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MECHANICAL PROPERTIES OF P91 AND PB2 STEEL AFTER LONG-TERM AGEING AT 620°C

WŁAŚCIWOŚCI MECHANICZNE STALI P91 I PB2 PO DŁUGOTRWAŁYM STARZENIU W TEMPERATURZE 620°C

The article presents the results of research on mechanical properties of martensitic steels, X10CrMoVNb9-1 (P91) and X13CrMoCoVNbNB9-2-1 (PB2), as-received and after 50,000 hours of ageing at 620°C. The scope of the tests of mechanical properties included a Vickers hardness test, Charpy impact test, and static tensile test. As received, the investigated steels were characterised by relatively high mechanical properties. The long-term effect of temperature and time contributed to a relatively slight decrease in the strength properties and hardness of the tested steels. However, a considerable decrease in the ductility of these alloys was observed. The decrease in mechanical properties after long-term ageing was smaller in the case of the PB2 steel, which was attributed to the beneficial effect of microalloying boron.

Keywords: *mechanical properties, P91 steel, PB2 steel, boron, ageing*

W artykule przedstawiono wyniki badań właściwości mechanicznych stali martenzytycznych X10CrMoVNb9-1 (P91) i X13CrMoCoVNbNB9-2-1 (PB2) w stanie dostawy oraz po 50 000 godzinach starzenia w temperaturze 620°C. Zakres badań właściwości mechanicznych obejmował pomiar twardości metodą Vickersa, próbę udarności oraz statyczną próbę rozciągania. W stanie dostawy badane stale charakteryzowały się względnie wysokimi właściwościami mechanicznymi. Długotrwałe oddziaływanie temperatury i czasu przyczyniło się do względnie niewielkiego spadku właściwości wytrzymałościowych i twardości badanych stali. Obserwowano natomiast znaczące obniżenie ciągliwości tych stopów. Spadek właściwości mechanicznych po długotrwałym starzeniu był mniejszy w przypadku stali PB2, co przypisano korzystnemu działaniu mikrododatku boru.

Słowa kluczowe: *właściwości mechaniczne, stal P91, PB2 stal, bor, starzenie*

1. INTRODUCTION

High-chromium 9% Cr martensitic steels are currently one of the basic construction materials used in the construction and modernisation of power units. The experience gained so far with the use of these materials indicates that the main mechanism of the degradation of their microstructure are the coagulation processes of $M_{23}C_6$ carbides and the precipitation and development of the Laves phase [1–3]. The $M_{23}C_6$ carbides play an important role in martensitic steels, stabilising the subgrain martensitic microstructure. However, these precipitates are characterised by low thermodynamic stability, which leads to limitation of their beneficial effects during operation. The precipitation and rapid development of the Laves phase particles leads to a decrease in resistance to cracking and an increase in brittleness [2–5]. One of the methods of preventing the negative effects of $M_{23}C_6$ carbides and the Laves phase is to modify the chemical composition of previously used steels by introducing microalloying boron. The introduction of this element leads to the separation of $M_{23}(C,B)_6$ carbides, which, compared to $M_{23}C_6$ carbides, are characterised by greater dispersion and higher stability. In addition, this element has a positive effect on Laves phase precipitates, limiting its tendency to coagulate [3, 5–7]. The increase in the stability of these precipitates slows down the processes of degradation of the microstructure of martensitic steels. This results not only in a slower decrease of basic mechanical properties, but also positively affects creep resistance of these materials [1, 6, 8, 9].

The paper presents the results of the investigation of the influence of long-term ageing for up to 50,000 hours and temperature of 620°C on the mechanical properties of the P91 and PB2 steels.

2. MATERIAL AND METHODOLOGY

The testing material consisted of samples from tube sections from the following steels: X10CrMoVNb9-1 (P91) and X13CrMoCoVNbNB9-2-1 (PB2) with the following dimensions: 160 × 16.8 mm and 219 × 32 mm. The chemical composition of the tested steels, determined using a SpectroLab spectrometer, is presented in Table 1. The tested steels

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Table 1. Chemical composition of tested steels, [wt%]

Tabela 1. Skład chemiczny badanych stali, [% mas.]

