Vigantas KUMŠLYTIS

EFFECT OF POST-WELD HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF CHROME-MOLYBDENUM STEEL WELDED JOINTS

SUMMARY OF DOCTORAL DISSERTATION

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Vigantas KUMŠLYTIS

TERMINIO APDOROJIMO POVEIKIS CHROMO-MOLIBDENO PLIENŲ SUVIRINTŲJŲ JUNGČIŲ MECHANINĖMS SAVYBĖMS

DAKTARO DISERTACIJOS SANTRAUKA

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Introducion

Topicality of the problem. One of the most dangerous petrochemical facilities are manufactured from chrome-molybdenum 5% Cr–0.5% Mo alloy steel. Pipeline and pressure vessels operating temperature is approximately 530 °C and medium auto-ignition point is at lower temperature than the pipeline operating temperature; therefore, it is necessary to apply all possible preventive measures in order to ensure the operational reliability of pipeline. Otherwise, there is a strong possibility of an accident with unpredictable consequences. One of the preventive measures is to ensure the reliability of welding joints. Welded joints heat treatment parameters specified in the normative documents for the installation of this piping do not expressly define the time of exposure at the tempering temperature. Minimum and maximum tempering temperature is specified in the standards, whereas only minimum exposure time is indicated there. When repairing or revamping the chrome-molybdenum piping, heat treatment exposure time is deliberately overincreased in order to ensure the required metal hardness value, because metal hardness value is the main criterion of heat treatment evaluation. It has not been properly examined what impact the intensive heat treatment has on other mechanical properties or microstructure changes of 5% Cr–0.5% Mo steels. 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 measures. The result of this research is identification of optimum heat treatment parameters for welded joints. The dependence of mechanical properties on heat treatment parameters has been identified and causes of mechanical property changes were determined by means of up-to-date microstructure analysis. It was determined that if very intensive new joint heat treatment parameters are chosen, it is possible to achieve metal microstructure and mechanical properties same as of steel operated at high temperatures for a long time, which is not acceptable.

Research object. Post-weld heat treated chrome-molybdenum 5% Cr–0.5% Mo steel joints. Also the analyses of the same-type steel pipes operated at high temperature for an extensive period of time were carried out. The results of those analyses were compared with the new steel welded joint test results.

Aim and tasks of the work. The main objective of the thesis is to identify the dependence of chrome-molybdenum (5% Cr–0.5% Mo) steel welded joint mechanical properties on heat treatment parameters. Also the goals of the thesis are the following:

- To develop a methodology for identification of optimum heat treatment parameters;

- Investigate the causes of alloy steel mechanical property changes. The following tasks were set in order to achieve the thesis objectives:
  1. Investigate 5% Cr–0.5% Mo steel heat-treated welded joint mechanical properties and microstructure changes.
  2. Investigate mechanical properties and microstructure of 5% Cr–0.5% Mo steel operated at high temperature and in aggressive conditions for an extensive period of time.
  3. Compare and analyze the new and in-service steel testing results, identify the causes of mechanical property changes.
  4. Investigate the dependence of 5% Cr–0.5% Mo steel mechanical properties on heat treatment parameters.

Develop a methodology for identification of optimum heat treatment parameters based on the research and science literature analysis.

Methodology of research. Analytical and experimental methods of research as well as comparative analysis were applied in the present thesis. In the course of experiments heat-treated welded joints were tested by changing heat treatment parameters. Welding joints, in-service steel and new steel was tested using classical methods of mechanical property determination. Up-to-date methods of electronic scanning microscopy and optical microscopy were used for the research. Heat treatment parameters identification methodology was developed based on analytic calculations and the comparative analysis of experimental research.

Scientific novelty. The following scientific novelties were discovered in course of writing this thesis:

1. Causes of early stage degradation of mechanical properties of chrome-molybdenum 5% Cr–0.5% Mo alloy steels welded joints were identified.
2. Optimum heat treatment parameter identification methodology was developed for chrome-molybdenum (5% Cr–0.5% Mo) alloy steel welded joints.
3. Dependence of chrome-molybdenum (5% Cr–0.5% Mo) alloy steel welded joint mechanical properties on heat treatment temperature/time parameter P was established.

Practical value. The dependence of 5% Cr–0.5% Mo steel welded joint mechanical properties on heat treatment temperature/time parameter P established in the course of the research and the developed methodology for identification of optimum heat treatment parameters was applied for chrome-molybdenum piping repair in AB Mažeikių Nafta reforming and diesel hydro treatment units. Based on the metal in-service analysis results, piping start-up loading schedule was developed for those pipelines.

Defended propositions

1. Optimum heat treatment parameter identification nomogram for chrome-molybdenum 5% Cr–0.5% Mo alloy steel welded joints.
2. Interdependence of chrome-molybdenum 5% Cr–0.5% Mo alloy steel welded joint mechanical properties and heat treatment temperature/time parameter *P*.
3. Provisions that deviations from the chrome-molybdenum steel welded joint optimum heat treatment parameters cause early degradation of metal properties and reduction of service life.

The scope of the scientific work. The scientific work consists of the general characteristic of the dissertation, 3 chapters, conclusions, list of literature, list of publications and addenda. The total scope of the dissertation – 100 pages, 59 pictures, 14 tables and 2 addenda.

