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Analysis of the microstructure and properties of T92 steel after long-term service

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ABSTRACT

Purpose: The purpose of the investigation was to determine and analyse the changes in the microstructure and mechanical properties of the T92 steel after service in creep conditions of the following parameters: temperature – 575°C, pressure – 28.2 MPa, service time – 41914 hrs.

Design/methodology/approach: The tests were performed on the test samples taken from a pipe section of a steam superheater after long-term service. The range of the investigations included: microstructural investigation – the optical and SEM microscopy, the analysis of precipitation – carbide isolates, the investigation of mechanical properties: the Vickers hardness measurement, the impact test and static tensile test.

Findings: The performed tests showed a slight degree of exhaustion of the structure of the analysed T92 steel. The relatively small changes in the microstructure of the examined steel were reflected in the still retained high mechanical properties.

Research limitations/implications: he analysis of the microstructure of the examined steel using SEM was performed to determine the influence of the service on the processes of changes in the precipitate morphology.

Practical implications: The metal science investigation of the sections taken from the elements of the power installations after long-term service is one of the basic elements of building the data base of materials and their joints used in the power industry. The results obtained from the performed research constitute a building block for the degradation characteristics of the microstructure and mechanical properties of martensitic steels of the 9-12%Cr type.

Originality/value: The results of investigation and analysis of the metallographic and mechanical properties of martensitic T92 steel after long-term service are presented.

Keywords: Power industry, T92 steel, Microstructure, Mechanical properties, Precipitate

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PROPERTIES

1. Introduction

Raising the parameters of work of the power units to limit their adverse impact on the environment and achieving the growth of efficiency is possible as a result of describing and implementing modern creep-resisting materials into the power industry. One of such modern construction materials used in the Polish power industry is high-chromium martensitic X10CrWMoVNbN-2 (T/P92) steel. The T/P92 steel was developed in Japan in the late 1990's as a result of the modification and optimisation of the chemical composition of X10CrMoVNb9-1(T/P91) steel. The modification mostly consisted in partial replacement of molybdenum with tungsten and in introducing the microaddition of boron, and resulted in higher creep resistance compared to T/P91 steel by around 10-20% at the temperature of 600°C [1,2].

The T/P92 steel, like any other material introduced into the power industry, was subject to intense experimental tests, whose purpose was to verify the usefulness of this material for long-term serviceability in the power installations. The results of many years of experimental tests on this steel have been presented in many publications, inter alia in [1-6]. However, as experience shows [7], the results of laboratory tests not always reflect the time of real service of the given material in the power unit installations. Therefore, many scientific research centres run experiments to determine the influence of service time on the changes in the microstructure and mechanical properties of the sections taken from a power unit installation. It allows determining the influence of the service parameters on the degree of degradation of the steel [6,8,9]. The results of the tests of T92 steel after around 42 000 hours of work in the conditions of creep, which are presented in the paper, are one of the stages of building a database necessary for the assessment of wear of the installation elements made of this steel grade.

2. Material and methodology of research

The material for testing was samples taken from a pipe section of the following dimensions: 50 x 10.7 mm, taken from the X10CrWMoVNbN9-2 (T92) steel. The chemical composition of the examined material, determined by means of a spark spectrometer SpectroLab K2, is presented in Table 1. The investigated material was serviced in the conditions of creep for 41 914 hours at the temperature of 575°C and pressure of 28.2 MPa.

Table 1.
Chemical composition of the examined steel, % wt.

C	Si	Mn	P	S	Cr	Mo	W	Nb	V	N
0.13	0.29	0.50	0.011	0.001	9.11	0.36	1.82	0.04	0.17	0.11

The scope of the performed tests included the tests of the microstructure and mechanical properties, as well as the analysis of carbide isolates. The structural tests were carried out on metallographic specimens etched with iron chloride, using the optical microscopy (OM) – Axiovert 25 microscope and the scanning electron microscope (SEM) – JEOL JSM-6610LV. The tests of mechanical properties included:

- the static test of tension performed on round samples of their initial gauge diameter amounting to d_o = 5 mm, using the Zwick Roel Z100 testing machine,
- the test of impact energy carried out on non-standard samples of the Charpy V type, with their width reduced to 7.5 mm,
- the hardness measurement by the Vickers method using the indenter load of 30 kG (294 N), by means of the FutureTech FV700 hardness tester.

The tests of mechanical properties were performed according to the guidelines included in the respective standards. Due to the lack of the data concerning mechanical properties of the examined steel in the as-received state, the obtained results were compared with the required minimum properties of T/P92 steel included in the standard [10]. The phase composition of the precipitates in the investigated steel was determined by the method of carbide isolates by means of an X-ray diffractometer, using filtered radiation of cobalt in configuration with the Pixcel detector.

