscopy methods. Tests were performed by means of optical microscope Nikon Epiphot 200 and scanning electron microscopes Hitachi S-2600N, Hitachi S-3500N and Hitachi S-5500 with Energy Dispersive X-ray Spectrometry (EDS) were employed. For characterisation of material structures the Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis (EDX) was applied (Fig. 1).



a



b

Fig. 1. EDX analysis of the structure (Fig. 5): a – point 1 (grain boundary), b – point 2 (solid solution area)

4. TEST RESULTS AND DISCUSSION

According to ASME B31.3-2006, the steel 5 % Cr-0.5 % Mo welded joint hardness should be not higher than 241 HB. The main task for the heat treatment of chrome-molybdenum steel welded joints is removal of the constituent of martensite and replacement thereof with a more acceptable, more plastic structure [8]. This also reduces residual stresses. The microstructure of specimens from the virgin state tube, which never has been put in service, is presented in the Fig. 2, a. Its microstructure consists of ferrite and constituents similar to grain-shaped pearlite. Carbides of different dispersion can be seen within the boundaries of ferrite grains and in the grains.

The microstructure of a welded only and non-heat-treated specimen consists of fine laths and needles, which, judging from the pattern-like arrangement may be referred to as martensite (Fig. 2, b). The fine carbides, which occur on the larger martensite needles, are likely to be carbides plates.

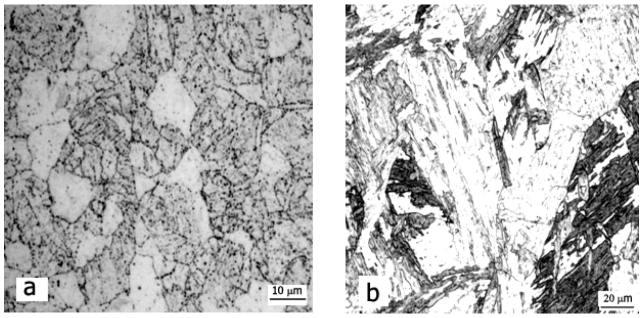


Fig. 2. Microstructure of 5 % Cr-0.5 % Mo steel: a – material in its virgin state, b – specimen No. 1 (welded joint after PWHT 500 °C – 1 h)

Upon the heat treatment temperature increased and exposure time extended, i. e. the value of P increased from 19.46 to 20.34, the changes in the microstructure are rather evident. Martensite has undergone full transformation; grain-shaped carbides of different dispersion are seen in the matrix of irregularly-shaped ferrite grains (Fig. 3, a).

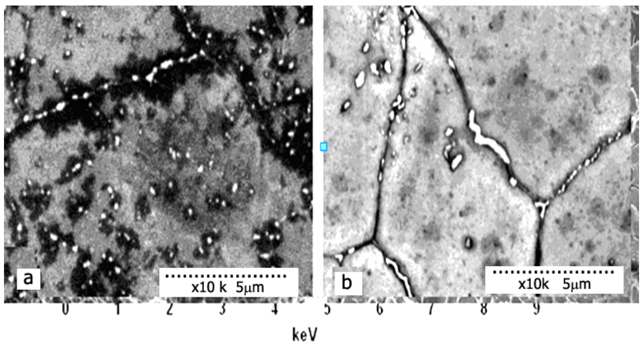


Fig. 3. Microstructure of 5 % Cr-0.5 % Mo steel welded joint: a – specimen No. 6, b – specimen No. 14

Brittle and hard martensite plates are no longer present and wide distribution of carbides of different dispersion prevails. Upon the value of P increased even more (over 22), carbides coagulate within the boundaries of ferrite grains, form carbide colonies, combine into long chain-like precipitate and are clearly visible in grain boundaries (Fig. 3, b).

Practically no fine, dispersive carbides left (Fig. 3, b). The microstructure of a specimen in-service (specimen from steel pipelines, which have been in service at 530 °C for more than 100 000 hours) is similar to that of specimen No. 14 (Fig. 4). The boundaries of ferrite grains characterized by carbide colonies are also visible, practically no pearlite grains can be seen (Fig. 5, b).

