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EXAMINATIONS OF THE WELDED JOINT T91 STEEL AFTER SERVICE AT ELEVATED TEMPERATURE

The article provides results of the microstructure examinations and mechanical properties (hardness and microhardness tests) of the welded joint T91 steel taken from the live steam pipeline. Examined joint has been exploited for about 45 000 hours in a temperature of 535°C and the steam pressure equals to 13.5 MPa. Examined joint was made as a double bead by the additional materials with a different chemical composition. It was proved that the joint was characterized by a differential microstructure on the cross-section of the weld. Moreover, decarburized zone in the lower alloyed material and carbides zone in the higher alloyed material were revealed in the weld line and on the boundary penetration of beads. Furthermore, it was shown that the main mechanism of a joint degradation is a privileged precipitation of carbides on the grain boundaries, and an increase of their size.

Keywords: T91 steel, welded joint, microstructure, hardness and microhardness

1. Introduction

A development of the power engineering connected with a reduction of greenhouse gasses mostly CO_2 into the atmosphere is possible only by introducing modern materials, which enable to increase parameters of steam in the power units. One of the first, modern classified to the new generation of creep – resisting steel for the power industry – martensite type of steel was the X10CrMoVNb9 – 1 (P/T91) steel. This type of steel has been created in the process of modifying a chemical composition of the X12CrMo9 – 1 steel used in the chemical plants and refineries so far. Above modification allowed to get a material characterized by a higher resistance to creeping, which has been obtained mostly as a result of strengthened precipitations particles of MX type nano-sized. The first time in Poland the P91 steel was used in the power plant in Opole in the live steam pipeline [1-3]. Modernization of already existing or building new power units is connected with inter alia a necessity of joining creep-resisting types of steel, therefore a proper weldability is a vital point. A technology of welding the P91 steel requires an initial pre-heating up to a temperature of about 200°C before welding, and a thermal treatment of the joint after welding. This treatment refers to the relief annealing of the joint in the range of the temperatures between 730-750°C [4]. It allows to obtain good plastic properties of the welded joint, while resistance properties of the heat-affected zone (HAZ) of the joint in comparison to the base material are lower than about 20% [5,6]. A similar relationship was observed in case of resistance to creeping [6,7]. Lower resistance to creeping of the joint in comparison to the base material requires getting to know an influence of exploiting parameters on the stability of the joint's microstructure, the more that according to the data [5,7,8] decohesion of the joint takes place the most often in HAZ heated during a welding process to the two-phase range. The article presents the results of the welded joint of the T91 steel in a temperature of 535°C in the creeping conditions.

2. Material and a methodology of examinations

A fragment of a welded joint of the T91 steel (X10CrMoVNb9-1) (Fig. 1) became a material used for examinations. It was taken from the live steam pipeline, which has been exploited for about 45 000 hours in a temperature of 535°C and a steam pressure equals to 13.5 MPa. Welded joint was made as a double bead. A chemical composition of the T91 steel – base material is presented in the Table No. 1, while in Tables No. 2 and 3 approximate chemical compositions of additional materials are compared.

Examinations of the microstructure of the joint were taken by the optical microscopy using the (OM) Axiovert 25 microscope, as well as the scanning electron microscopy (SEM) by using the Joel JSM 6610LV microscope. Above examinations were taken

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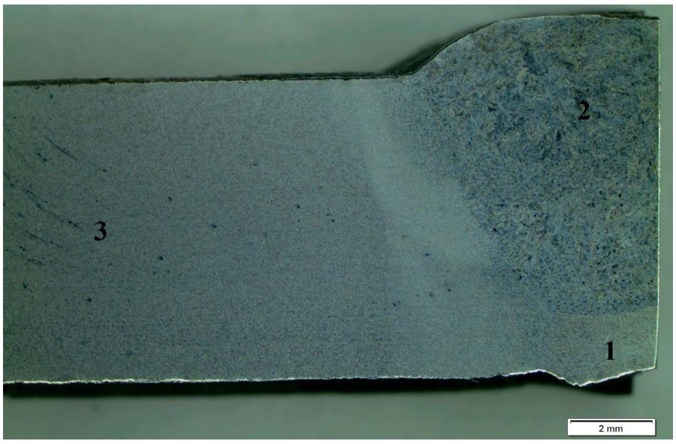