1. Chrome-molybdenum steel welded joints operational issues

The first chapter covers the literature reference review. The chapter provides the review of works analyzing the peculiarities of industrial appliance of chrome-molybdenum steels, the issues of heat treatment and long-term service of welded joints of those steels. At the end of the chapter conclusions are provided and the objectives of the thesis are specified.

2. Methodology of research

The second chapter is a methodical section presenting the research methodology. The essence of experiments, their application, the layouts of instruments and their mode of operation, the experiments and the methods of their treatment are presented there.

Chrome-molybdenum 5% Cr–0.5% Mo, P5 (ASTM A335) steel piping Ø219×15 specimens were post-weld heat treated, applying different parameters (Table 1). For the purpose of comparison of the results were also examined next samples: as welded P5 steel specimen (No. 0), new P5 steel specimen (A) and 15X5M (GOST 20072) steel pipe specimen after 100 000 h in service at 530 °C temperature (specimen B). Temperature and time parameter P was calculated for each heat treatment process according to formula (1):

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

Table 1. Heat treatment parameters of specimens

Specimen No.	Heating / cooling, °C/h	Temperature, °C (K)	Holding time, h	Parameter *P*
1	50 / 100	500 (773.15)	1	15.46
2	50 / 100	550 (823.15)	1	16.46
3	50 / 100	600 (873.15)	1	17.46
4	50 / 100	650 (923.15)	1	18.46
5	50 / 100	700 (973.15)	1	19.46
6	50 / 100	750 (1023.15)	1	20.46
7	50 / 100	500 (773.15)	8	16.16
8	50 / 100	550 (823.15)	8	17.21
9	50 / 100	600 (873.15)	8	18.25
10	50 / 100	650 (923.15)	8	19.3
11	50 / 100	700 (973.15)	8	20.34
12	50 / 100	750 (1023.15)	8	21.4
13	50 / 100	780 (1053.15)	7	21.95

The following tests were performed on all the specimens: radiographic inspection of the welded specimens, mechanical property testing (hardness test, tensile test, impact tensile test), microstructure test and comparative analysis.

Radiographic inspection was performed in order to ensure the reliability of other test results and to avoid the impact of internal defects of welding joint.

Welded joints testing as well as in-service and new pipe metal microstructure testing is performed using optical microscopy and electronic scanning microscopy method. Tests were performed by means of optical microscope Nikon Epiphot 200 and electronic microscopes Hitachi S-2600N, Hitachi S-3500N and Hitachi S-5500 with EDS. By analyzing the results of microstructure research, the causes of welded joint mechanical property changes may be identified. Thus specimens with mechanical properties acceptable for operation are selected, i. e. heat treatment parameters of those specimens are acceptable as well. Based on the mechanical testing results, the graphic curves of mechanical property dependence on heat treatment temperature–time parameter *P* are developed. Optimum *P* value is identified when analyzing those dependence curves. The empirical formulas for determination of 5% Cr–0,5% Mo steel welded joint heat treatment temperature and time shall be resulted upon expressing temperature T and holding time t from the parameter *P* formula and inserting an optimum *P* value into the representations. Since the dimensions of a heat treated welded joint are not considered in those representations, therefore the exposure time may have to be increased in order to equalize the temperature throughout the whole cross-section of a joint. Using ANSYS software, by means of Finite Element Method of calculation, temperature profile throughout the whole welded joint cross-section during the heat treatment is identified. Thus it can be identified how much time is required for the temperature to equalize throughout the whole joint cross-section in the items of different wall thickness. By applying the above research methodologies, the graphic curves of welded joint mechanical property (tensile strength, yield point, hardness, impact tensile strength) dependence on the temperature/time parameter *P* can be developed. Upon the analysis of the dependence curves, optimum *P* values for welded joint heat treatment can be distinguished and empirical formulas for the identification of temperature and exposure time can be developed, as well as nomogram of the optimum heat treatment temperature and exposure time. The causes of mechanical property changes are determined and explained by microstructure analysis.

3. Test results and their analysis

Welding joint, heat-affected zone (HAZ) and basic metal hardness was measured; furthermore, hardness of new and in-service metal was measures for the purpose of comparison and analysis of the two values. Based on the obtained hardness test results, 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. In order to make the tempered areas of welded P5 steel joint softer, heat treatment with at least 18.7 temperature and time parameter should be applied. It was determined that the hardness of a pipe in service for 100 000 hrs at 530 °C is 127 HB only. During the long period of operation, hardness decreased by ~50 HB. As we can see from the graph representing the dependence of joint hardness on the parameter *P* (Fig. 1), the joint metal and heat-exposed area hardness decrease rather smoothly when increasing *P* value. The acceptable hardness value (241 HB) of the welding joint metal is reached when the temperature/time parameter $P>18.7$. With *P* increasing, the base metal hardness change is insignificant; upon *P* increased from 15.5 to 22.5 the base metal hardness decreased by 15 HB only. The HAZ hardness curve is by ~10 HB below the curve representing the welding joint metal hardness and it reaches the acceptable value at a lower *P* value, however, since all the areas of the welded joint are taken into account, the joint is considered to be unacceptable, in case at least one area does not meet the established requirements.