Temperature is the main heat treatment parameter which has the greatest impact on structural changes. The microstructure transformation of brittle structures starts at a temperature higher than 600 °C [8]. At least 8 hours are needed for full martensite transformation at 650 °C. Upon the temperature increased up to 700 °C, martensite transformation takes 1 h. Based on the obtained hardness test results [6], it was determined that, in order to achieve the acceptable hardness value of the welded joint, heat treatment temperature should not be lower than 650 °C with the exposure time being at least 8 h. When exposure time is 1 h, the acceptable hardness is reached at 700 °C only. Upon the exposure time at the particular temperature extended to 8 hours, with *P* reaching 20.36, no evident changes in the structure (in contrast to the 1-hour exposure) occurred. No martensite plates can be seen in the structure and there are no carbide clusters at the grain edges. The same is observed when the heat treatment temperature is increased up to 750 °C and exposure time is 1 hour (*P* equals 19.46). At such parameters, the structure is acceptable too. Further increase of temperature and extension of exposure time accelerates the diffusion of carbon and alloy elements atoms, and forms clusters of chrome/molibden carbides at grain edges. The amount of fine, dispersive carbides in grains decreases thereby reducing tensile strength of steel.

Chemical analysis of the microstructure revealed that the precipitated phases within the grain boundaries, as seen in the photos of the microstructure of the specimen with $P > 22$ (Fig. 3) and in the erstwhile in service pipe specimen (Fig. 5), consist mostly of complex chrome-molybdenum carbides (Fig. 1, Table 3, Table 4).

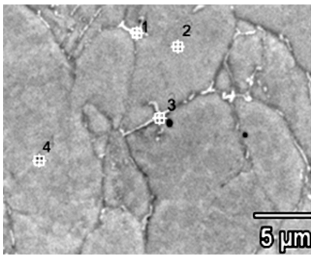


Fig. 4. Microstructure of 5 % Cr-0.5 % Mo steel welded joint specimen No. 14, (characters – location of chemical composition analysis areas)

Table 3. Chemical composition of microstructure phases, specimen No. 14 (at. %)

Point No.	Si-K	Cr-K	Fe-K	Mo-L
1	0.76	14.45	83.10	0.71
2	0.73	4.95	93.17	0.41

Noticeable changes were observed in the carbide composition, size and morphology. These carbides were mainly M_2C, M_3C, M_7C_6 type where M stands for Fe or Cr or Mo or a combination of them.

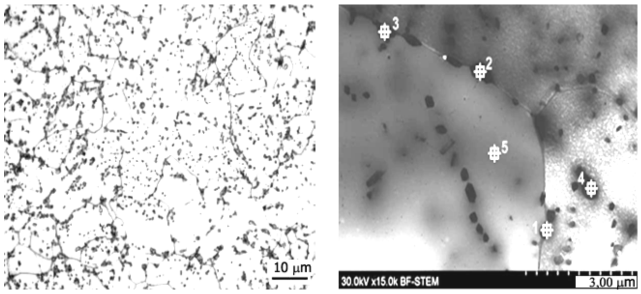


Fig. 5. Microstructure of 5 % Cr-0.5 % Mo steel welded joint material (after the service 100 000 h, 530 °C). Characters in the right picture – location of chemical composition analysis areas

The content of chrome in the grain boundaries exceeds the content in the middle of a grain by 3 to 4 times. It means that, by applying heat treatment, the structure is forced to degrade without even putting the item into service. Based on the obtained results, it can be stated that heat treatment of 5 % Cr-0.5 % Mo steel welded joints is acceptable at a temperature not lower than 650 °C and not higher than 750 °C, and with *P* value from 19.3 to 20.5.