Fig. 1. Macrostructure of an examined joint: 1 – analysed area No. 1; 2 – analysed area No. 2; 3 – a base material – the T91 steel

TABLE 1

Chemical composition of the base material – the T91 steel, % wt

C	Mn	Si	P	S	Cr	Mo	V	Nb	N
0.11	0.44	0.30	0.012	0.002	8.26	0.99	0.22	0.07	0.05

TABLE 2

Chemical composition of the additional material – No. 1, % wt

Mn	Si	Cr	Mo
0.70	0.69	3.83	1.33

TABLE 3

Chemical composition of the additional material – No. 2, % wt

Mn	Si	Cr	Mo	V
0.67	0.43	8.17	1.08	0.24

on the metallographic specimen etched by the iron chloride. The identification of precipitations was made with the use of carbon extraction replicas, whereas the microstructural tests were conducted using thin foils. The above research was carried out with the transmission electron microscope Jeol 2100plus. A microhardness and hardness test of the joint was done by the Vicker's method using a load of the intender of respectively: 0.5 kG (4.903 N) and 10 kG (98.1 N) by the Future – Tech FV – 700 [9,10] hardness tester. Thermodynamic examinations were taken by the ThermoCalc (TCW) programme with the TCFe4 database.

3. Results of examinations and their analysis

Macroscopic examinations of the tested welded joint have not shown a presence of any welding non-compliance. Figure No. 1 shows a macrostructure of the examined joint. Microstructure examinations, which were taken for all the areas of the welded joint did not show a presence of micro cracks, as well as they proved their proper structure. The base material – the T91 steel is characterized by the typical for this type of martensite steel a microstructure of lath martensite with numerous precipitations (Fig. 2, 3).

Both areas with plainly seen elongated subgrain, mostly depicting previous martensite microstructure of a high denseness of dislocation (Fig. 3a), as well as the areas of poligonised ferrite (Fig. 3b) were observed in the microstructure of the T91 steel.

A presence of a poligonised ferrite in the microstructure shows an accelerated recovery and recrystallization processes of these areas of microstructure which are parallel to the direction of an effect of the stress field. Numerous precipitations of a variable morphology were observed both on the grains boundaries of former austenite, on the boundaries of lath martensite, as well as inside the grains/laths. In some areas an amount of precipitated carbides on the grains boundaries was so high that they made so called 'continuous web' of precipitations (Fig. 2b). Identifications, which have been carried out, showed a presence of carbides of $M_{23}C_6$ type and precipitations of MX – VX, NbC type in the base material. An average diameter of carbides of $M_{23}C_6$ type was 161 ± 29 nm, while precipitations of MX type was 13 ± 6 nm. Carbides of $M_{23}C_6$ type were revealed mostly on the grains boundaries of former austenite, on the boundaries of lath martensite and on the grains boundaries of poligonised ferrite. While precipitations of MX type were observed inside laths/grains. Carbides of $M_{23}C_6$ type precipitated on the boundaries of the grains by stabilizing