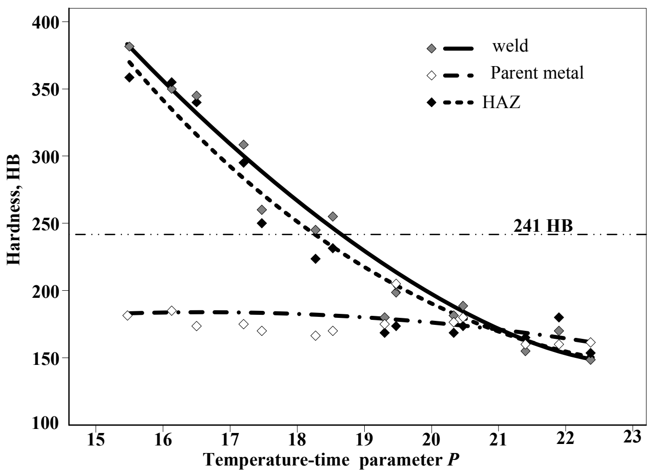

Fig. 1. Dependence of 5% Cr–0.5% Mo steel welded joint hardness (HB) on the temperature/time parameter *P*

Therefore, based on the dependence graph, it can be stated that a heat-treated P5 steel welding joint reaches the acceptable hardness value when the heat treatment temperature/time parameter *P* is over 18.7. Upon the performance of tensile testing of specimens, tensile strength R_m and yield strength R_e were determined. It has been determined that tensile strength of as welded specimen is the highest when compared to all the specimens; however, the specimen features practically no plasticity. The same result was obtained for the specimens with lower PWHT parameters (500–550 °C, 1 hr) applied. Therefore it can be stated that non-heat-treated P5 steel joints and joints with low tempering applied, according to the mechanical criteria for decay, are unacceptable for critical, bearing structures. It was also determined that the intensive heat treatment applied causes the reduction of material strength just like after a long service period. The dependence curves of tensile and yield strength of 5% Cr–0.5% Mo steel welded joints (Figs. 2–3) show that, with *P* increasing, the tensile and yield strengths are decreasing. Tensile strength decreases smoothly – by ~15 MPa per each unit of increase of *P* value. When *P* is from 17 to 20.5, yield strength remains practically unchanged; as *P* continues to increase, yield strength decreases by ~50 MPa per each unit of increase of *P*. It was determined that the value of yield and tensile strength this steel is optimum when *P* is from 17 to 20.5.

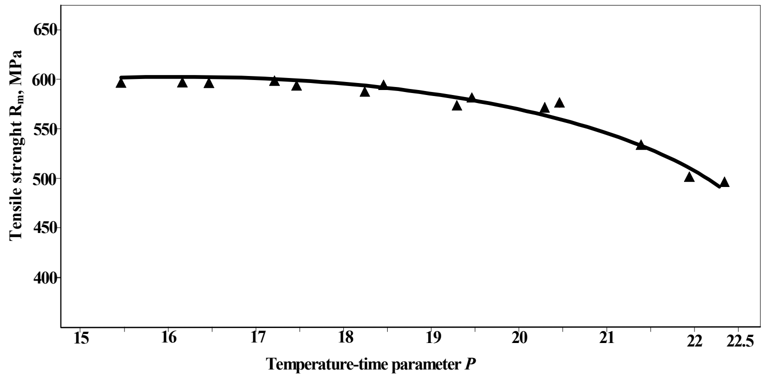

Fig. 2. Dependence of 5% Cr–0.5% Mo steel welded joint tensile strength on the temperature/time parameter *P*

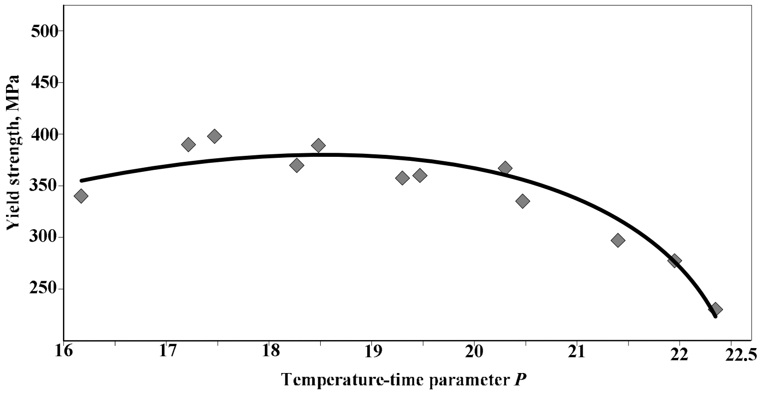

Fig. 3. Dependence of 5% Cr–0.5% Mo steel welded joint yield strength on the temperature/time parameter *P*

Impact strength testing of all the specimens was performed at room temperature and 0 °C temperature. The 5% Cr–0.5% Mo steel welded joint impact tensile strength dependence curve (Fig. 4) shows that the impact strength of the heat-exposed area increases smoothly at room temperature while *P* increases from 15.5 to 20.5. Starting from 20.5, impact strength of the heat-exposed area decreases by ~40 J/cm^2 per each unit of increase of *P*. The value of impact strength of a welding joint is much lower; this can be explained by the fact that the welding joint metal has been melted and, therefore, it predominates with structural non-integrities and high stresses. When increasing *P* from 15.5 to 19, impact tensile strength of a welding joint increase by ~45

