Archives of Materials Science and Engineering

Volume 95
Issue 2
February 2019
Pages 55-66

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

DOI: 10.5604/01.3001.0013.1731

The influence of the parameters of heat treatment on the mechanical properties of welded joints

K. Łuczak *, W. Wolany
Katowice School of Technology, ul. Rolna 43, 40-555 Katowice, Poland
* Corresponding e-mail address: katarzyna.luczak@wst.com.pl

ABSTRACT

Purpose: The main goal of the work is to determine the influence of the parameters of stress relief annealing on the mechanical and structural properties of welded joints made of chromium-molybdenum type 10CrMo9-10 steel.

Design/methodology/approach: In the study, commercial 10CRMO9-10 steel was used, the Polish equivalent of 10H2M. This is a chromium-molybdenum toughened steel, i.e. after normalization (910-960°C) and high tempering (650-780°C). The materials were subjected to heat treatment, tests of mechanical properties, Charpy impact test, hardness of individual material zones, as well as macro and microscopic observations.

Findings: The hardness tests indicated, that materials subjected to a single heat treatment possess the greatest hardness. Materials undergoing several heat treatments, possess hardness on a similar level to materials that have been annealed once, however they are characterized by low reproducibility of results. The most important parameter of heat treatment of the tested steel is heating up to a temperature of 690°C. Due to such heating, optimal mechanical properties are achieved, which results in long and safe exploitation of the produced elements.

Research limitations/implications: The processes of heat treatment are very important to achieve optimal strength properties of welded joints.

Practical implications: The development of energy worldwide has caused the creation of machines working in higher pressure and temperature ranges. The influence of temperatures decreases the service life of a given element. The adaptation and completion of the appropriate process of heat treatment extends the exploitation time of elements.

Originality/value: Determining the mechanical properties of 10H2M steel, dependent on the temperature of heat treatment and heating time. It was concluded that the optimal parameter of heat treatment for the tested materials – is heating at a temperature of 690°C.

Keywords: Heat treatment, Welded joints,10CrMo9-10 steel

Reference to this paper should be given in the following way:

K. Łuczak, W. Wolany, The influence of the parameters of heat treatment on the mechanical properties of welded joints, Archives of Materials Science and Engineering 95/2 (2019) 55-66.

PROPERTIES

1. Introduction

Despite the rapid development of technology, welding still remains the most popular method of combining metal materials [1-6]. The requirements for welded construction materials are becoming greater and greater. In order to improve the quality of welded joints, materials undergo additional processes of heat treatment. The quality of welded joints and their safe exploitation is most of all influenced by the elimination of the possibility of the creation of brittle fractures as well as the relaxation of welding residual stresses. Quality is improved through stress relief annealing. As a result, the values of the created internal stress of the welded joint are lowered, while in case of the creation of brittle structures, the process of stress relief annealing causes the dissolution of the created hard areas of steel. Utilizing, the appropriate for a given steel, process parameters, such as heating temperature, heating time as well as speed of temperature growth, guarantees the optimal mechanical properties. The aim of these actions is the improvement of the mechanical properties of the material as well as extension of its service life [7,8]. Steels for work in high temperatures, including chromium-molybdenum and high-alloy steels, are part of a group of materials with limited weldability. These materials require initial heating prior to the welding, maintenance of the appropriate temperature, as well as heat treatment after welding – especially in case of high-alloy steels. The aforementioned procedures as well as the welding process itself turn the production of welded joints into a long and costly process. Materials which are difficult to weld have a tendency to alter their grain structure in intermediate processes. Therefore, initial heating is used, while later the process itself, with the aim of achieving weld and heat affected zone parameters, similar to parameters of the base material [9-15]. In most cases the necessity to conduct heat treatment is a result of domestic law or the demands of the client. Most often, the information regarding heat treatment ends with the provision of the process cycle while maintaining the appropriate norms. However, there are cases, in which the client supplies information regarding the placement of thermocouples which control the heating mats. The placement of thermocouples has a significant influence on the distribution of temperature in the material, while inappropriate placement may cause the occurrence of abnormalities. The control of welded joints generally boils down to testing the weld elements as well as the heat affected zone of the material, while less attention is devoted to the whole construction of the produced detail. The aim of the present work is to determine the influence of parameters of stress relief annealing on the mechanical and structural properties of welded joints made out of conventional, low-alloy chromium-molybdenum steel.

2. Materials and methodology

In order to complete the research 10CRMO9-1O (DIN) steel was selected, the Polish equivalent of 10H2M. This is a chromium-molybdenum toughened steel i.e., after normalization (910-960°C) and high tempering (650-780°C) guaranteed by the supplier. The chemical composition of the selected steel is shown in Table 1.

Table 1.
Chemical composition of 10H2M steel

Chemical composition, %								
C	Mn	Si	P	S	Cu	Cr	Ni	Mo
0.08>0.15	0.40>0.60	0.15>0.50	Max 0.030	Max 0.030	Max 0.25	2.00>2.50	Max 0.30	0.90>1.10

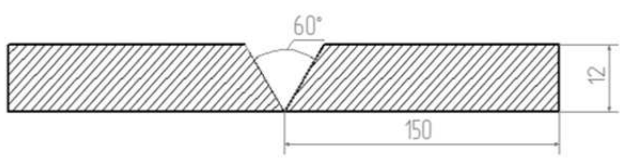

Fig. 1. Preparation of the material for welding

Preparation of the material for welding was based on cutting forms out of sheet metal, with a length of 350 mm and a width of 150 mm. The forms underwent milling until an angle of 60°C (Fig. 1) was obtained in order to combine the forms using butt-welding. Then they were combined with one another and welded using the TIG/MMA method.

Then, part of the prepared materials were heat treated with different parameters. The control of the heat treatment for the prepared materials was based on checking the appropriate placement of thermocouples, becoming familiar with the obtained chart of heat treatment and evaluating the appropriateness of parameters of the heat treatment process. The following four materials were used in the research:

- 10H2M steel, not subject to heat treatment after welding;
- 10H2M steel subject to stress relief annealing at a temperature of 690°C;

- 10H2M steel subject to stress relief annealing at a temperature of 690°C – three times;
- 10H2M steel subject to heat treatment at a temperature 790°C.