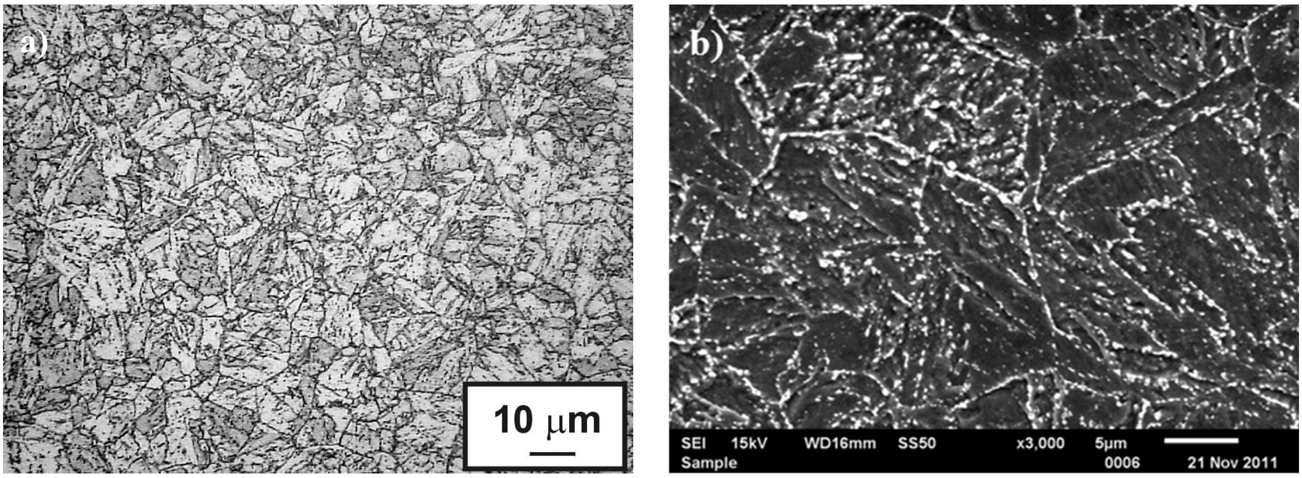

Fig. 2. Microstructure of the base material – the T91 steel: a) OM; b) SEM

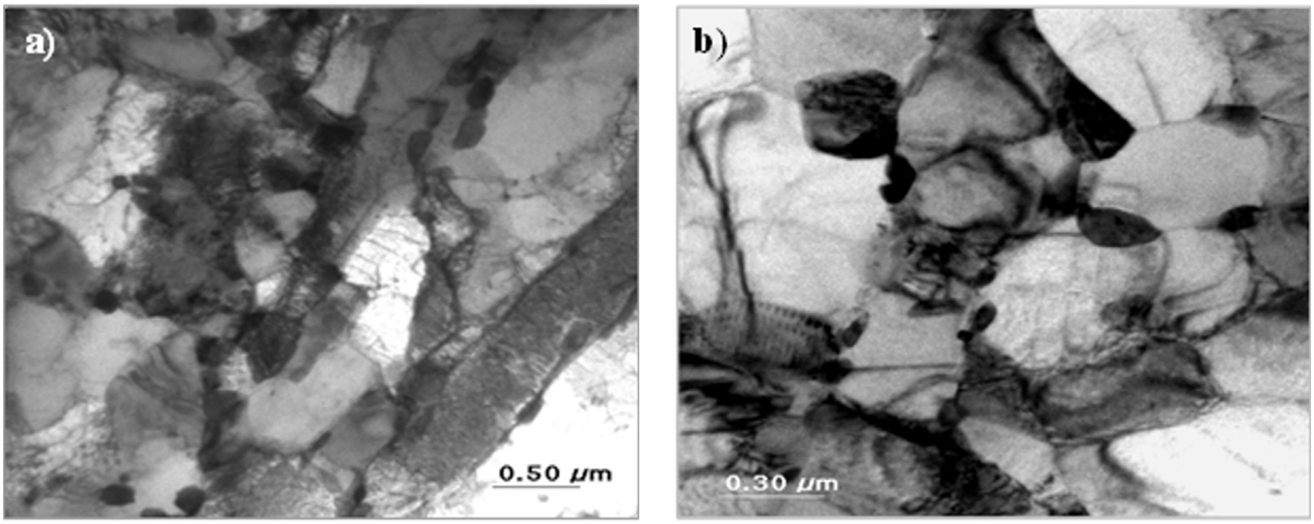

Fig. 3. Microstructure of the base material – the T91 steel, TEM

a subgrain microstructure of martensite they inhibit a dislocation movement of boundaries. Fine dispersion precipitations of MX type are mostly responsible for a high resistance to creeping of the T91 steel because they anchor and impede a dislocation movement. A detailed description of changes in the microstructure of the T91 steel after exploitation in a temperature of 535°C is presented in the article [11]. A size of the grain described according to the range of patterns [12] for the base material was 8, which corresponds to an average diameter equals to 22 μm.