J/cm^2 per each unit of increase of *P*. Further on, by the time *P* reaches 20.5, the value of impact tensile strength remains practically unchanged ~190 J/cm^2; starting from 20.5, impact tensile strength of a welding joint decreases by ~35 J/cm^2 per each unit of increase of *P.* The form of the curve representing the dependence of impact tensile strength of a joint on the parameter *P* at the temperature of 0 °C is very much the same like the dependence curve at +20 °C; the values of impact tensile strength are by ~ 20–50 J/cm^2 lower. A sharper drop of the curve is observed when the parameter *P* reaches 21.4 and impact tensile strength of a joint decrease by ~100 J/cm^2 per each unit of increase of *P*. Based on the results of impact test, it can be stated that heat treatment of 5% Cr–0.5% Mo steel welded joints is acceptable when the value of *P* is from 19 to 20.5. Use of welded joints with the heat treatment parameter *P* higher than 20.5 is not recommended at lower than room temperature. This also applies to the steel pipelines, which have been in service at 530 °C for more than 100 000 hours. Even though chrome-molybdenum steel pipelines are operated at high temperatures, there are cases when, in winter time, during the commissioning of pipelines, they are subject to internal pressure and subzero temperatures.

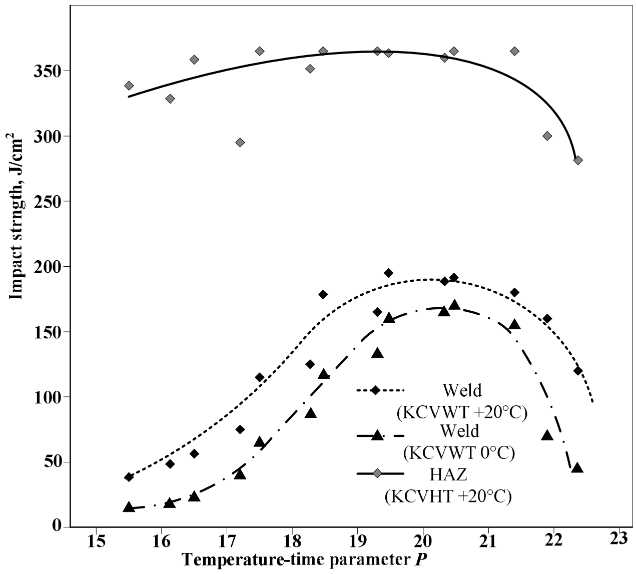

Fig. 4. Dependence of 5% Cr–0.5% Mo steel welded joint impact strength on the temperature/time parameter *P*

Therefore, the arrangements made for the commissioning process have to assure that pipelines are exposed to pressure at a higher than 20 °C temperature only. The main task, when heat treating chrome-molybdenum steel welded joints, is removal of the constituent of martensite and replacement thereof with a more acceptable, more plastic structure. This also reduces residual stresses. The microstructure was analyzed at Warsaw University of Technology. The microstructure of a welded only and non-heat-treated specimen consists of fine ferrite bands which, judging from the pattern-like arrangement may be referred to as martensite bands (Fig. 5). The structure of welding joint metal is predominant with martensite plates rather than homogenous. The fine carbides, which occur on the larger martensite needles, are likely to be cementite plates. No evident changes in the microstructure of heat-treated specimens occurred until the value of the temperature/time parameter *P* reached 17.46. The structure of welding joint metal is not homogenous either; martensite plates can be seen.

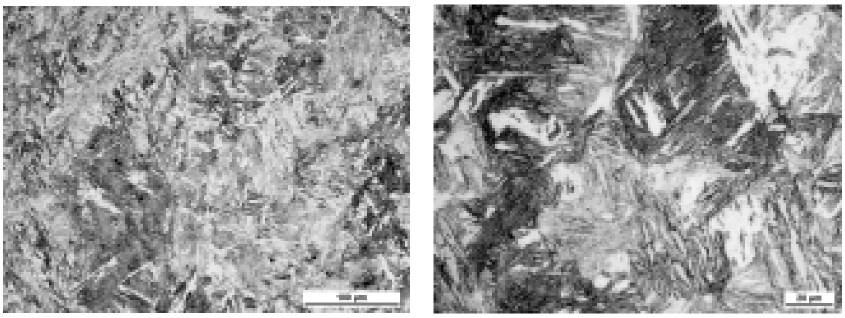

Fig. 5. Microstructure of 5% Cr–0.5% Mo steel welded joint (No. 0)

Upon 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. 6). Such structure, as shown in Figure 6, is acceptable because 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 solid compounds with clearly visible grain boundaries.

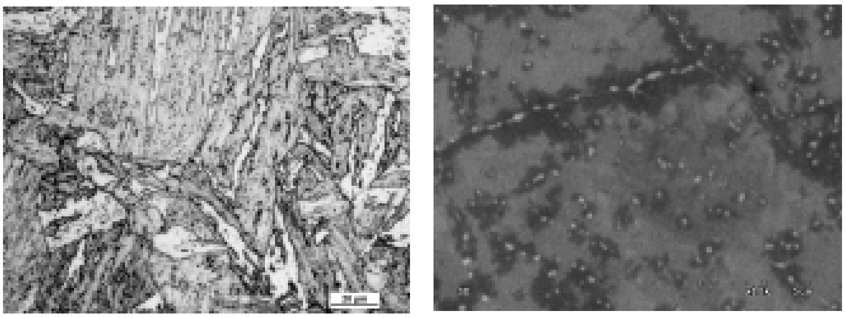

Fig. 6. Microstructure of 5% Cr–0.5% Mo steel welded joint (No. 6)

Practically no fine, dispersive carbides left (Fig. 7). The microstructure of a specimen in-service is similar to that of specimen No. 14; the boundaries of ferrite grains characterized by carbide colonies are also visible, practically no pearlite grains can be seen (Fig. 8).