Materials were prepared for destructive tests by removing excess weld face, in order to standardize the thickness, and cutting out steel samples of appropriate dimensions for the destructive tests. Materials were subject to tensile test, the Vickers hardness test, Charpy impact test as well as a microscope observation of welded joints. Investigation of tensile test were carried out according to the norm PN-EN 6892-1:2016-09. The test was based on the samples being subject to controlled tension until failure. The prepared samples possessed a gauge length equal to 120 mm, which equals 10 times the sample thickness. Hardness testing of the materials was conducted using the Vickers method according to the norm PN-EN ISO 6507-1:2018. A resilience test was conducted according to the norm PN-EN ISO 148:2010.

3. Research and result analysis

3.1. Static tensile test

As a result of static tensile test, elongation-force curves were obtained for the tested sample. The obtained results are shown in Figure 2.

The obtained graphs allowed to determine the characterization of force, the apparent yield strength, the calculation of resistance to tension and relative elongation. The results are presented in Table 2.

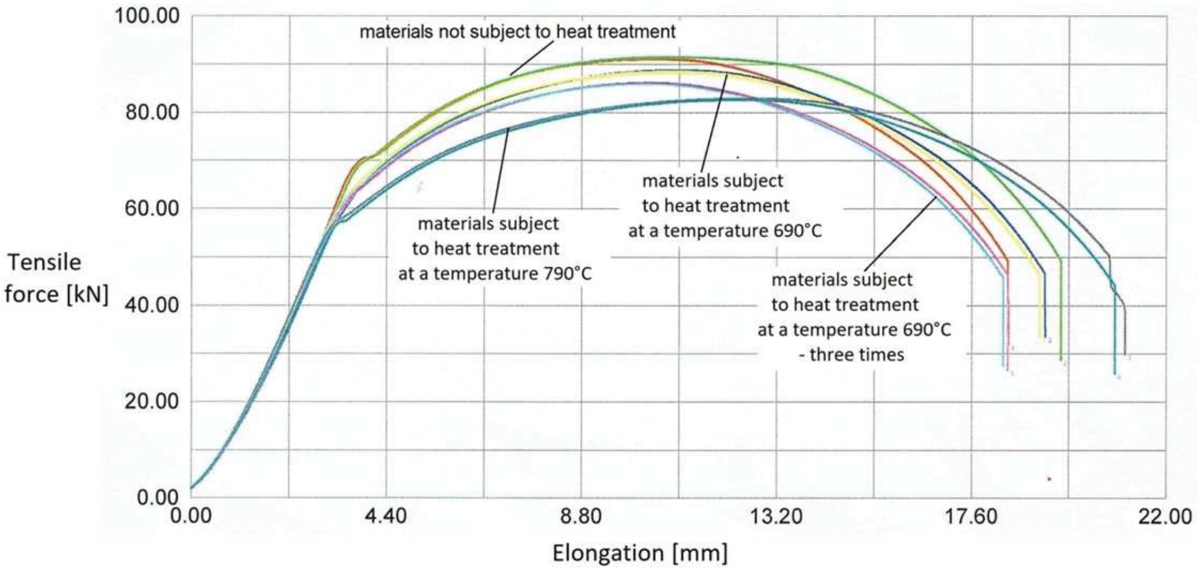

Fig. 2. The comparison of results obtained in tension testing for the tested materials

Table 2.
The results obtained from static tensile test.

Samples	Fm, kN	$Rp_{0.2}$, MPa	A, %	Rm, MPa
Materials not subject to heat treatment after welding				
Average value	91.33	476.87	23.76	594.44
Materials subject to stress relief annealing at a temperature of 690°C				
Average value	88.71	449.38	24.03	576.99
Materials subject to stress relief annealing at a temperature of 690°C – three times				
Average value	86.14	430.51	22.99	560.19
Materials subject to heat treatment at a temperature 790°C				
Average value	82.88	388.16	26.21	538.90

Comparing the strength parameters of the tested materials, it was concluded that steels not subject to heat treatment are characterized by the highest average tensile strength equaling 594.44 MPa. They also have the highest value of apparent yield strength equaling on the average 476.87 MPa. Slightly lower parameters were obtained for materials subject to a single heat treatment at a temperature of 690°C. The apparent yield strength for these materials equaled on the average 449.38 MPa, with tensile strength of 576.99 MPa. Annealing several times at a temperature of 690°C caused the lowering of strength parameters in comparison to steel undergoing a single heat treatment. These materials are characterized by tensile strength of 560.19 MPa, as well as apparent yield strength on the level of 430.51 MPa. The lowest results were obtained for materials stress relief annealing at a temperature of 790°C. The tensile strength for these materials equaled on the average 538.90 MPa, while their apparent yield strength was 388.16 MPa. Comparing the plastic properties of the tested steel depending on the parameters of the heat treatment it may be concluded that heat treatment at a temperature of 690°C does not has a significant influence on plastic parameters. A significant drop in the $R_{p0.2}$ value is only visible in case of overheated materials, i.e., annealed at a temperature of 790°C. This is a decrease of nearly 89 MPa in comparison to the material not subjected to heat treatment, with a noticeable decrease in mechanical properties as well.

3.2. Hardness test

The hardness results of 10CrMO9-10 steel are presented on graphs (Figs. 3-5). The distribution of the hardness for each individual zone of materials not subject to heat treatment is presented in Figure 3. The trendline displayed on the graph shows changes in hardness for all of the material. Hardness of the base material does not exceed 205HV/10, while for the heat affected zone 197-283 HV/10 and finally 205-301HV/10 for the weld. There is a sudden increase in hardness in the heat affected zone on one side of the weld as well as an unevenness of hardness measured on the other side of the weld. The average hardness for the whole material equals 222.58 HV/10 and does not exceed the upper limit which is 380HV/10, and which constitutes a norm for allowing the materials for further production and exploitation.