Microstructure of the weld was differential (Table 2 and 3) on the cross-section due to used additional material. Microstructure consisted of bainite or a mixture of a bainite-martensite (Fig. 4) from the root side of the weld was observed. Similar to the base material are numerous precipitations of different sizes, which are a result of a remitting influence of the second bead or/and a thermal treatment after welding.

A different chemical composition of a additional material determined also a different phase composition of precipitations in the mentioned area. Equilibrium phases for the above composition (Table 2) are ferrite + $M_{23}C_6$ + M_6C according to examinations taken by means of the TCW in the exploiting temperature of an examined joint. A lack in the chemical composition a additional material No. 1 element (elements) making stable, fine dispersion precipitations of MC (MX) type e.g. vanadium has a negative influence on the resistance to creeping of a given area. Resistance to creeping of the 10CrMo9 – 10 (10H2M) steel, which contains the following alloy elements: molybdenum and chromium, is 135 MPa in a temperature of 500°C (for 100 000 hours), while in the temperature of 550 and 600°C is respectively 68 and 34MPa [13]. On the other hand, resistance to creeping of the P/T91 steel is as following: 258, 166 and 94 MPa, therefore it is higher than resistance of the CrMo steel from 48 to over 70%. It can be presumed that during exploitation in the creeping conditions an area of a chemical composition close to the CrMo steel is subject to a faster degradation. As a consequence it may lead to shorten a time of a safe exploitation of this element.

Lower content of chromium in the additional material No. 1 (Table 2) in comparison to the base and additional material No. 2 (Table 1 and 3) resulted in making a weld line in the T91 steel (Fig. 5), and on the boundary of the fusion line layer 1/layer 2 (Fig. 6) on the side of a higher alloyed material of carbides zone, while in the case of material No. 1 decarburized layer. Such mi-

