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The strength-related characteristics of chromium-molybdenum P5 steel dependence on postweld heat treatment parameters

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1. Introduction

Welding is the principal joining technology used in the fabrication of metallic structures. An important issue associated with welding is the generation of residual stresses. During welding there is a differential cooling rate in the structure which results in nonuniform deformation and the subsequent generation of a residual stress field which is triaxial in nature. The existence of a triaxial state of stress can cause cracking and this may present a serious risk to the integrity of components.

Heat treatment, once performed after welding, provides welded joints with numerous positive properties such as softened hardened areas of metal, increased ductility, positively modified microstructures of heat treated areas of metal, reduced internal stresses. Heat treatment improves corrosion resistance as well as stress-corrosion cracking resistance under the influence of internal stresses. Heat treatment of welded joints may also have some negative impacts such as reduced tensile and impact strength, precipitation hardening of certain steels which may cause fractures on heat-exposed areas of the metal. The cumulative effects of time and temperature during post weld heat treatment have a deleterious effect on normalized base metal properties [1]. Some scientific works report that mechanical properties of various steels are strongly connected to their complex microstructure obtained after heat treatment that are generally performed in order to achieve a good hardness and/or tensile strength with sufficient ductility [2]. The deterioration of mechanical properties caused by post weld heat treatment in carbon steels has been well documented in 1972, as has the association of those changes with time-temperature parameters [3]. During the later eighties studies by Konkol detailed the effects on carbon steels of tempering and showed the deterioration effects of 650°C for just 5 hours to be a 7°C shift in the transition temperature [4]. As a matter of convenience, and because data seemed to fit, the conventional Larson-Miller parameter *LMP* (without dimension value) has been used to compare post weld heat treatment cycles [4, 5]. This formula is shown as

$$LMP = (T + 460)(C + \log t) \times 10^{-4} \tag{1}$$

where C equals 20 and t is the time held in hours at temperature T, °F.

For quantitative evaluation of the heat treatment parameters, European Union normative documents [5] provide temperature-time parameter P analogous to *LMP* parameter, which is calculated according to the formula:

$$P = T(20 + lg\, t) \times 10^{-3} \tag{2}$$

where T is the heat treatment temperature (in Kelvin), t is time (hours) of exposure at heat treatment temperature.

The scientists every so often made hardness test, when they want check quality of the welded joints, they proposed the method of evaluating the reliability of the welded joints of using maximum hardness of weld material and heat afected zone and the plasticity of structure [6]. But hardness tests isn't enough when we research of chromium-molybdenum steels.

As witnessed by the previous tests, mechanical characteristics of chromium-molybdenum, P5 steel welds tend to get worse upon the temperature and time parameter P increased by more than 20.4. It has also been determined that simultaneous reduction of post weld heat treatment temperature and increase of holding time has no impact on strength-related characteristics [7]. Exact changes in strength-related characteristics of welds of the particular types of steel, with the parameter P less than 20, have not been determined yet.

For over several decades, the chromium-molybdenum steel has been widely used for high temperature furnace components operating at temperatures above 800°C. It has been the standard alloy for different tubes in furnaces and heaters. Numerous studies describing their microstructure, mechanical and weldability properties have been carried out on these alloys.

The aim of the analysis is to determine the mechanical properties dependence of chromium-molybdenum steel welded joints upon thermal treatment parameters: i. e. the variation of tensile strength and impact strength of joints by ranging of temperature–time parameter P from 15.5 to 22.5.

2. Materials

Chromium-molybdenum steel (ASTM A335 Grd. P5) was selected for the analysis. Heat-resistant chromium-molybdenum steels are used for manufacture of structures operated at higher temperatures.

The experimental research was performed on specimens made from a 15 mm thick hot-rolled pipe (Ø219 x 15) steel ASTM A335 Grd. P5 (Tables 1 - 2).

Table 1

Chemical composition of the main component of the specimens (manufacturer's data)

Steel grade	Composition (mass), %						
	C	Si	Cr	Mn	Mo	S	P
P5 ASTM A335	0.09	0.34	4.73	0.33	0.46	0.004	0.007

Table 2

Mechanical properties of the main component of the specimens (manufacturer's data)

Steel grade	Tensile strength, R_m, MPa	Yield strength, R_e, MPa	Elongation, A_5, %
P5 ASTM A335	595	420	42

Table 3

Chemical composition of the weld metal

Wire grade	Composition (mass) %				
	C	Si	Mn	Cr	Mo
BÖHLER CM 5-IG	0.08	0.4	0.5	5.8	0.6

Table 4

Mechanical properties of the weld metal

Wire grade	Tensile strength R_m, MPa	Yield strength R_e, MPa	Elongation A_5, %	Impact work ISO-V KV, J
BÖHLER CM 5-IG	620	510	20	200 (at +20°C)

Specimens from ASTM A335 P5 steel were welded using gas shielded tungsten arc welding process (141 EN 24063 process). Auxiliary wire type EN12070: WCrMo5Si (BÖHLER EMK 5-IG electrode wire) was used.