The values of hardness for each individual material zone subject to a single heat treatment at a temperature of 690°C, are presented in Figure 4. In case of these materials there is a noticeable decrease of the average material hardness in comparison with materials not subjected to heat treatment. The average hardness value equaled 197.66 HV/10, while the individual zones were characterized by the following hardness values: base material 172-185 HV/10, heat affected zone 184-218 HV/10, as well as 217-249 HV/10 for the weld.

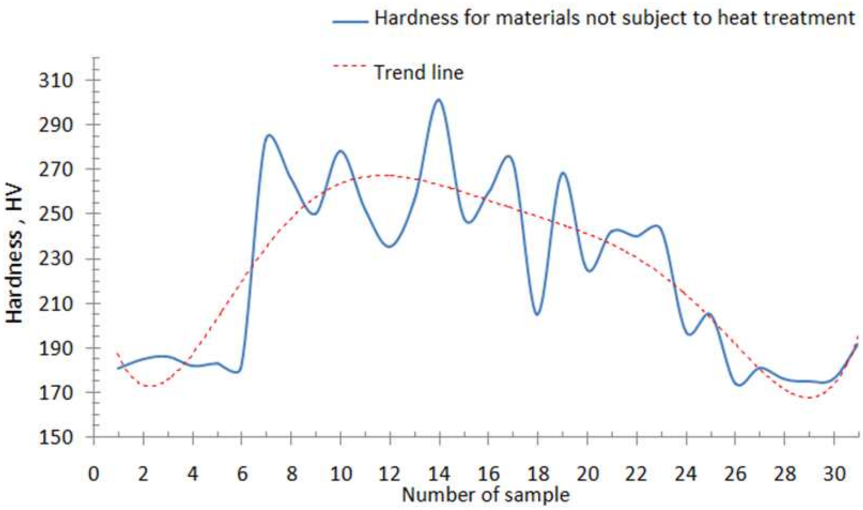

Fig. 3. Distribution of hardness for material which was not subjected to heat treatment

Materials which were subjected to multiple treatment with stress relief annealing show varied results in the tested zones, which is shown by the distribution of hardness (Fig. 5).

The greatest spread for the obtained results was exhibited by the weld area. The difference between maximum and minimum weld hardness equaled 52 HV/10. The base material zone exhibited the greatest stability of obtained results, where the hardness of this zone is at the level of 173 HV/10. For materials undergoing multiple treatments the following levels of hardness were obtained in the separate ones: base material 171-175 HV/10, heat affected zone 179-213 HV/10, weld 194-246 HV/10. Observing the trendlines for materials subjected to multiple heat treatment it may be concluded that these materials exhibit a slight increase in hardness in the heat affected zone. The line also shows that values for the base material remain on the same average level, equal to 173.25 HV/10.

Analyzing the weld area it may be unambiguously concluded that it still exhibits the greatest hardness, however there is a noticeable trend of decrease in hardness in relation to materials not subjected to heat treatment and those subjected to a single stress relief annealing.

The hardness tests for materials heated at a temperature of 790°C (Fig. 6) showed, that along with an increase in temperature, the border allowing for the distinction between each individual material zones disappears. For materials subjected to heat treatment at a temperature of 790°C, the following values of hardness were obtained: base material 166-172 HV/10, heat affected zone 165-182 HV/10, weld 163-184 HV/10. It may be unequivocally concluded that all the zones exhibit uniform hardness.

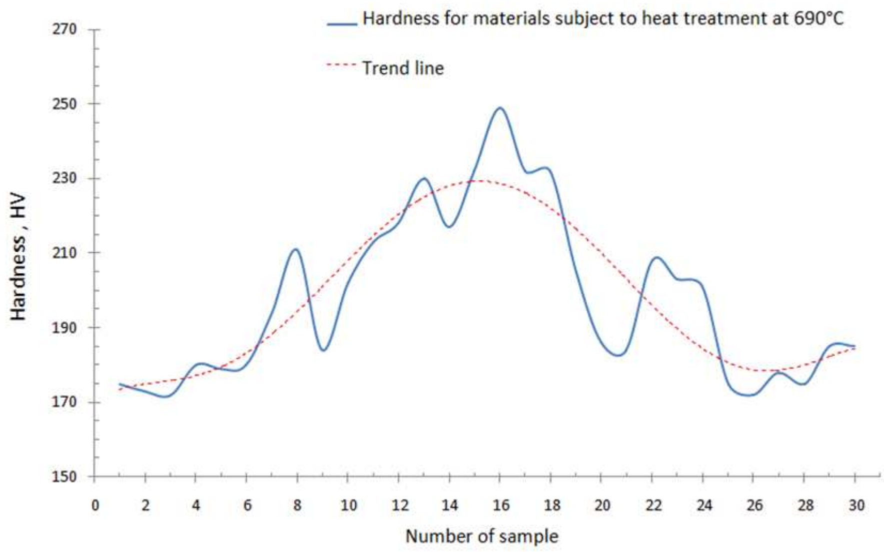

Fig. 4. Distribution of hardness for material which was subjected to a single heat treatment at 690°C

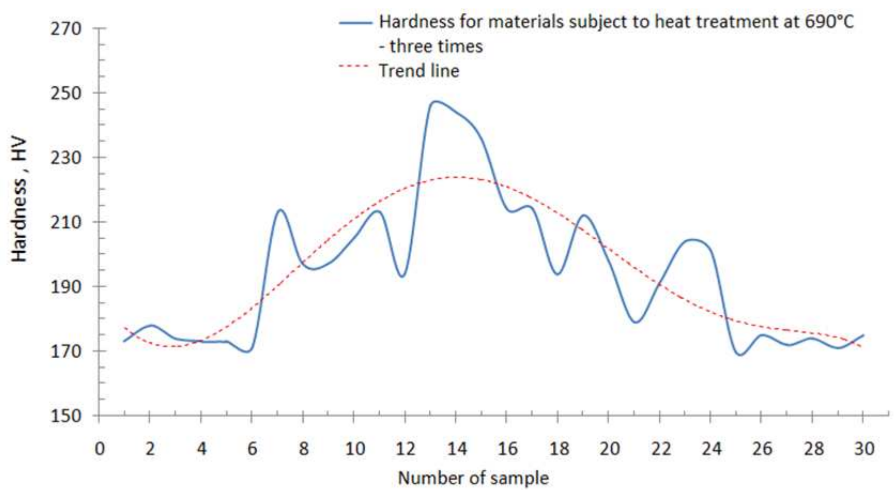

Fig. 5. Distribution of hardness for materials subjected to heat treatment at 690°C three times

In case of this material there is a noticeable decrease in hardness value equaling approx. 50 HV in relation to materials heated at a temperature of 690°C and even 115 HV of hardness in comparison with materials which were not subjected to heat treatment.