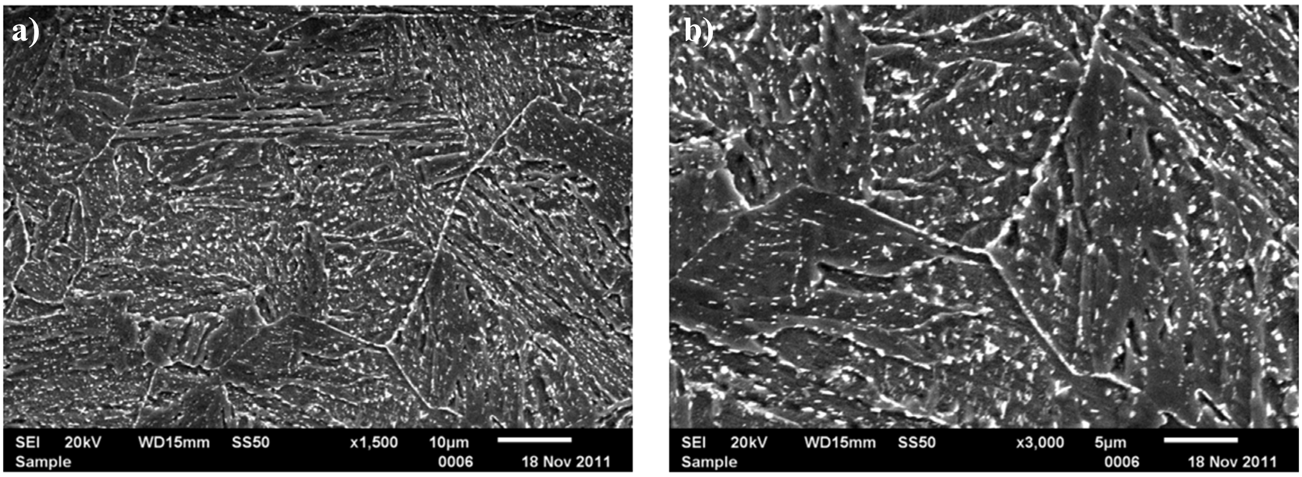

Fig. 4. Microstructure of the weld from the root of the weld, SEM

crostructure is made as a result of an up-hill diffusion of carbon during annealing of the joint or during exploitation. Diffusion of carbon takes place from the place of a higher carbon potential to the material of a lower potential. Carbide-forming elements such as chromium, molybdenum, vanadium or niobium dissolved in the metal matrix have a considerable influence on a reduction of a chemical activity, as well as they cause a carbon diffusion into the material characterised by the higher content of these elements [14]. A presence of an above microstructure is very unfavourable, which has an influence on a decrease of quality and durability (resistance to creeping) of such a joint. A detailed description of a mechanism of formation, and a review of methods preventing a formation of this unfavourable microstructure in the welded joint are provided in the article [14,15].

Microhardness tests HV0.5 done in the transition zone showed a noticeable increase of microhardness in a given area, and a decrease in the weld (Fig. 7).

A comparable process of changes in microhardness was observed on the fusion boundary of layer1/layer2. Similar results of examinations of an inhomogeneous microstructure in the weld line during welding the P91 steel with other types of low-alloyed steel are presented in the article [15].

Microstructure of the weld from the face side of the weld was characterised by the microstructure close to the base material i.e. martensite with numerous precipitations, mostly precipitated on the boundaries (Fig. 8). There were also places in this area where carbides made a continuous web of precipitations on the boundaries of the grains. Moreover, privileged precipitations of carbides were revealed at the point of three boundaries, which is very unfavourable, because it allows to form creep voids by the intercrystalline mechanism of slotted cracks in these areas.

Identifications of carbides, which have been carried out, showed only a presence of carbides of $M_{23}C_6$ type. Similar results of a phase analysis in the welded joint of steel of 9-12% Cr type were obtained [16,17]. Nevertheless, a chemical component of a additional material No. 2 allows to assume that except of chromium rich carbides of $M_{23}C_6$ type in the microstructure of the weld should also be present vanadium rich carbides of MC type. An analysis by means of TCW programme, which has been carried out, showed that for the joint of a certain content of balanced phases in the working temperatures are ferrite + $M_{23}C_6$ +MC + the Laves phase. A specified size of the grain was respectively for an area 1-4 (88.4 μm), and for an area 2-3 (125 μm).