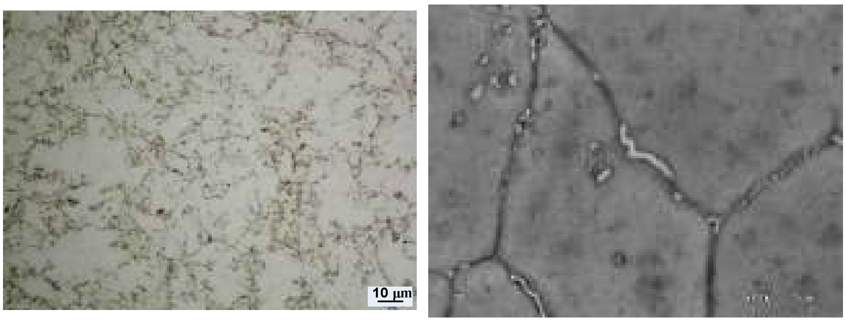

Fig. 7. Microstructure of 5% Cr–0.5% Mo steel welded joint (No. 14)

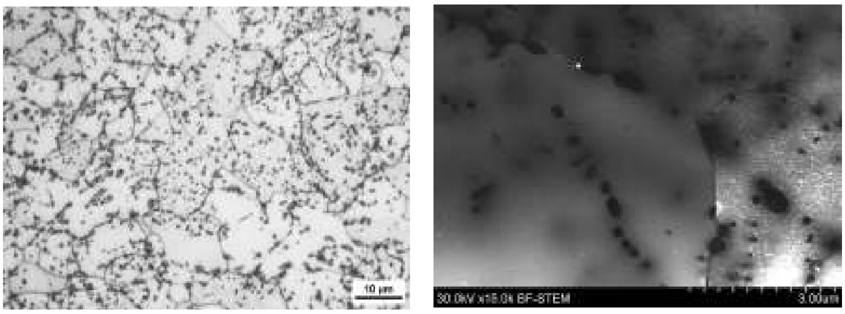

Fig. 8. Microstructure of 5% Cr–0.5% Mo steel (in service specimen B)

For the purpose of comparison, a new 5% Cr–0.5% Mo steel specimen was tested. 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 tests helped to determine that full transformation of brittle structures starts at a high enough temperature only, i.e. higher than 650 °C. Temperature is the main heat treatment parameter which has the greatest impact on structural changes. Temperature increase is also the factor, the impact of which on the change of *P* is greater than that of time. At least 8 hours are needed for full martensite transformation at 650 °C; in such a case, *P* will be equal to 19.3. Upon the temperature increased up to 700 °C, martensite transformation takes 1 hour with *P* being 19.46. 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, the arrangement of carbides is acceptable, and there are no clusters at grain edges. The same is observed when 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 chrome atoms, and forms clusters of chrome 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 inserts within grain boundaries, as seen in the photos of the microstructure of the specimen with $P>22$ and of the used pipe coupon (Figs. 7–8), consist mostly of chrome compounds. The concentration of chrome in the inserts between grains exceeds the concentration in the middle of a grain by 3 to 4 times. The microstructures of such compounds are very similar; which means that, by applying heat treatment, we forced the structure to degrade without even putting the item in 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. Two optimum heat treatment parameter identification methodologies were identified for 5% Cr–0.5% Mo steel welded joints. Heat treatment parameters may be selected as per nomogram (Fig. 9) or calculated according to Formulas 2 and 3. Heat treatment parameters should be selected form the grey zone of the graph.

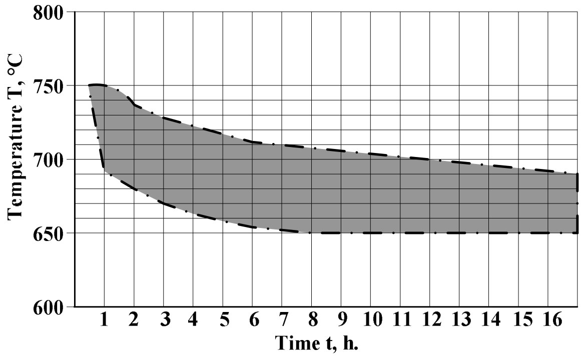

Fig. 9. Optimal post-weld heat treatment parameters of 5% Cr–0.5% Mo steel welded joints

$$T = \frac{20 \times 10^3}{20 + \lg t}, \tag{2}$$

$$t = 10^{(20000/T) - 20}. \tag{3}$$

In such case, 5% Cr–0.5% Mo steel welded joint mechanical properties will be optimum and microstructure acceptable. Temperature value from 650°C to 750 °C shall be selected when calculating heat treatment time according to Formula 3. The parameters should be selected with consideration to economy indicators and equipment possibilities.