3.3. Charpy impact test

The average values of impact energy used to break the samples are presented in Figure 7.

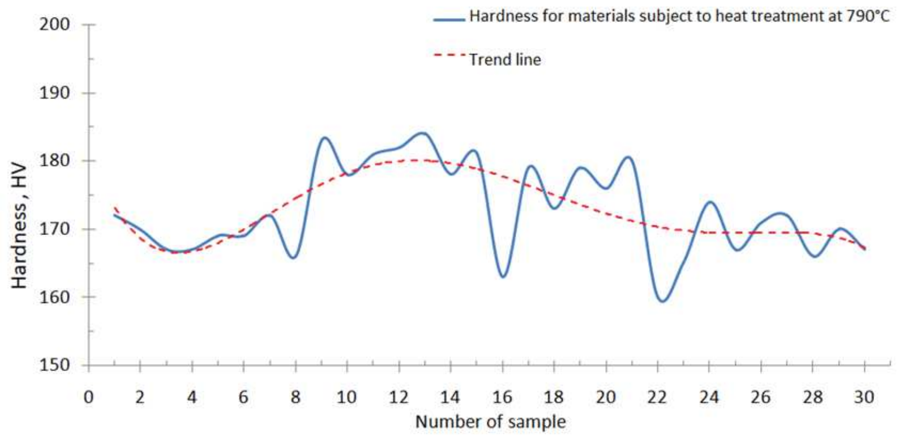

Fig. 6. Distribution of hardness for material which was subjected to a single heat treatment at 790°C

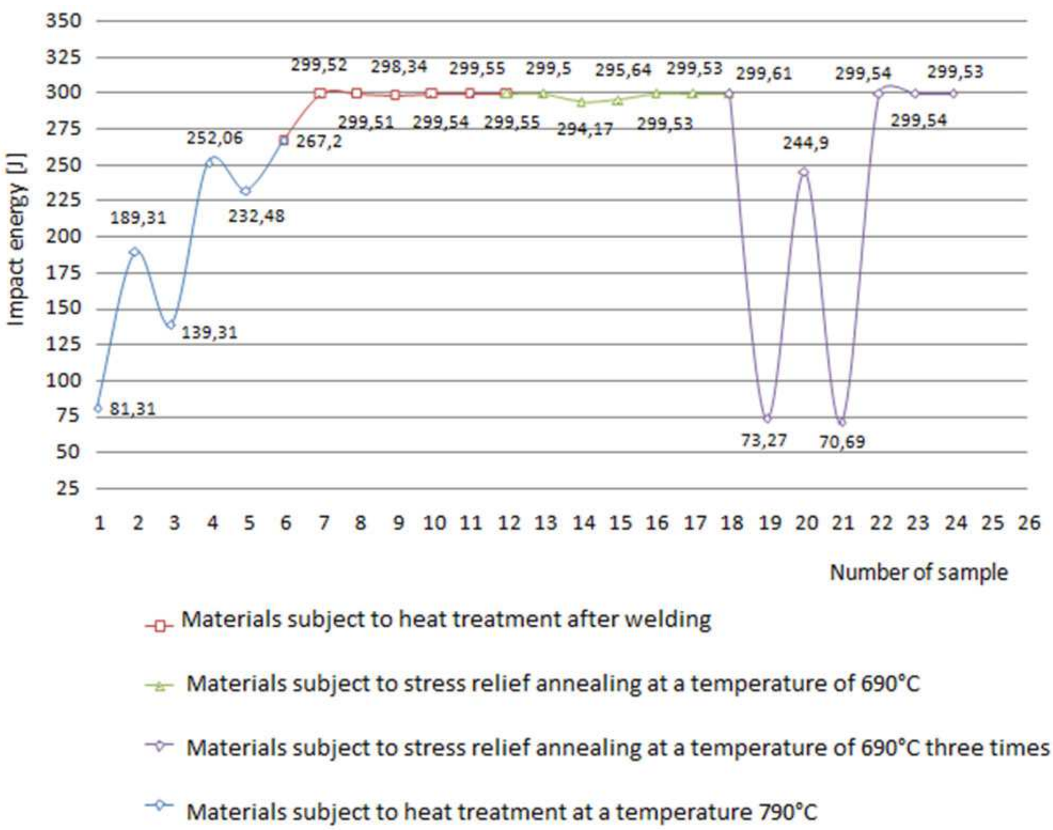

Fig. 7. Results of impact energy used to break samples obtained for each individual material

The impact tests of the weld of materials which were not subjected to heat treatment exhibited brittle fractures which did not show any deformations, while in the heat affected zone a brittle fracture was observed exhibiting certain sample deformations. Materials subjected to heat treatment at a temperature of 690°C exhibited a cleavage fracture without visible brittleness or steel delamination. In materials which were heated multiple times two distinct fractures of samples were observed. The heat affected one was characterized by a cleavage fracture with a visible material yielding, while the weld zone exhibited a cleavage fracture with a visible area of material brittleness. The greatest variety in sample fractures was achieved in case of materials subjected to heat treatment at a temperature of 790°C. In the weld zone a brittle fracture was obtained (all samples were broken), while in the heat affected zone a fracture of high yielding was visible (all samples were bent). During an inspection of the performed tests material delamination was concluded in the heat affected zone. In steels which were not annealed the impact strength value equaled 2.47 J/cm^2. This result means that the steel can be approved for further exploitation since the minimal average impact strength value for 10H2M steel equals 3.14 J/cm^2 (as delivery stated of material). The average impact strength value obtained for overheated materials equaled 2.68 J/cm^2. The average calculated impact strength was presented in Table 3. For steels heated at a temperature of 690°C the results of impact energy were on an equal level (high repetitiveness of results) as well as impact strength on a level above 3.7 J/cm^2, a result which allows for such steel to be approved for further use.