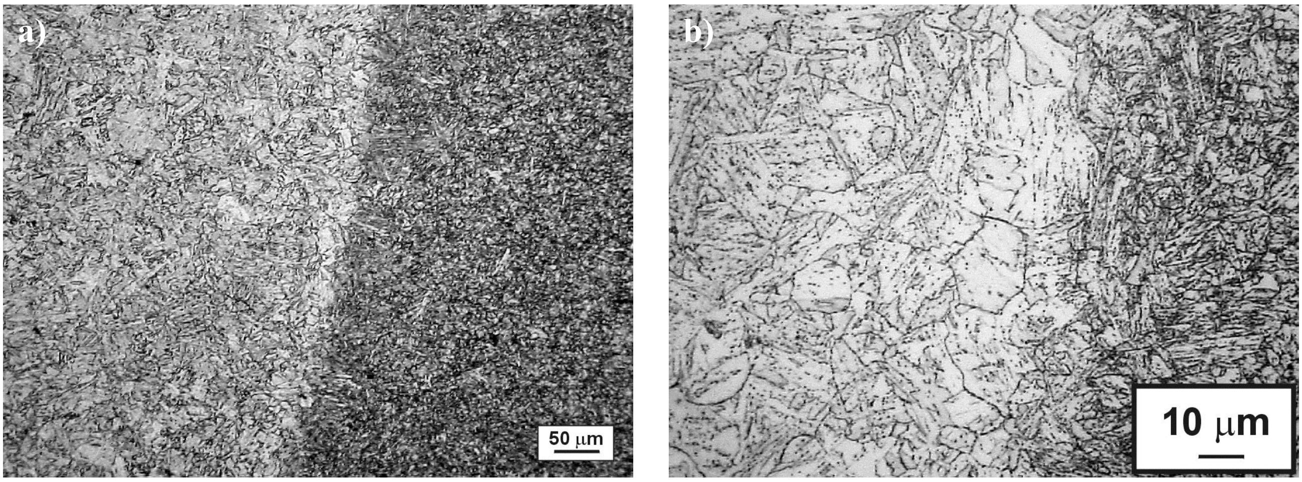

Fig. 5. Microstructure of the joint near the weld line, OM

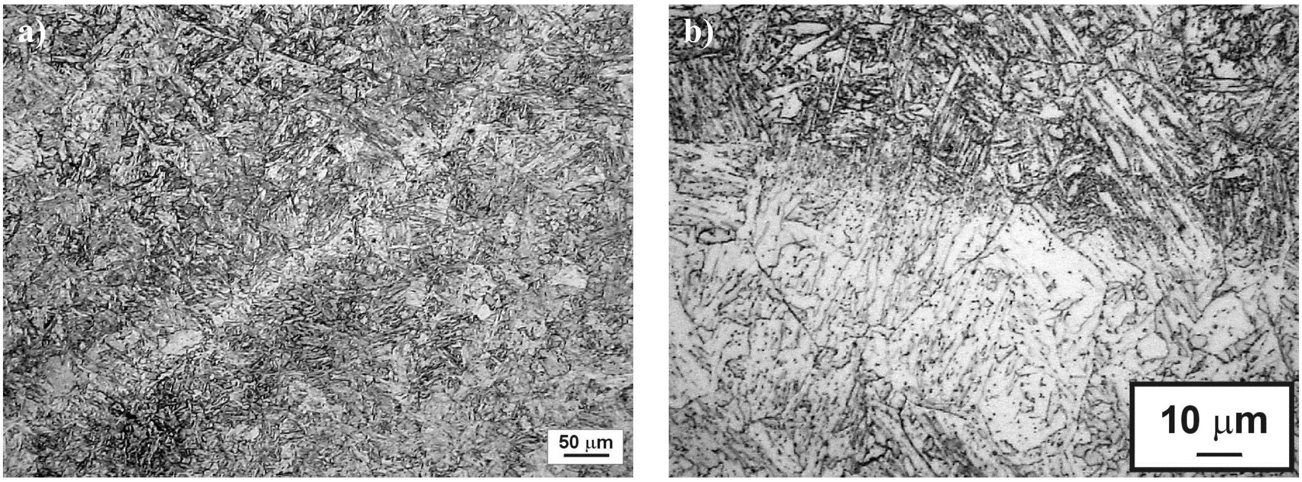

Fig. 6. Microstructure of the joint at the point of two layers of the additional metal, OM

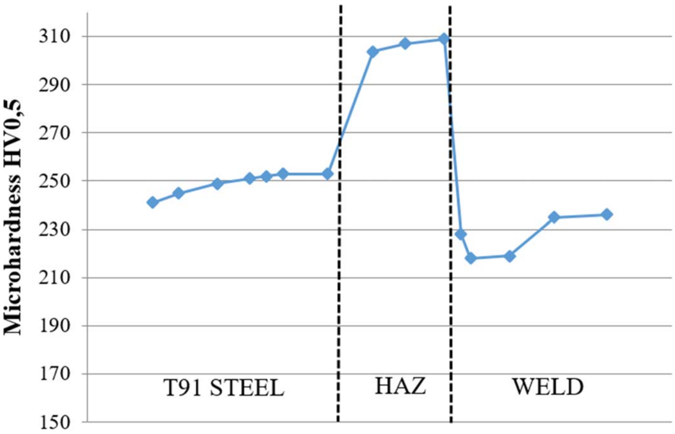

Fig. 7. Distribution of microhardness HV0.5 in a transition zone from HAZ of the T91 steel into the weld