The rate of heating and cooling of welded joints is also very important in the process of heat treatment. The heating rate for Cr-Mo steel has to be as low as possible so that volumetric or structural transformations did not cause any cracks or additional stresses. At the temperature below 400 °C, no structural changes take place in chrome-molybdenum steel; therefore, cooling rate shall be regulated starting from 400 °C. The 300 °C/hr heating and cooling rate, as prescribed in European normative documents is too high as this may result in brittle structures. This can be observed in isothermal transformation diagrams provided in reference literature. The 50 °C/hr heating and cooling rate, as indicated in ASME standards, is acceptable because no brittle structures are formed and no additional stresses are caused while cooling a welded joint at this particular rate. Low heating rate has another advantage – equalization of temperature along the entire cross-section of a joint. By applying Finite Element Method and using ANSYS software, we determined the distribution of temperature on cross-sections of welded joints of pipes of various thicknesses when the heating rate was 50 °C/h. As proven by the results of the calculation using Finite Element Method, it is not necessary to extend the exposure time when heating rate is 50 °C/h. When the thickness of a pipe wall is rather big, i. e. 70 mm with the largest (from those used for calculation) diameter, with the temperature at outside point reaching 700 °C, the temperature at inside point is only 10 °C lower. When the temperature at point A reaches 750 °C, the temperature on the inside of the wall will also be 10 °C lower. Such difference of temperatures should not cause different microstructural processes at different points of a cross-section.

General conclusions

1. 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. Non-heat-treated 5% Cr–0.5% Mo steel welded joints are not acceptable for service due to their excessive hardness and brittleness. Hardness of the welding joint is ~380 HB, impact tensile strength at room temperature is only ~26 J/cm^2, and at 0 °C temperature – only ~9 J/cm^2.

2. The temperature-time parameter *P*, applicable for creep process, simplifies the procedure of identification of optimum post-weld heat treatment parameters. Having developed the interdependences of welded joint mechanical properties and parameter *P*, such *P* values are established, at which the optimum mechanical properties of the joint are obtained.

3. 5% Cr–0.5% Mo steel welded joint post-weld heat treatment temperature/time parameter *P* value should not be less than 19.3. Although the acceptable or optimum values of mechanical properties are obtained at lower *P* values (acceptable hardness <240 HB, when P>18,7; tensile and yield strength values, when P>17; maximum values of impact tensile strength, when P>19), the acceptable microstructure is obtained when heat treatment temperature is from 650°C to 750°C and *P* value is at least 19.3.

4. 5% Cr–0.5% Mo steel post-weld 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 carbide colonies, combine into long solid compounds, and none of the fine, dispersive carbides remain. Also mechanical property values decrease, as well as joint strength and impact tensile strength.

5. It has been determined that 5% Cr–0.5% Mo steel pressure equipment, which has been in service over 100000 hours at 530 °C, and new equipment with heat treatment temperature/time parameter *P* above 20.5, cannot be

exposed to pressure at the temperature lower than room temperature. Impact tensile strength values at lower temperatures decrease to unacceptable values (min 58 J/cm^2).

6. When performing post-weld heat treatment of 5% Cr–0.5% Mo steel welded joints, optimum mechanical properties and acceptable microstructure is achieved when parameter *P* value is from 19.3 to 20.5 and temperature is from 650 to 750 °C.

7. It has been determined that when performing 5% Cr–0.5% Mo steel thick-walled piping welded joint heat treatment using flexible heating elements, the optimum heating rate is 50 °C/hr.

8. Two optimum post-weld heat treatment parameters identification methodologies were identified for 5% Cr–0.5% Mo steel welded joints. Heat treatment parameters may be selected as per nomogram (Fig. 9) or calculated according to formulas 2 and 3.

9. The established methodologies for 5% Cr–0.5% Mo steel welded joint optimum heat treatment parameter identification were used during AB Mazeikiu Nafta reformer piping repair. As the result of in-service piping analysis, reformer piping loading graph (pressure and temperature increase dependence) was developed, which is especially useful during the cold season when commissioning the pipeline after forced shutdowns.

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TERMINIO APDOROJIMO POVEIKIS CHROMO-MOLIBDENO PLIENŲ SUVIRINTŲJŲ JUNGČIŲ MECHANINĖMS SAVYBĖMS