Table 3.
Impact strength of materials tested

Types of samples	Kc, J/cm^2
Material not subject to heat treatment after welding	2.47
Material subject to stress relief annealing at a temperature of 690°C	3.74
Material subject to stress relief annealing at a temperature of 690°C – three times	3.73
Material subject to heat treatment at a temperature 790°C	2.68

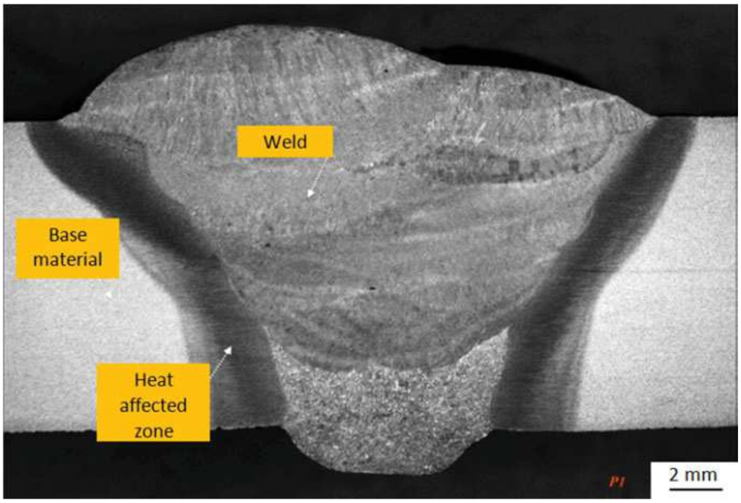

Fig. 8. Macrostructure of weld overlay of the material subject to heat treatment, magnified x 4

3.4. Macrostructure observations

On the base of the macroscopic observation it was found that material which was not subjected to heat treatment it was noticed that the heat affected zone, base material zone and the weld are simple to identify. The base material is characterized by a light-colored field with fine grain. The heat affected zone is dark, without the possibility to identify the grain, while the weld zone can be divided into two areas, in which with ease we can separate the weld penetration made using the TIG method from the filling as well as the weld face made using the MMA method. The macrostructure of the material which was not subjected to heat treatment is presented in Figure 8.

Based on the observation of these materials it can be concluded that there is a regular structure (with thick grain) in the base material zone. The weld zone of these materials is characterized by non-uniform structure with distinctive needles, which is presented in Figure 9. In the heat affected zone fragmentation and uneven placement of grains was observed.

Based on microscopic observation the surface of materials which were subjected to heat treatment at a temperature of 690°C, a partial disappearance of the heat affected zone was concluded, the observation of the tested structure exhibited a difficulty in distinguishing the penetration from the filling. The material became uniform which is presented in Figure 10.

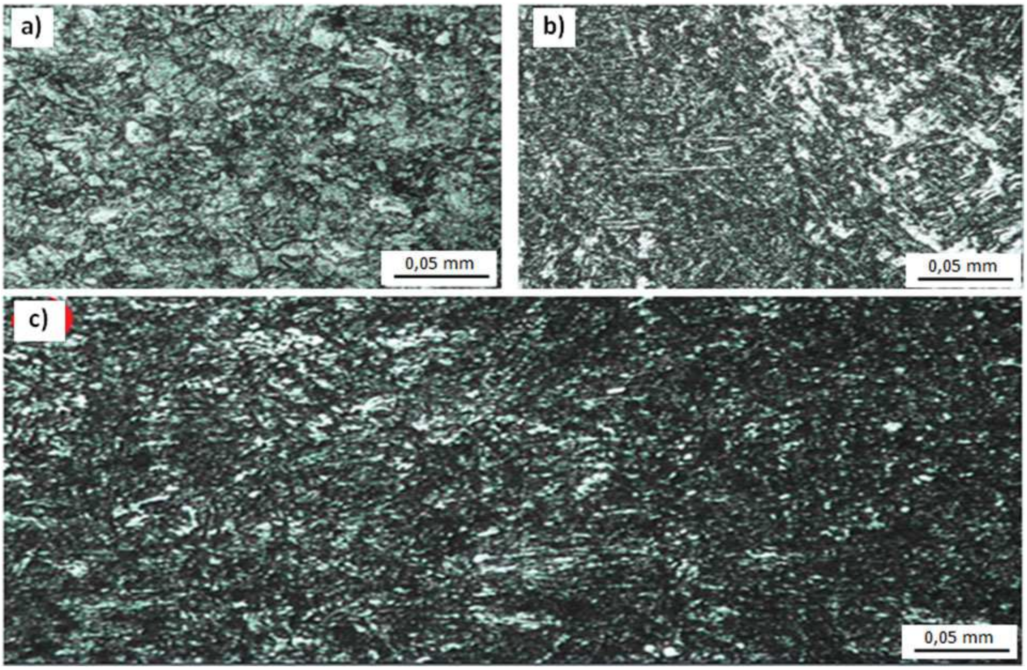

Fig. 9. Microstucture of materials not subject to heat treatment: a) base material structure, b) weld structure, c) heat affected structure, mag. x200

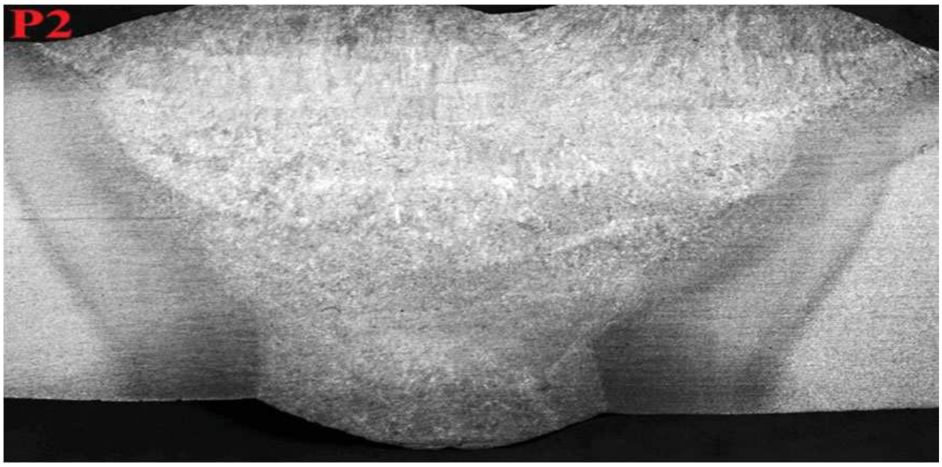

Fig. 10. Macrostructure of materials subject to a single heat treatment, mag.4x

Microscopic observations show even distribution of grains in the base material zone with a thick-grain structure. Uniformity of the weld structure and the heat affected structure was observed. The size of the sample grain in each zone is identical not indicating any great growth caused by the heating temperature, which is presented in Figure 11.