Steel	C	Si	Mn	Cr	Mo	V	Nb	N	Co	P	S	B
P91	0.11	0.42	0.51	9.12	0.93	0.22	0.077	0.05	–	0.018	0.0040	–
PB2	0.14	0.11	0.34	9.42	1.55	0.19	0.057	0.04	1.38	0.011	0.0008	0.008

were subjected to ageing at 620°C and annealing for up to 50,000 hours.

The microstructure examination was carried out using a TITAN 80-300 transmission electron microscope (TEM) with an accelerating voltage of 220 kV. The observation of the microstructure was carried out with the use of thin foils, for the as condition and after long-term ageing at 620°C.

The investigation of mechanical properties included: static tensile test, impact test on standard Charpy V samples and hardness measurement using the Vickers method. The static tensile test was carried out on round samples with an initial measuring diameter up to 5 mm using a Zwick/Roell Z100 universal testing machine. The impact strength test was carried out using standard Charpy V-type impact samples, while the hardness measurement was carried out using a Future-Tech FV-700 hardness tester with an indenter load of 30 kg (294.3 N). The tests of mechanical properties included the material in as-received condition and after selected ageing times up to 50,000 hours at 620°C.

3. TEST RESULTS

3.1. MICROSTRUCTURE IN AS-RECEIVED CONDITION AND AFTER AGEING FOR 50,000 HOURS

As-received the steels for testing had a similar microstructure characterised by tempered lath martensite with subgrain structure with a high density of free dislocations inside the grains and numerous precipitates (Fig. 1). The following types of precipitates were revealed in the tested steels in the as-received condition: $M_{23}C_6$ carbides and MC (MX) carbides and carbonitrides [7]. $M_{23}C_6$ carbides were observed on grain boundaries of former austenite and on the boundaries of martensite subgrains/laths. In the case MX-type precipitates, two morphologies are visible: spherical, niobium-rich – NbC carbides, and lamellar, vanadium-rich – VX precipitates (nitrides/carbonitrides). As compared to the P91 steel, the average diameter of both $M_{23}C_6$ particles and MX precipitates was smaller in the PB2 steel [7]. The difference in the size of $M_{23}C_6$ and MX precipitates in these steels in the as-received condition may result from the difference in heat treatment parameters (austenitising and tempering temperature and time), as well as in the case of the PB2 steel, stabilisation of $M_{23}C_6$ carbides with boron. The significant influence of heat treatment parameters on the morphology of the precipitates in martensitic steels was demonstrated in various articles [9, 10].

After long-term ageing, the lamellar arrangement of the martensitic microstructure was still partially preserved, and areas of polygonised ferrite were also visible in the microstructure of the tested steel (Fig. 2).

The ageing of the tested steels contributed mainly to changes in their dislocation microstructure as well as in the morphology and type of precipitates. In the tested steels after long-term ageing, apart from $M_{23}C_6$ and MX particles, two types of secondary precipitates were additionally observed: the Laves phase and the Z phase – complex chromium nitride Cr(V, Nb)N. The Laves phase precipitates were observed mainly at the former austenite grain boundaries, usually near the $M_{23}C_6$ carbides and at grain boundaries. On the other hand, Z phase precipitates were observed only in the P91 steel in border areas. After long-term ageing, finer $M_{23}C_6$ carbides and Laves phase precipitates were observed in the PB2 steel compared to the P91 steel. The