Mokslo problemos aktualumas. Vieni iš pavojingiausių naftos chemijos pramonės įrenginių daugelyje pasaulio šalių pagaminti iš legiruotų chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų. Įrenginių eksploatacijos temperatūra yra apie 530 °C, o darbinis slėgis siekia 4 MPa. Įrenginiuose esančios terpės savaiminio užsiliepsnojimo ore temperatūra žemesnė už eksploatacijos temperatūrą, todėl būtina imtis visų įmanomų prevencijos priemonių norint užtikrinti patikimą įrenginio darbą. Pagrindinė tokių įrenginių avarijų priežastis yra suvirintųjų jungčių plyšiai. Užtikrinti suvirintųjų jungčių patikimumą – viena iš prevencijos priemonių. Įrenginių montavimo norminiuose dokumentuose nurodyti suvirintųjų jungčių terminio apdorojimo parametrai tiksliai neapibrėžia išlaikymo trukmės atleidimo temperatūroje. Standartuose nurodoma minimali ir maksimali atleidimo temperatūra, tačiau pateikiamas tik minimali išlaikymo trukmė. Daugelyje mokslinių darbų įrodyta, kad anglinių plienų ir mažai legiruotų plienų mechaninių savybių reikšmės mažėja labai padidinus terminio apdorojimo temperatūrą arba išlaikymo trukmę. Remontuojant ar rekonstruojant chromo-molibdeno įrenginius terminio apdorojimo išlaikymo trukmė yra pernelyg sąmoningai padidinama siekiant užtikrinti norimą metalo kietumo reikšmę, nes kietumo matavimo reikšmė yra pagrindinis terminio apdorojimo įvertinimo kriterijus. Iki šiol nėra gerai ištirta intensyvaus terminio apdorojimo įtaka 5 % Cr–0,5 % Mo grupės plienų mechaninėms savybėms ir mikrostruktūrai, todėl kompleksinis šių plienų suvirintųjų jungčių mechaninių savybių bei mikrostruktūros prikausomybės nuo terminio apdorojimo parametrų tyrimas yra viena iš avarijų prevencijos priemonių. Šių tyrimų rezultatas yra optimalių suvirintųjų jungčių terminio apdorojimo parametrų nustatymo metodika. Disertacijoje nagrinėjami termiškai apdorotų, taikant įvairius režimus, chromo-molibdeno plienų suvirintųjų jungčių ir ilgą laiką eksploatuoto plieno mechaninių savybių bei mikrostruktūros tyrimų rezultatai. Nustatyta, kad, pasirinkus labai intensyvius naujų jungčių terminio apdorojimo parametrus, gaunama nepriimtina metalo mikrostruktūra ir nepriimtinos mechaninės savybės, tokios pat, kaip ilgai aukštoje temperatūroje eksploatuoto plieno. Nustatytos mechaninių savybių ir terminio apdorojimo parametrų tarpusavio priklausomybės, šiuolaikiškais mikrostruktūrų tyrimais išaiškintos mechaninių savybių pokyčių priežastys. Šių tyrimų pagrindu sudaryta 5 % Cr–0,5 % Mo plienų grupės optimalių terminio apdorojimo parametrų parinkimo metodika.

Tyrimų objektas. Tiriamos suvirintos ir termiškai apdorotos chromo-molibdeno (5 % Cr–0,5 % Mo) grupės plieno vamzdžių jungtys. Taip pat tiriami ilgą laiką aukštoje temperatūroje eksploatuoto 15X5M (GOST 20072) plieno vamzdžiai ir naujas chromo-molibdeno 5 % Cr–0,5 % Mo grupės plieno vamzdis.

Darbo tikslas ir uždaviniai. Pagrindinis šio darbo tikslas – nustatyti chromo-molibdeno (5 % Cr–0,5 % Mo) grupės plienų suvirintųjų jungčių mechaninių savybių ir terminio apdorojimo parametrų tarpusavio priklausomybes. Taip pat disertacijoje siekiama:

- sukurti metodiką, skirtą optimaliems terminio apdorojimo parametrams nustatyti;
- ištirti legiruoto plieno mechaninių savybių pokyčių priežastis.

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Ištirti chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų įvairiais režimais termiškai apdorotų suvirintųjų jungčių mechanines savybes ir mikrostruktūrą.
2. Ištirti ilgą laiką aukštoje temperatūroje ir agresyvioje terpėje eksploatuoto chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų mechanines savybes ir mikrostruktūrą.
3. Palyginti ir išanalizuoti mechaninių savybių ir mikrostruktūros tyrimų rezultatus, nustatyti mechaninių savybių pokyčių priežastis.
4. Nustatyti chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų mechaninių savybių ir terminio apdorojimo parametrų tarpusavio priklausomybes.
5. Sudaryti optimalių terminio apdorojimo parametrų nustatymo metodiką, pagrįstą tyrimų ir literatūros analize.

Mokslinis naujumas. Rengiant disertaciją buvo gauti šie mokslui nauji rezultatai:

- nustatytos legiruoto chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų suvirintųjų jungčių pirmalaikės mechaninių charakteristikų degradacijos priežastys įrenginių gamybos metu;
- sudaryta legiruoto chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų suvirintųjų jungčių optimalių terminio apdorojimo parametrų nustatymo metodika;
- nustatytos legiruoto chromo-molibdeno 5 % Cr–0,5 % Mo grupės plienų suvirintųjų jungčių mechaninių savybių ir terminio apdorojimo temperatūros ir laiko parametro *P* tarpusavio priklausomybės.

Tyrimų metodika. Darbe taikomi analitiniai ir eksperimentiniai tyrimo metodai ir lyginamoji analizė. Eksperimentų metu buvo tiriamos termiškai apdorotos suvirintos jungtys, keičiant terminio apdorojimo parametrus. Suvirintos jungtys, eksploatuotas ir naujas plienas buvo tiriami klasikiniais mechaninių savybių nustatymo metodais. Tyrimams naudoti šiuolaikiški nuskaitančiosios elektroninės mikroskopijos, rentgeno spindulių difrakcijos, optinės mikroskopijos metodai. Terminio apdorojimo parametrų nustatymo metodika parengta taikant analitinius skaičiavimus ir eksperimentinių tyrimų rezultatų lyginamąją analizę.

Praktinė vertė. Tyrimais nustatyta 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių mechaninių savybių ir terminio apdorojimo temperatūros ir laiko parametro *P* tarpusavio priklausomybė ir sudaryta terminio apdorojimo optimalių parametrų nustatymo metodika buvo pritaikyta AB „Mažeikių nafta“ riformingo ir dyzelino hidrovalymo chromo-molibdeno vamzdynų remontui.

Pagal eksploatuoto metalo tyrimų rezultatus sudarytas šių vamzdynų apkrovimo grafikas paleidimo metu.