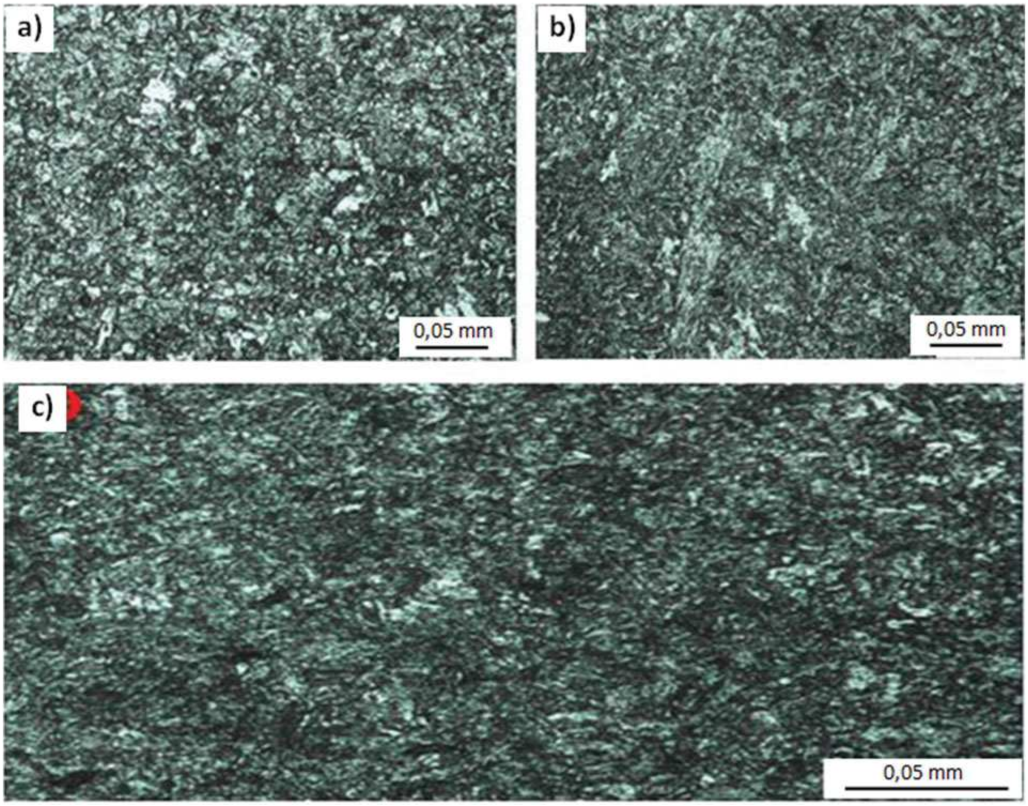

Fig. 11. Microstructure of materials which were subject to a single heat treatment: a) base material structure, b) weld structure, c) heat affected structure, mag. x200

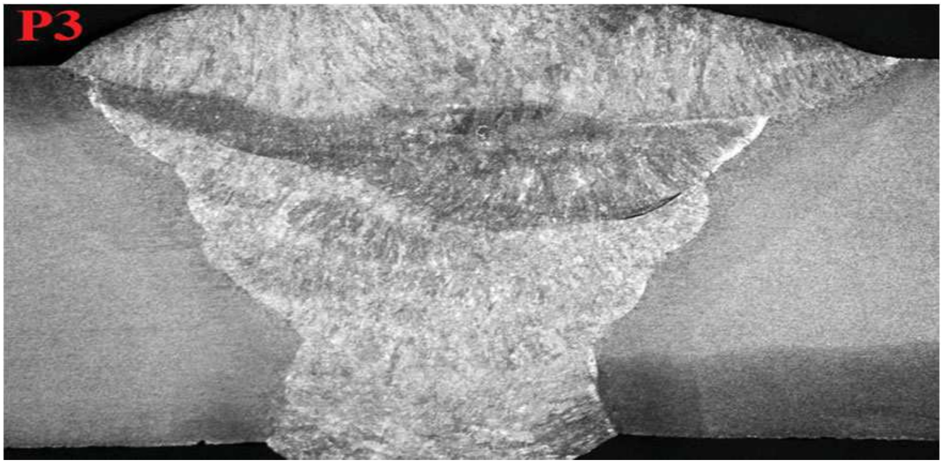

Fig. 12. Macrostructure of materials which were subject to multiple heat treatment, mag. x4

The structure of materials which were subject to multiple heat treatments is presented in Figure 12. A complete disappearance of the heat affected zone was observed along with a noticeable separation of the whole weld in relation to the base material. This may have been caused by multiple heating of this material. The influence of repeated heating allowed for complete uniformity of the base material with the heat affected zone.

Microscopic observations (Fig. 13) of materials heated multiple times show that the heat affected zone, the weld, as well as the base material possess a thick and fine grain structure. During the observations of all zones no significant growth of steel grains was observed.