Chemical composition as well as mechanical properties of the weld metal is presented in Tables 3, 4.

3. Research technique

All 14 specimens from ASTM A335 P5 steel were welded. All the samples were welded at the same position (PF ISO6947, vertical upward weld). When welded, all thespecimens were heat treated under different regimes (Table 5). Heat treatment modes for chromium-molybdenum steel samples were selected those that commonly are applied by " Mazeikiu nafta" company in piping of such steel repair. The temperature-time parameters of each regime were calculated according to formula (2). After evaluating the possible deviation of post weld heat treatment temperature and tolerances of time measures, the tolerance of parameter P should be equal 0.026.

After heat treatment process, the analyses of welded metal as were carried out listed below:

- to check the weld quality the radiographic X-rays analysis was used (level B). The analysis was performed using X-ray generator RAPAN M200/100;
- 3 specimens were cut out of each welded joint. The tensile test was carried out in a MIRI-500K tensile machine. The tolerances of cross-tensile test are 1%;
- strenght properties were evaluated by impact strength test. Three specimens were cut out of each welded joint. Specimen type - KVWS 0/1 (Charpy pendulum V-notch, weld-metal notch, notched surface parallel to the specimens surface, notch over central area of weld). The tolerances of impact strength test were 1%.

Table 5

Heat treatment parameters of welded specimens from ASTM A335 P5 steel

Spec. No.	Preheat and cooling rate, °C/h	Temperature of heat treatment T, °C (K)	Holding time t, h	Temperature-time parameter P
1	200	500 (773.15)	1	15.46
2	200	550 (823.15)	1	16.46
3	200	600 (873.15)	1	17.46
4	200	650 (923.15)	1	18.46
5	200	700 (973.15)	1	19.46
6	200	750 (1023.15)	1	20.46
7	200	500 (773.15)	8	16.16
8	200	550 (823.15)	8	17.21
9	200	600 (873.15)	8	18.25
10	200	650 (923.15)	8	19.3
11	200	700 (973.15)	8	20.34
12	200	750 (1023.15)	8	21.4
13	200	780 (1053.15)	7	21.95
14	200	800 (1073.15)	7	22.37

4. Results and discussion

After the X-rays analysis it was established that all welded joints conform to technical requirements. No defects, influencing the results were detected.

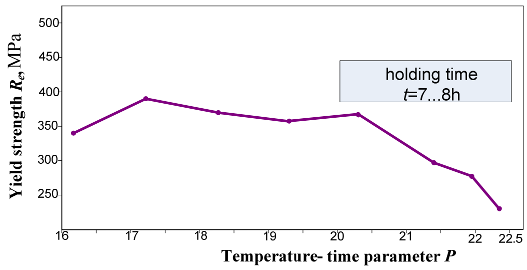

Fig. 1 Dependence of yield strength of welded joints from P5 steel on temperature-time parameter P, holding time 7-8 h

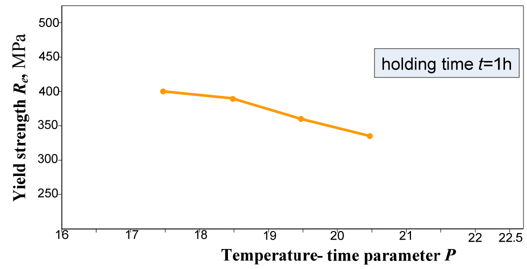

Fig. 2 Dependence of the strength of welded joints from P5 steel on temperature-time parameter P

Yield test results for the steel P5 when PWHT holding time is 8 hours, except the 14th and 15th specimens holding time of which is 7 hours show in the Fig. 1. Yield strength increases by ~ 50 MPa when increasing the parameter *P* from 16 to 17. With the parameter *P* variation from 17 to 20.3, yield strength remains stable. In case the parameter *P* value continues on rising, yield strength is suddenly drops. The yield strength reduces by ~ 65 MPa for each unit of the parameter *P* increase. Yield test results for the steel P5 when PWHT holding time is 1 hour are shown in Fig. 2. The diagram makes it evident that post weld heat treatment modes when the parameter *P* does not exceed 17.5 are not recommended at all since before the *P* value is reached the welds characterize practically no yield strength.