3. Research results and their analysis

The T/P92 steel belongs to the group of high-chromium martensitic steels containing around 9% of chromium. This steel in the as-received state is hardened and tempered, that is after air hardening (often called normalising) from the austenitising temperature 1040-1080°C, with the subsequent high-temperature tempering in the temperature range of 730-780°C. In the as-received state, the T/P92 steel has the structure of high-tempered martensite of very high density of inner dislocations of subgrains (at the level of 10^{14} m^{-2}) with numerous precipitates of the $M_{23}C_6$ and MX (VX, NbC) type [1,6,11,12]. The particles of the $M_{23}C_6$ and VX type are secondary phases precipitating during the tempering of martensitic steels. The $M_{23}C_6$ carbides are located mostly on the boundaries of prior austenite grains and on the boundaries of subgrains/martensite laths. Only some scarce carbides of this type are observed inside the ferrite subgrains. The $M_{23}C_6$ carbides precipitated on the subboundaries stabilise the subgrain substructure by inhibiting the movement of dislocation boundaries. Additionally, the elongated shape of $M_{23}C_6$ carbides precipitated during the tempering has a favourable influence on the boundary anchoring by these carbides, because the surface of their contact with the boundary, in the same volume fraction, is bigger than for the particles of the spherical shape [1,2,6]. Inside the subgrains, often on the dislocations and subgrain boundaries, the fine-dispersive precipitates of the MX type nucleate. Three types of the MX precipitates can be observed in T/P92 steel [1,6]:

- spherical NbX,
- lamellar VX,
- complexes of precipitates referred to as V-wings.

The NbX particles are primary phases precipitating during the coagulation and their role is limited to inhibiting the grain growth during the austenitising or thermoplastic treatment. The VX precipitates are secondary phases that occur in the structure of the examined steel during tempering, and due to their nano-metric size they are mostly responsible for high creep resistance. The precipitate complexes of the v-wings type observed in T/P92 steel consist of the spherical NbX precipitate and the lamellar VX precipitate nucleating on it. In T/P92 steel also the occurrence of the insignificant amount (around 5%) of delta ferrite is possible, especially after the austenitising at the temperature above 1100°C [6,12,13].

High strength properties and creep resistance of the investigated steel or basically of the creep-resisting martensitic steels with the chromium content of 9-12% result from the optimisation of their chemical composition and the heat (thermo-plastic) treatment parameters, which ensures the occurrence of potentially four micro-mechanisms of strengthening, that is [14]:

- solution strengthening – with the atoms of alloy elements dissolved in the matrix, in the case of the examined steel the atoms of substitution elements: Cr, Mo, W,
- dislocation strengthening – with high dislocation density,
- precipitation strengthening – by means of numerous fine-dispersive precipitates present in the micro-structure: nitrides and carbonitrides of the MX type,
- strengthening with the grain boundaries – the boundaries of prior austenite grain, the boundaries of martensite laths, the boundaries of subgrains.

The microstructure of T/P92 steel in the hardened and tempered condition, in spite of high temperature of tempering, is far from the state of thermodynamic equilibrium. Hence during the service of T/P92 steel the processes of their microstructure degradation are running and these processes influence the decrease in mechanical properties. The rate of the degradation process as the diffusion phenomenon strictly depends on the actual temperature of work. The higher temperature of the actual service, the more noticeable the changes that run in the microstructure. The microstructure degradation rate of the steel working in the creep conditions is also influenced by the level of stress. The stresses intensify all of the processes activated thermally both in the dislocation substructure of the matrix and during the coagulation of secondary phases.

The examined steel after service had the microstructure with still retained lath structure of tempered martensite (Fig. 1). In the microstructure numerous precipitates were observed, forming the so-called continuous grid of precipitates on the boundaries of prior austenite grains (Fig. 2). Many particles were also visible on the boundaries of martensite laths and inside the grains/laths. The analysis of carbide isolates showed the presence of $M_{23}C_6$ carbides and the precipitates of the MX type in the examined steel after service (Fig. 3). The $M_{23}C_6$ carbides precipitate in the steels with 9-12% chromium mostly on the boundaries of prior austenite grains and on the boundaries of laths/subgrains of martensite. They are characterised by fairly low thermodynamic stability, which results in their high susceptibility to coagulation [15,16]. The boundaries of grains/subgrains as the surface defects constitute an easy way for the diffusion, with the result that they quicken the process of coagulation of the particles. The process of coagulation of the particles precipitated on the boundaries of subgrains can lead to the reduction of the force inhibiting the dislocation movement, in accordance with the Zener mechanism, at the constant volume fraction.