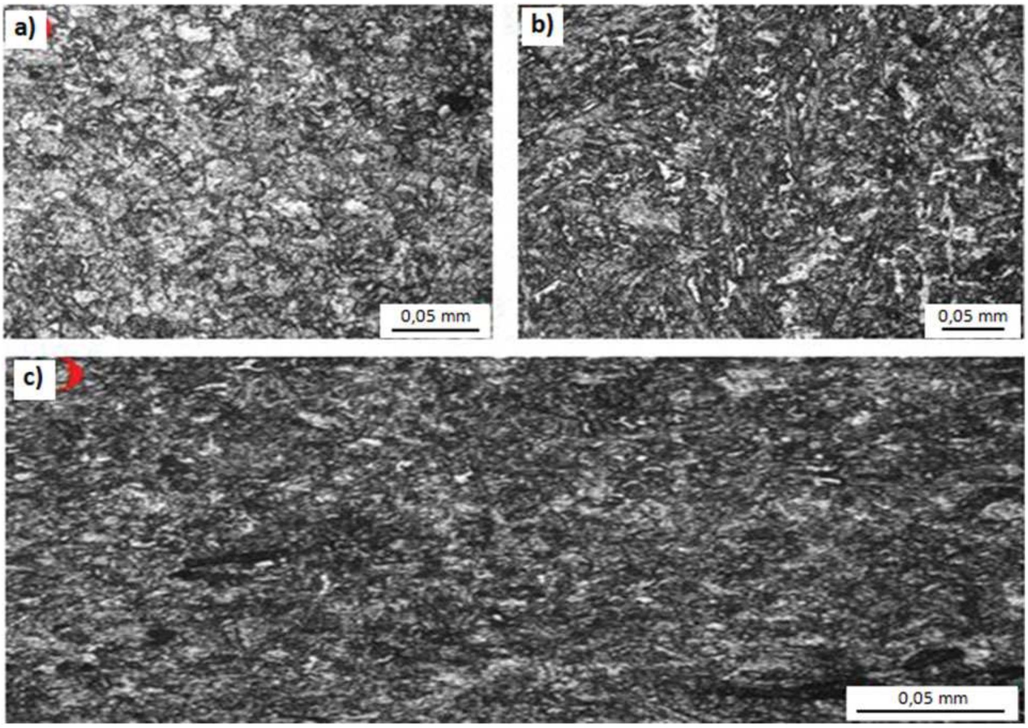

Fig. 13. Microstructure of materials subject to multiple heat treatments: a) base material structure, b) weld structure, c) heat affected structure; mag. x200

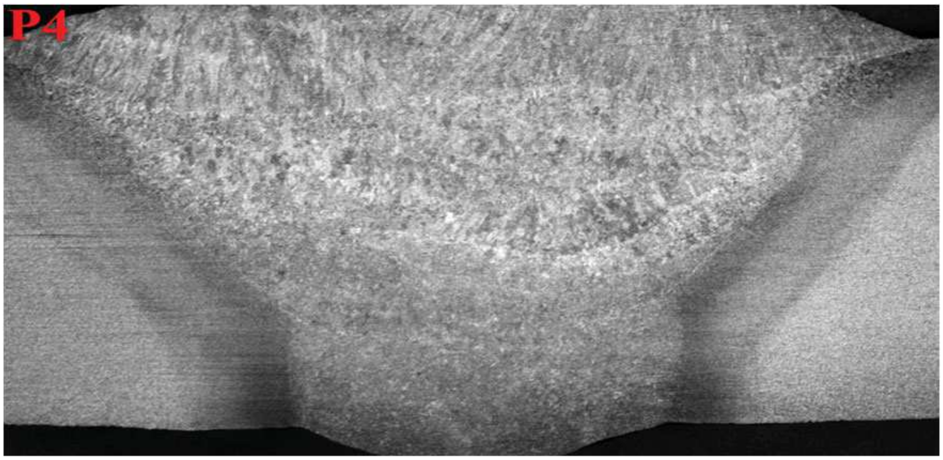

Fig. 14. Macrostructure of materials heated at a temperature of 790°C, mag. x4

Materials which were subjected to heat treatment at a temperature of 790°C, during macroscopic observations exhibited a disappearance of the border between the penetration and the filling, which was visible in materials not subjected to heat treatment. The heat affected zone is easy to distinguish due to a visible dark color (outline of the whole weld) which is presented in Figure 14.

During microscopic observations (Fig. 15) changes in the material structure were noticed. The weld exhibits a thick-grain structure with large areas of ferrite, while in the heat affected zone an area of significant grain growth was noticed. Such large grains in the heat affected zone may cause a decrease in the mechanical properties of the material.

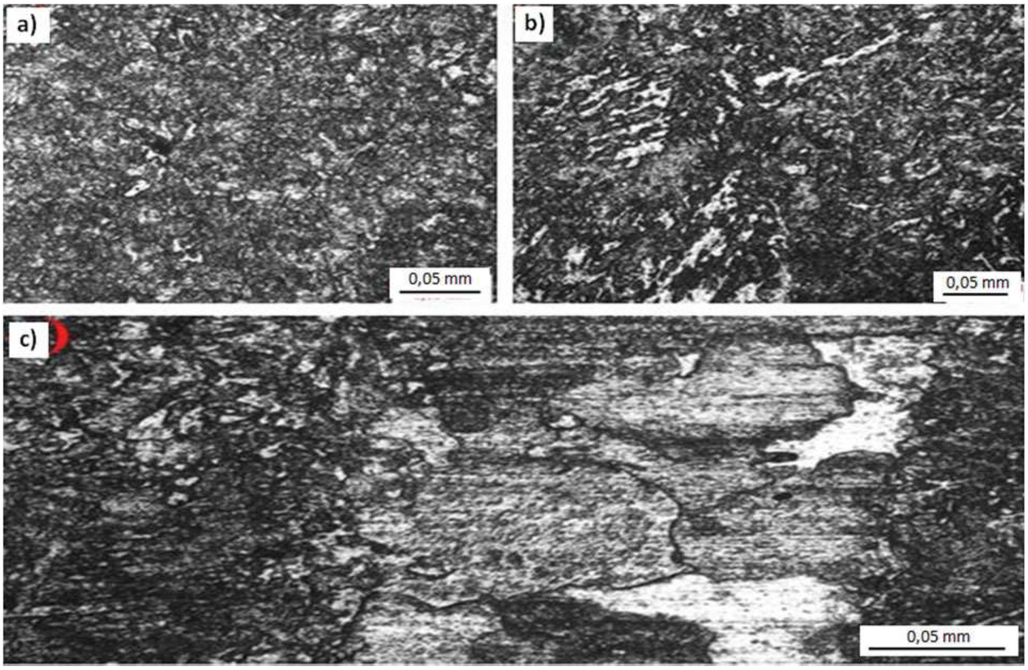

Fig. 15. Macrostructure of materials heated at a temperature of 790°C: a) base material structure, b) weld structure, c) heat affected structure; mag. x200