Table 4. Chemical composition (at. %) of specimen microstructure after the service 100 000 h, 530 °C (Fig. 5)

Point No.	Si-K	Cr-K	Fe-K	Mo-L
1	0.53	23.31	1.17	1.50
5	0.73	4.95	4.31	

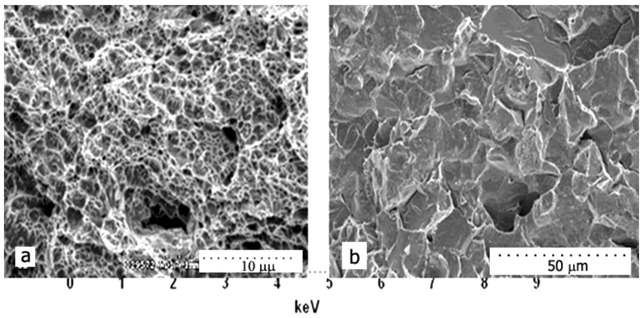


Fig. 6. Fractographs of fractured surfaces: a – post-weld heat treated specimen No. 14, b – specimen which have been in service (test temperature 20 °C)

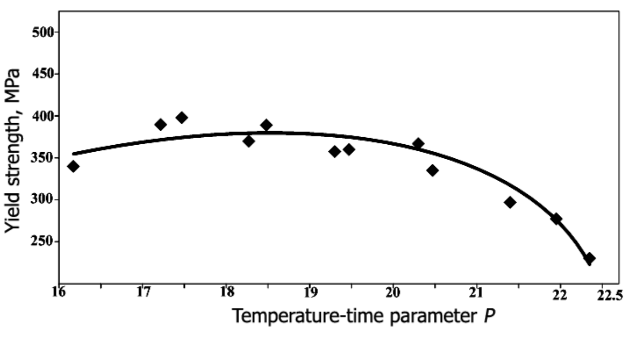


Fig. 7. Dependence of 5 % Cr-0.5 % Mo steel welded joint yield strength on the temperature/time parameter

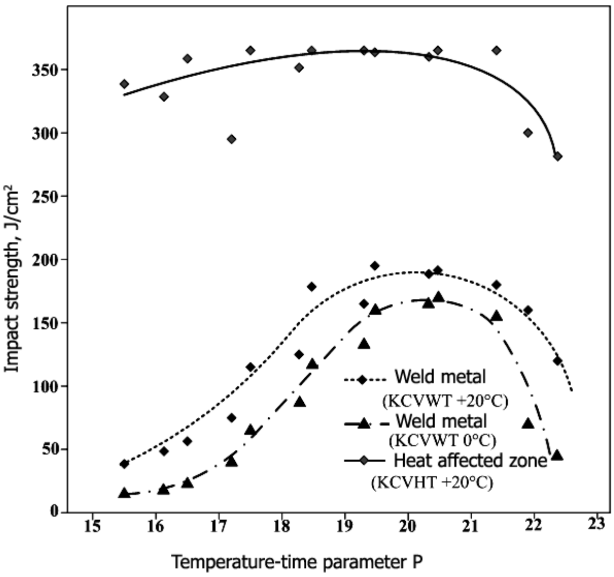


Fig. 8. Steel impact strength dependence on temperature-time parametre *P*

It was also determined that the intensive heat treatment applied causes the reduction of material strength just like after a long service period (Fig. 6, b). The dependence curves of yield and impact strength of 5 % Cr-0.5 % Mo steel welded joints (Fig. 7, Fig. 8) show that, with *P* increasing, the yield strengths is decreasing. The optimal value of yield (and tensile) strength is when *P* is from 17 to 20.5 [9].

5. CONCLUSIONS

Only post-weld heat treatment may be applied for the reduction of internal stresses in chrome-molybdenum steel welded joints. Other methods of stress relieving are not acceptable for these steels.

It has been determined that 5 % Cr-0.5 % Mo steel welded connection heat treatment temperature/time parameter *P* value should not exceed 20.5. Upon the above value exceeded, the structure degradation process is taking place, carbides coagulate within the boundaries of ferrite grains, form chromium-molybdenum carbides colonies. Precipitate phases combine into long chain-like formations.

The investigation of microstructure showed that with ageing, the carbides within the grain interior are slowly transformed to $M_{23}C_6$ type of carbides. The mechanical properties values decrease, as well as joining yield and impact strength.

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