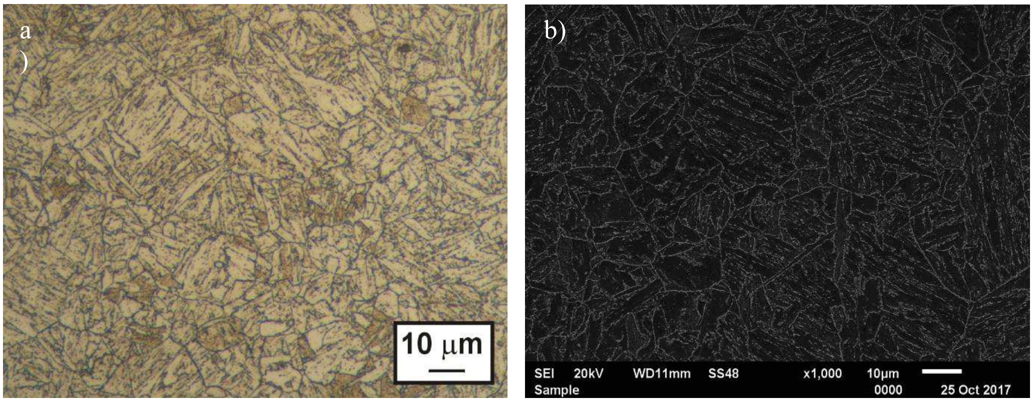

Fig. 1. Microstructure of the examined steel after service: a) OM; B) SEM

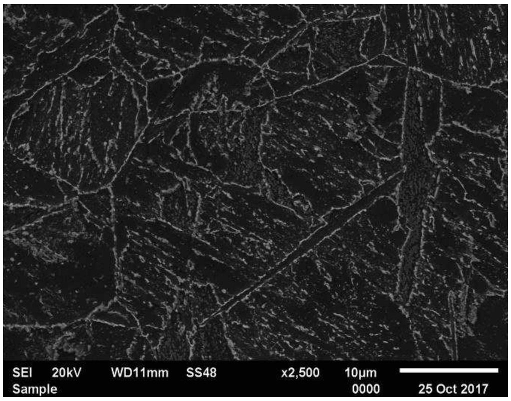

Fig. 2. Precipitates on the boundaries of grains/laths in T92 steel after service, SEM

It results in a decrease in the role of $M_{23}C_6$ carbides as the inhibiting factor for the dislocation migration of the boundaries. The factor which delays and moderates the process of coagulation of the $M_{23}C_6$ carbides during the service is the chemical composition of the steel. In the steels with boron addition the precipitation of $M_{23}(C, B)_6$ carbides occurs, which in comparison with the „classic" $M_{23}C_6$ carbides are far more fine-dispersive and stable. The growth of thermodynamic stability of $M_{23}C_6$ carbides in the steels with the boron addition, and the related stabilisation of the lath structure of tempered martensite, contributes to the growth of the strength properties, including creep resistance of the steel enriched in this addition [3,5,12,15].