4. Conclusions

The results obtained in static tensile test showed that the most optimal mechanical properties were achieved in case of a material which was subject to single heat treatment. For this material the relative elongation equaled 24.3%, which indicates optimal plasticity while maintaining high tensile strength. Overheated materials, i.e. those heated at a temperature of 790°C, are characterized by a slightly lower tensile strength. In these materials the tensile strength was lower by approx. 7% in comparison to the materials which were subject to stress relief annealing at a temperature of 690°C. Stress relief annealing also influences impact strength of materials. Materials subjected to a single heat treatment were characterized by the greatest impact strength. During hardness testing using the Vickers method, it was observed that the value of heat treatment temperature influences the hardness of metal in each individual zone. In all the tested materials the most optimal hardness was obtained with materials undergoing a single heat treatment at a temperature of 690°C where hardness equaled 230HV/10. For materials subject to multiple heat treatments at a temperature of 690°C, the obtained hardness was at a similar level to materials undergoing a single heat treatment, however these are characterized by a low reproducibility of results. The lowest hardness values were obtained for overheated materials, since the weld hardness of this material was 13.5% lower than of materials subjected to a single heat treatment at a temperature of 690°C. At the same time it was concluded, that materials heated at a temperature of 790°C exhibit equal hardness for all zones, which is not the expected result, since the hardness of the weld should be higher.

Heat treatment conducted at different parameters also had an influence on the obtained structure of the material. In overheated materials, structure observation showed an overly large growth of grain. Such a structure also shows variety in the results of hardness as well as impact energy, which was confirmed by the testing itself. The most uniform structure, was obtained with materials which were subjected to a single heat treatment at a temperature of 690°C, which indicates that these materials are the most desirable ones and they fulfill all the norms.

The presented results confirm the need to use heat treatment for 10CrMo9-10 steel as well as the relevance of the influence of the performed tests on the strength parameters of the tested materials. The test results also showed that the most optimal parameters of heat treatment are heating until a temperature of 690°C, maintaining such temperature for 30 minutes, while using a speed of cooling and heating the temperature equal to 200°C/h. As a result of such heating the optimal mechanical properties are achieved, which allows for long and safe exploitation of the manufactured elements. Long-lasting usage of alloy steel elements is possible thanks to significantly decreasing the possibility of occurrence of brittle fractures on the welded joint as well as uniformity of structures. Achieving such a result is only possible through a selection of the appropriate parameters of heat treatment.

References

[1] L. Jeffus, Welding and Metal Fabrication, Cengage Learning, Delmar, 2012.

[2] L.A. Dobrzański, Engineering materials and material design, WNT, Warszawa, 2006.

[3] L.F. Jeffus, Welding: Principles and Applications, Cengage Learning, Delmar, 2004.

[4] K. Wesołowski, Metallurgy and heat treatment, WNT, Warszawa, 1978 (in Polish).

[5] B.-J. Jin, M.-H. Park, T.-J. Yun, J.-Y. Shim, B.-Y. Kang, I.-S. Kim, A study on welding quality for the automatic vertical-position welding process based on Mahalanobis Distance method, Archives of Materials Science and Engineering 91/1 (2018) 31-40.

[6] M. Blicharski, Introduction to materials engineering, WNT, Warszawa, 2003 (in Polish).

[7] A. Zieliński, J. Dobrzański, The assessment of condition and suitability for further service of the material of steam pipelines operated beyond the design work time, IMŻ Works 3 (2013) 42-55.

[8] A. Hernas (Ed.), J. Dobrzański, J. Pasternak, S. Fudali, Characteristics of new-generation materials for the energy industry, Silesian University of Technology Publishing House, Gliwice, 2015 (in Polish).

[9] M. Zeman, J. Brózda, Selected aspects connected with manufacturing mixed welded joints made of steel for working in high temperatures, 93-99 (in Polish).

[10] D.M. Madyira, J.A. Liebenberg, A. Kaymacki, Comparative Characterization of P91 and 10CrMo9-10 Creep Resistant Steel Welds, Procedia Manufacturing 8 (2017) 345-352.

[11] M. Urzynicok, K. Kwieciński, J. Słania, Analysis of problems occured during welding of new genreation bainitic steel 7CrMoVTiB10-10 (T24), Archives of Metallurgy and Materials 58 (2013) 691-696.

[12] E. Armentani, R. Esposito, R. Sepe, The effect of thermal properties and weld efficiency on residual stresses in welding, Journal of Achievements in Materials and Manufacturing Engineering 20/1-2 (2007) 319-322.

[13] M. Cieśla, R. Findziński, G. Junak, T. Kawała, The Effect of Heat Treatment Parameters on Mechanical Characteristics of 10CrMo9-10 Steel Tube Bends, Archives of Metallurgy and Materials 60/4 (2016) 2971-2975.

[14] Y.H. Yao, J.F. Wei, J.N. Liu, Z.P. Wang, Y.H. Jin, Aging Behavior of T91/10CrMo910 Dissimilar Steel Welded Joints, Advanced Materials Research 146-147 (2011) 156-159.

[15] J. Dobrzański, Material characteristics of 10CrMo910 (10H2M) steel after prolonged use under creep conditions necessary in evaluating the state and usefulness for further exploitation of material in pressure elements of power boilers, Energetics, Thematic Issiue XIX (2009) 27-33.

[16] J. Dobrzański, H. Krztoń, A. Zieliński, Development of the precipitation processes in low-alloy Cr-Mo type steel for evolution of the material state after exceeding the assessed lifetime, Journal of Achievements in Materials and Manufacturing Engineering 23/2 (2007) 19-22.