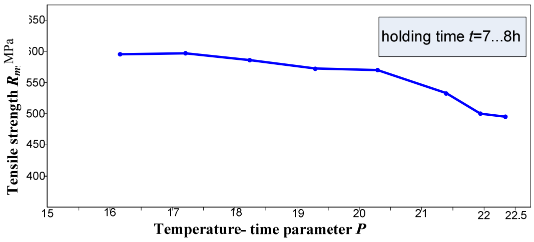

Fig. 3 Dependence of tensile strength of welded joints from P5 steel on temperature-time parameter *P*, holding time 7-8 h

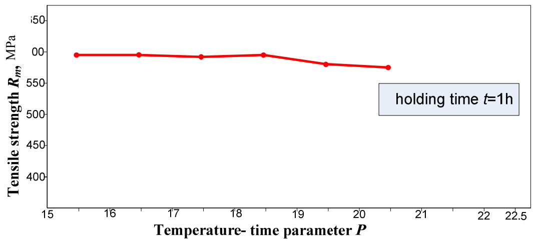

Fig. 4 Dependence of tensile strength of welded joints from P5 steel on temperature-time parameter *P*

Fig. 4 and Fig. 5 show that tensile strength undergoes practically no changes by the time the parameter *P* reaches 20.3. Starting from this value, more significant – 35 MPa per each unit of *P* increase – reduction of tensile strength is observed.

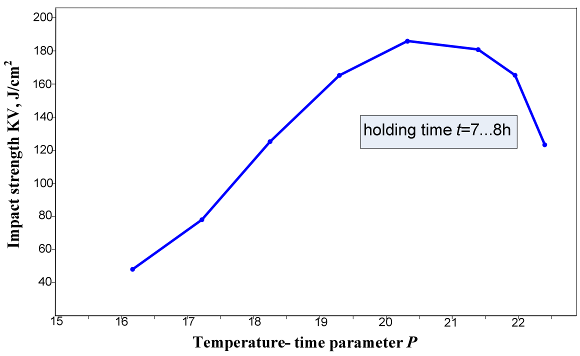

Fig. 5 Dependence of impact strength of welded joints from P5 steel on temperature-time parameter *P*

Impact strength test results are presented in Fig. 5 and Fig. 6. With the parameter *P* rising up to 19.4, the value of impact strength is also growing. Thereafter, an insignificant drop of the value of impact strength is observed when the holding time is 1 hour (Fig. 6). When the holding time is 8 hours, the value of impact strength rises up to *P*–20.3; afterwards, sudden decreasing (~30 J/cm^2 per each parameter *P* unit) can be observed. Impact strength is the highest when the parameter *P* value is within the range from 18.5 to 20.3.

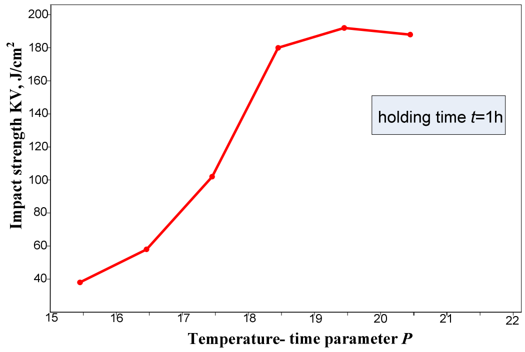

Fig. 6 Dependence of impact strength of welded joints from P5 steel on temperature-time parameter *P*

Findings of all the mechanical tests showed that when the temperature and time parameter is higher than 20.3 the values of all the three mechanical characteristics (considered by us) tend to reduce. This means, that such parameters of post weld heat treatment are not recommended. The best results are obtained when *P* is within the range from 18.5 to 20.3. Sudden drop of the value of impact strength and tensile strength may result from the increased amount of carbides' M_3C and $M_{23}C_6$ particles with higher heat treatment temperatures or longer exposure time used [8].

American scientists K. Orie and Ch. R. Roper [1] investigated the behavior of low-alloy manganese steel plate (ASTM A516 Grade 70) subjected to post weld heat treatment. They found, that the cumulative effects of time and temperature during post weld heat treatment have a deleterious effect on base metal properties. Each increase 1.0 magnitude in parameter *P* above 17.5 in general lowers tensile strength by approximately 2%. Our results are a bit different because the studied materials are different, but quantitatively they are on agreement with.