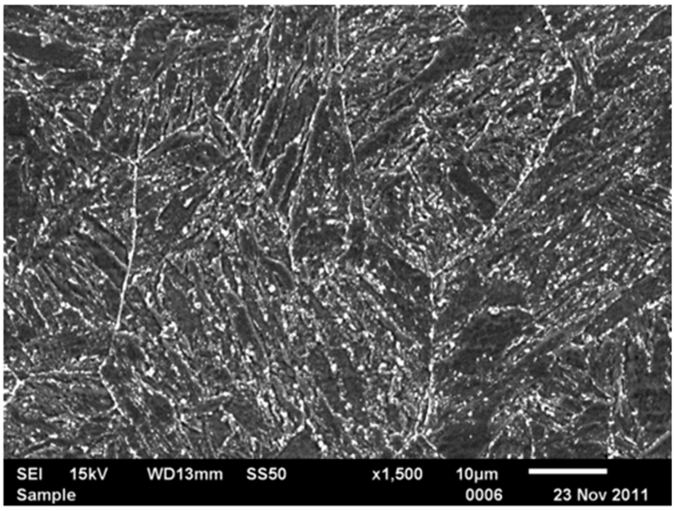

Fig. 8. Microstructure of the weld from the face side of the weld, SEM

A martensite microstructure with numerous precipitations of carbides was observed on the whole area of the cross-section in the heat-affected zone (HAZ) (Fig. 9). In the mentioned area singular, big precipitations on the boundaries of grains were seen. Coagulation of carbides of $M_{23}C_6$ type precipitated on the boundaries of grains results from a thermally activated in the process of welding, as well as a thermal treatment after welding a diffusion of substitutional elements into these precipitations. An increase of the size of $M_{23}C_6$ carbides results in an impoverishment of the matrix in chromium and molybdenum, and also causes an increase of the role of these precipitations as a factor inhibiting recovery processes and recrystallization of matrix. According to [17,18] a similar process of coagulation of carbides of $M_{23}C_6$ type was also observed in case of precipitations of MX type. Above changes cause an accelerated damage of a mentioned area during a process of exploitation in the creeping conditions. This type of damage is called cracks of Type IV [18-20]. A size of the grain in this area was variable and according to the range patterns was from 7 to 10, which corresponds to an average diameter respectively 31.2 and 11 mm.

A distribution of hardness HV10 on an analysed welded joint is presented in Fig. 10. A distribution of hardness (Fig. 10) was made for a half of the joint because authors did not have the whole joint.

Tests of joint's hardness proved previously obtained results during examinations of a microstructure, which showed a variable microstructure on the cross-section of the weld. Hardness of the weld from the root side of the weld was 206 HV10, and was lower of about 60 units from the hardness of the weld from the face side of the weld. Differences of hardness in an analysed joint result from an obtained microstructure in the following areas: bainite (bainite-martensite) in an area No. 1, and martensite in an area No. 2, which is strictly connected with a use of applied additional materials. Hardness of the base material the T91 steel was 206 HV10. According to the literature [2,5,6,12] hardness of the base material and the weld in an initial state (after a thermal treatment) for the P/T91 steel is respectively 200-217 HV, and 240-270 HV. High hardness of the base material and the joint after exploitation suggests a high stability of a microstructure of an examined steel, as well as it proves an information included in the literature [2,7,12,19], which points a lower decrease of resistance properties in comparison to plastic properties during a process of exploitation.