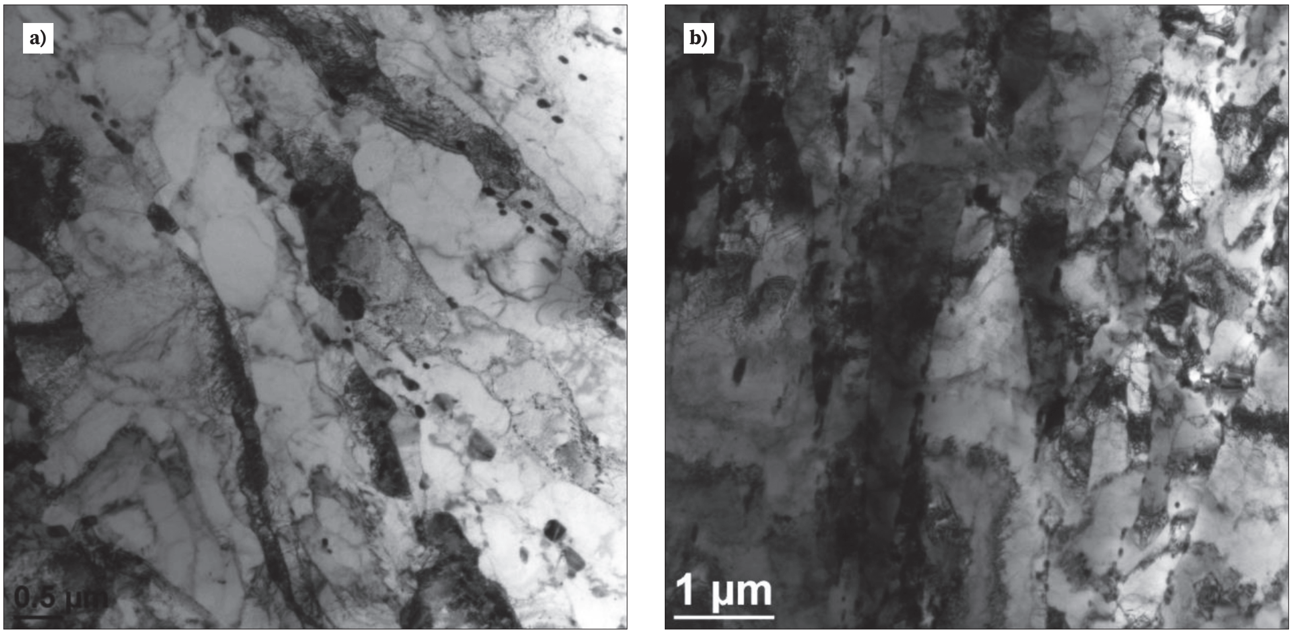

Fig. 1. Microstructure of tested steels in as-received condition: a) P91; b) PB2, TEM