Ginamieji teiginiai

1. Legiruoto chromo-molibdeno 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių optimalių terminio apdorojimo parametrų parinkimo nomograma.
2. Legiruoto chromo-molibdeno 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių mechaninių savybių ir terminio apdorojimo temperatūros ir laiko parametro P tarpusavio priklausomybės.
3. Nuostatos, kad nukrypus nuo chromo-molibdeno plienų suvirintųjų jungčių optimalių terminio apdorojimo parametrų sukeliama pirmalaikė metalo savybių degradacija ir sutrumpinamas įrenginio eksploatacijos laikas.

Darbo apimtis. Disertaciją sudaro įvadas, 3 skyriai ir rezultatų apibendrinimas. Bendra disertacijos apimtis yra 100 puslapių, 59 paveikslai ir 14 lentelių. Taip pat yra 2 priedai.

Pirmajame skyriuje pateikti atliktos literatūros analizės rezultatai ir suformuluoti uždaviniai. Antrajame skyriuje aprašyta tyrimų ir optimalių 5 % Cr–0,5 % Mo plienų terminio apdorojimo parametrų nustatymo metodika. Trečiajame skyriuje aprašyta eksperimentų atlikimo eiga, gauti rezultatai bei jų aptarimas, pateikti mechaninių bandymų rezultatai. Lūžių paviršiaus ir mikrostruktūros tyrimais paaškinamos mechaninių savybių pokyčių priežastys.

Bendrosios išvados

1. Chromo-molibdeno plienų suvirintųjų jungčių vidiniams įtempiams mažinti turi būti taikomas tik terminis apdorojimas. Kiti įtempių mažinimo metodai šiems plienams yra nepriimtini.

2. Termiškai neapdorotos 5 % Cr–0,5 % Mo plienų suvirintosios jungtys yra netinkamos eksploatuoti, labai trapios ir kietos. Siūlės kietumas ~380 HB ir smūginis tąsumas kambario temperatūroje tik ~26 J/cm^2, o 0 °C temperatūroje tik ~9 J/cm^2.

3. Temperatūros ir laiko parametras P, naudojamas valkšnumo procesui prognozuoti, supaprastina suvirintųjų jungčių optimalių terminio apdorojimo parametrų nustatymo procedūrą. Sudarius suvirintųjų jungčių mechaninių savybių ir parametro P tarpusavio priklausomybę, nustatomos tokios P reikšmės, kurioms esant gaunamos geriausios jungčių mechaninės savybės.

4. 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių terminio apdorojimo temperatūros ir laiko parametro P reikšmė turi būti ne mažesnė už 19,3. Nors mechaninių savybių priimtinos ar optimalios reikšmės gaunamos ir esant mažesnėms P reikšmėms (priimtinas kietumas <240 HB, kai $P>18,7$; optimalios takumo ir stiprumo reikšmės, kai $P>17$; smūginio tąsumo aukščiausios

reikšmės, kai P>19), priimtina mikrostruktūra (nematyti martensito plokštelių, tolygus karbidų pasiskirstymas, nėra sankaupų grūdelių pakraščiuose) gaunama, kai terminio apdorojimo temperatūra yra nuo 650 iki 750 °C ir *P* reikšmė yra ne mažesnė už 19,3.

5. Nustatyta, kad 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių terminio apdorojimo temperatūros ir laiko parametro *P* reikšmė neturi viršyti 20,5. Viršijus šią reikšmę, vyksta struktūros degradacijos procesas, karbidai koaguliuoja ferito grūdelių ribose, sudaro karbidų kolonijas, jungiasi į ilgus vientisus junginius, smulkių, dispersiškų karbidų nelieka. Taip pat mažėja mechaninių savybių reikšmės, mažėja jungties stipris, mažėja smūginis tąsumas.

6. Daugiau kaip 100 000 valandų 530 °C temperatūroje eksploatuoto 5 % Cr–0,5 % Mo plieno slėginiai įrenginiai ir nauji įrenginiai, kurių terminio apdorojimo temperatūros ir laiko parametras *P* yra didesnis už 20,5, negali būti veikiami slėgio žemesnėje nei kambario temperatūroje. Žemesnėje temperatūroje smūginio tąsumo reikšmės sumažėja iki nepriimtinų reikšmių (min 58 J/cm^2).

7. Nustatyta, kad atliekant 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių terminį apdorojimą optimalios mechaninės savybės ir priimtinos mikrostruktūros gaunamos, kai parametro *P* reikšmė yra nuo 19,3 iki 20,5 ir kai terminio apdorojimo temperatūros reikšmė yra nuo 650 iki 750 °C.

8. Atliekant 5 % Cr–0,5 % Mo plienų storasienių vamzdžių suvirintųjų jungčių terminį apdorojimą lanksčiais kaitinimo elementais, optimalus įkaitinimo greitis yra 50 °C/h.

9. Nustatytos dvi 5 % Cr–0,5 % Mo plienų suvirintųjų jungčių optimalių terminio apdorojimo parametrų parinkimo metodikos. Terminio apdorojimo parametrai pasirenkami pagal sudarytą nomogramą arba apskaičiuojami pagal išvestas empirines formules.

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EFFECT OF POST-WELD HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF CHROME-MOLYBDENUM STEEL WELDED JOINTS

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

Vigantas KUMŠLYTIS

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