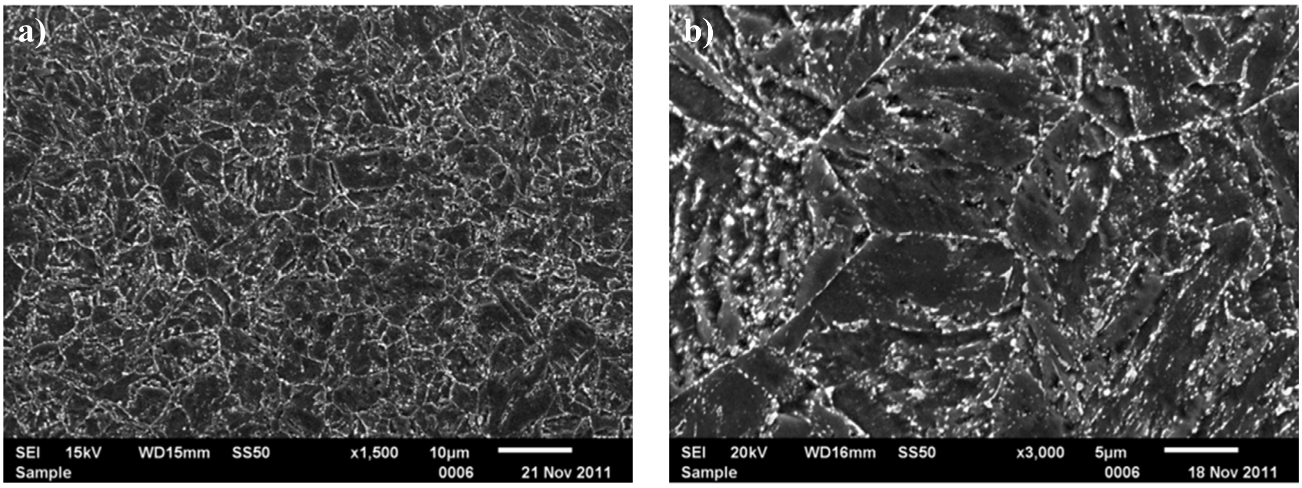

Fig. 9. HAZ microstructure of the T91 steel, SEM

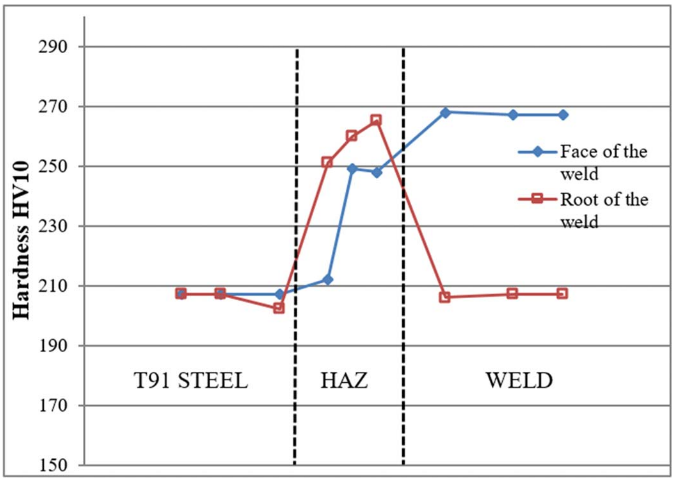

Fig. 10. Distribution of hardness HV10 in an examined joint

4. Conclusion

1. Examined welded joint is characterised by a variable microstructure in the cross-section: bainite (bainite – martensite) from the root side of the weld and a martensite microstructure in the weld from the face side of the weld. Obtained microstructures in the joint mostly result from a chemical composition of additional materials.
2. A use of the additional material of a chemical composition close to CrMo steel seems to be a rather unfortunate solution. A lack of carbide-forming elements ensuring precipitations of elements of MX type, which inhibit a dislocation movement, can lead into a faster degradation, and as a consequence a destruction of this area of the joint.
3. A variable chemical composition of additional materials is a major cause of a formation of decarburized zone from the side of a lower alloyed material, and a rich carbides area in the higher alloyed material, both in the weld line, and at the point of two beads.
4. The main mechanism of a degradation of the microstructure of both the base material – the T 91 steel, and the welded joint was a privileged precipitation of carbides of $M_{23}C_6$ type on the boundaries of the grains and an increase of their size.

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