Rys. 1. Mikrostruktura badanych stali w stanie dostawy: a) P91; b) PB2, TEM

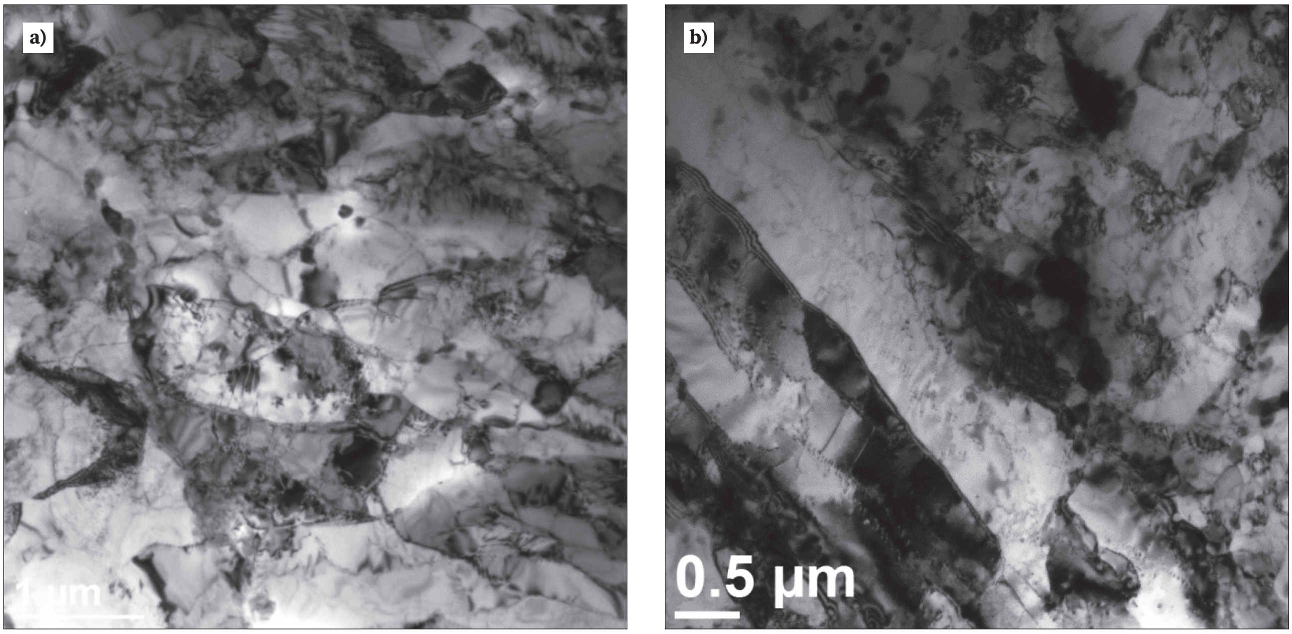

Fig. 2. Microstructure of tested steels after long-term ageing: a) P91; b) PB2, TEM

Rys. 2. Mikrostruktura badanych stali po długotrwałym starzeniu: a) P91; b) PB2, TEM

literature presents a detailed description of the microstructure of the tested steels in the as-received condition and after long-term ageing [7].

3.2. MECHANICAL PROPERTIES IN AS-RECEIVED CONDITION CONDITION AND AFTER LONG-TERM AGEING

As-received, in the quenched and tempered condition, martensitic steels should have optimal mechanical properties, i.e. still high strength properties as well as high impact energy and plastic properties. Obtaining such a combination of properties depends not only on the tempering parameters, but also on the steel austenitisation parameters [5, 10, 11]. In the as-received condition, both P91 steel and PB2 steel were characterised by high strength properties: yield strength in both cases was higher than the required minimum by approx. 30%, while tensile strength by approx. 12% and 17%, respectively for steel P91 and PB2 (Table 2).

Table 2. Mechanical properties of the P91 and PB2 steels in the as-received condition

Tabela 2. Właściwości mechaniczne stali P91 i PB2 w stanie

Steel	YS [MPa]	YS [MPa]	El. [%]	RA [%]	KV [J]	HV30
P91	570	704	22	70	211	223
PB2	584	740	20	70	154	231

The impact energy of the P91 steel in the as-received condition was also more than 7 times higher than the required minimum of 27 J, while in the case of the PB2 steel it was more than 5 times higher. As received, the PB2 steel compared to the P91 steel, was characterised by higher strength properties with similar plastic properties and lower ductility (Table 2). The higher strength properties and hardness in the case of the PB2 steel probably result from the differences in the chemical composition of the tested steels (Table 1) and the presumably applied heat treatment parameters. Higher carbon content in the PB2 steel results in a greater amount of carbides, which leads to an increase in strengthening using the precipitation mechanism. On the other hand, the higher content of substitute elements (Cr, Mo, Co) should increase strengthening with the solution mechanism and the stability of the structure subjected to tempering or ageing [12].

One of the numerous requirements for steels for the power industry is, among others, stability of the (micro) structure, understood as the limitation of changes taking place in the microstructure, which translates into a very slow decrease in functional properties during long-term use. Long-term ageing of the tested steels for up to 50,000 hours had little effect on their strength properties, i.e. yield strength and tensile strength. These properties decreased after long-term ageing by a maximum of 15% compared to the initial state (Fig. 3). The decrease in strength properties after ageing was smaller for the PB2 steel than for the P91 steel.