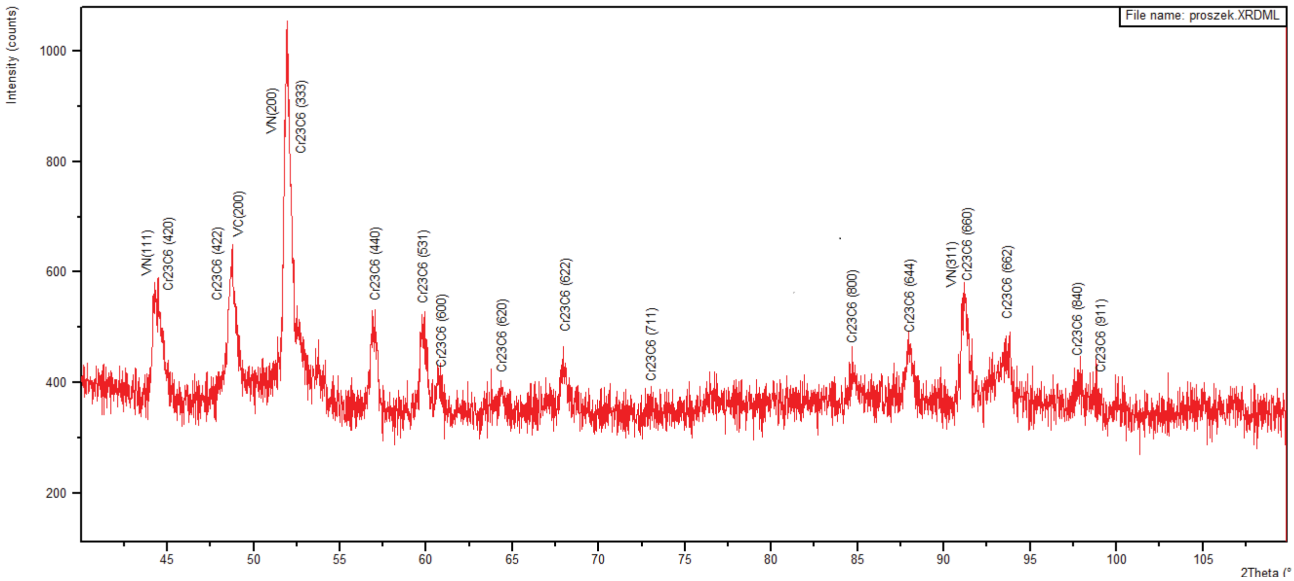

Fig. 3. Diffractogram of carbide isolates of T92 steel

The tungsten addition in high-chromium martensitic steels also influences the moderation of the growth of $M_{23}C_6$ carbides size. In the researchers' view [6,16], the atoms of tungsten in T/P92 steel stabilize the coherence of $M_{23}C_6$ carbides with the matrix and delay their coagulation, hence the lower increase in the size of these carbides in the steel containing tungsten. Long-term service causes the enrichment of the $M_{23}C_6$ carbides in chromium, which has an influence on the matrix depletion of this element [6,9,24]. During the service of high-chromium martensitic steels, one of the basic mechanisms of degradation of their microstructure is the precipitation of the intermetallic Laves phase on the grain boundaries [5,16-19]. In the examined steel after service, no precipitates of such type were revealed, in spite of the fact that the literature data [5,6,17,19] indicate the possibility of the Laves phase occurrence in the structure of T/P92 steel.

The changes running in the microstructure of T92 steel during the service affect its functional properties. The mechanical properties of the examined steel after long-term service are presented in Table 2.

Table 2.
Mechanical properties of the investigated steel

	YS	TS	El.	KCV300/7.5	HV30
After service	512	709	23	67	227
Requirements according to [10]	min. 440	min. 620	min. 17	min. 35*	-

* – impact energy determined on the standard Charpy V samples.

The tests of the basic mechanical properties of T92 steel after service showed that the properties of the examined steel were still above the required minimum. The values of both the strength properties: offset yield strength YS and tensile strength TS, as well as the plastic properties – percentage elongation El. were higher than the standard required minimum [10]. Long-term service of the investigated steel probably leads to a slow and moderate decrease in the strength properties and hardness. Such a type of degradation of the strength properties was also observed inter alia in low-alloy CrMo and CrMoV steels [20,21], as well as in high-chromium martensitic steels [8,22,23]. According to [24], at the initial stage of service/ageing (the holding time up to 9800 hours) of martensitic steels with 9-12% chromium, the reduction of strength properties is connected with the process of the dislocation density drop. At longer times (up to around 38000 hours) these changes are related to the growth of subgrain size. In the Author's opinion, the decrease in the strength properties and hardness can also be influenced by the matrix depletion of substitution elements (Cr, Mo, W), as a result of the precipitation and growth of the $M_{23}C_6$ carbides size. In martensitic steels, a rapid decrease in the impact energy during the service/ageing is observed in comparison with other mechanical properties. The fall of the impact energy in this group of materials is mostly ascribed to the precipitation processes on the boundaries of prior austenite grains and on the boundaries of laths/subgrains of $M_{23}C_6$ carbides and Laves phase [5,6,8]. The reduction of ductility is probably also influenced by the process of the matrix polygonisation and the related disappearance of lath structure. Nevertheless, it should be expected that the ductility of the examined steel after service meets at least the required minimum KV $\geq$ 27 J. Detailed description of the influence of long-term ageing on the changes in the microstructure and mechanical properties of T/P92 steel is presented in other works [8,22].

4. Summary

The tests were performed on the T92 steel after long-term service at the temperature of 575°C. In the analysed steel after around 42 000 hours of service, the lath microstructure of tempered martensite was still observed, which proves its relatively high stability. The visible result of long-term service was numerous precipitates observed mainly on the boundaries of prior austenite grain and on the boundaries of martensite laths. In the examined steel after service the $M_{23}C_6$ carbides and the MX type precipitates were revealed. The changes in the microstructure of T92 steel were relatively small, which probably resulted in a slight decrease in the basic mechanical properties. The properties of T92 steel after long-term service were higher than the required standard mechanical properties for this grade of steel.

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