5. Conclusions

1. Heat treatment leading to the increase of temperature-time parameter *P* has a negative impact on strength-related characteristics of welded joints from ASTM A335 P5 steels. Such heat treatment regime decreases the tensile and impact strength of welded joints.

2. The values of strength characteristics of welded joints are alike, when the temperature-time parameter *P* is similar, though the temperature and time of exposure differs.

3. As for ASTM A335, the mode for post weld heat treatment of P5 steel welds has to ensure the value of the temperature and time parameter *P* is from 18.5 to 20.3. With such values, the values of mechanical characteristics of the welds are optimal.

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TERMINIO APDOROJIMO PO SUVIRINIMO ĮTAKA CHROMINIO- MOLIBDENINIO PLIENO STIPRUMINĖMS CHARAKTERISTIKOMS

R e z i u m ė

Straipsnyje pateikta chrominio-molibdeninio plieno (ASTM A335 Grd. P5) suvirintųjų jungčių tyrimo po terminio apdorojimo medžiaga. Šio plieno suvirintosioms jungtims būdingi dideli liekamieji įtempiai. Suvirintųjų jungčių suirimo pavojaus galima išvengti, sumažinant liekamuosius įtempius terminiu apdorojimu. Šio tyrimo programos tikslas yra nustatyti tokius suvirintųjų jungčių terminio apdorojimo parametrus, kad jų stipruminių charakteristikų vertės būtų didžiausios. Straipsnio medžiagoje pateikiamos jungčių stiprumo charakteristikų priklausomybės nuo terminio apdorojimo temperatūros ir laiko parametro *P* analizė. Suvirintųjų jungčių pavyzdžiai buvo termiškai apdoroti, atliktas aukštasis atleidimas. Kiekvienas bandinys buvo apdorotas skirtingu režimu. Bandymų temperatūros buvo nuo 500 iki 800°C, o išlaikymo trukmė, nuo 1 iki 8 h. Esant tokiems terminio apdorojimo režimams, temperatūros ir laiko parametro *P* vertė yra nuo 15.5 iki 22.5. Po terminio apdorojimo buvo atlikti kiekvieno pavyzdžio tempimo ir smūginio tąsumo bandymai.

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THE STRENGTH-RELATED CHARACTERISTICS OF CHROMIUM-MOLYBDENUM P5 STEEL DEPENDENCE ON POSTWELD HEAT TREATMENT PARAMETERS

S u m m a r y

The article deals with the analysis of chromium-molybdenum steel (ASTM A335 Grd. P5) joints after post weld heat treatment. The finished welds typically exhibit high levels of tensile residual stresses. The risk of weld failure may be alleviated by reducing the magnitude of the tensile residual stresses. The objective of the research program outlined in this paper is to develop a short-term post-weld heat treatment procedure than can be used to produce the highest values of strength-related characteristics of welded joint. The article materials present the investigation of the strength-related characteristics dependence on temperature-time parameter *P*.

The welded joints samples were heat treated by tempering mode. When performing post weld heat treatment, the temperature was changed from 500 to 800 ºC and the exposure (hold) time was changed from 1 to 8 hours. The chosen tempering parameters were to ensure the value of the temperature and time parameter was from 15.5 to 22.5. After post-weld heat treatment each sample was tested subject to tensile, yield and impact strength.

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ВЛИЯНИЕ ТЕРМООБРАБОТКИ НА ПРОЧНОСТНЫЕ ХАРАКТЕРИСТИКИ СВАРНЫХ СОЕДИНЕНИЙ ХРОММОЛИБДЕНОВОЙ СТАЛИ

Р е з ю м е

В статье представлены результаты об исследования сварных соединений хроммолибденовой стали (ASTM A335 Grd. P5) после термической обработки. Сварным соединениям из этой стали свойственны очень большие остаточные напряжения, уменьшить которые можно, применив термообработку. Цель этой программы – установить параметры термообработки, соответствующие наивысшим прочностным характеристикам сварных соединений. В статье представлен анализ зависимости прочностных характеристик от параметра температуры и времени *P*. Образцы сварных соединений были термообработаны, применялся высокий отпуск. Каждый образец был обработан разным режимом. Температура обработки была от 500 до 800°C и время выдержки от 1 до 8 часов. При таких режимах термообработки, значение параметра температуры и времени *P* изменялось от 15.5 до 22.5. После термообработки были проведены испытания на разрыв и ударную вязкость.

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