The decrease in strength properties should be associated with the processes of matrix softening, in particular with the decrease of the dislocation density and the increase in the width of martensite laths [7]. This results in the reduc-

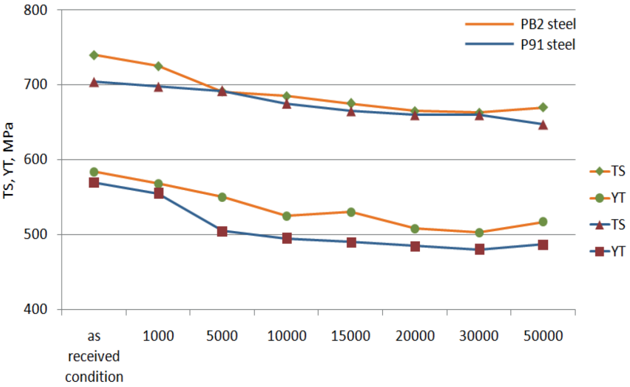

Fig. 3. Change in strength properties for the P91 and PB2 steels after ageing at 620°C

Rys. 3. Zmiana właściwości wytrzymałościowych stali P91 i PB2 po starzeniu w temperaturze 620°C

tion of strengthening with the following mechanisms: dislocation and grain boundaries, respectively. The decrease in strength properties is also influenced by the reduction of strengthening using the solution mechanism, which is related to the precipitation and increase in the size of secondary phase particles. In high-chromium martensitic steels, the main strengthening mechanisms influencing the yield strength of these steels are: strengthening using grain boundaries and solutions [12]. Changes in the strength properties and hardness of martensitic steels in the initial period of ageing (up to approx. 6000 hours at 650°C) that are associated with the processes of decrease in dislocation density described in [13]. In turn, with longer ageing times (up to approx. 38,200 hours), these changes are mainly related to the particle growth processes.

In turn, the hardness of the tested steels after raging (Fig. 4) was comparable to the as-received condition, which indirectly indicates the high stability of the microstructure of these materials and that the observed matrix softening process was probably partially compensated by the precipitation of secondary phases.

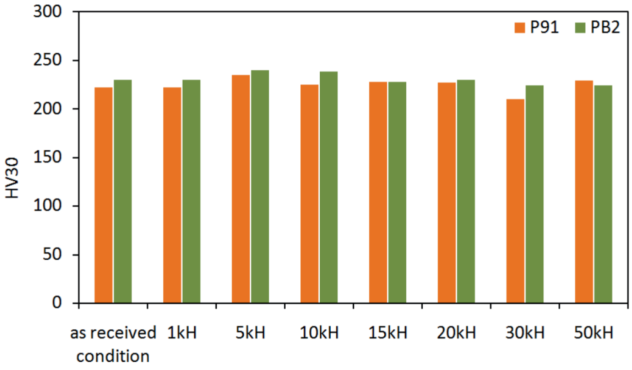

Fig. 4. Influence of ageing time at 620°C on the change in hardness of steels P91 and PB2, where: kH – 1000 hrs

Rys. 4. Wpływ czasu starzenia w temperaturze 620°C na zmianę twardości stali P91 i PB2, gdzie: kH – 1000 hrs

A slight decrease in the strength properties of the tested steels was accompanied by a significant decrease in impact energy KV during ageing. Two stages may be observed on the impact energy KV change curve as a function of ageing (Fig. 5). In the initial period of ageing (up to 5,000 hours) – stage I, a sharp decrease in ductility was observed, from the value of approx. 210 J to approx. 70 J for P91 steel and from the value of approx. 150 J to approx. 50 J for steel PB2. A significant decrease in impact strength in the initial stage of ageing/use of martensitic steels was related to the appearance of Laves phase precipitates and an increase in the number and size of $M_{23}C_6$ carbides in the microstructure [7]. It was shown that a significant decrease in the impact strength in 10Cr-1Mo steel after 1000 hours of ageing is related to the precipitation of numerous and fine particles of the Laves phase at the boundaries of the grains and martensite laths [14]. $M_{23}C_6$ carbides, precipitated at the boundaries of martensite grains/laths, and the Laves phase reduce their boundary cohesion and contribute to low-energy cracking [14–16]. Longer annealing times (> 5000 h – stage II) resulted in a further, but not so intensely progressive, decrease in impact energy KV (Fig. 5). After 50,000 hours of ageing at 620°C, the reduction of impact energy KV for steel P91 was over 80%, and for steel PB2 about 70% in relation to the as-received condition.

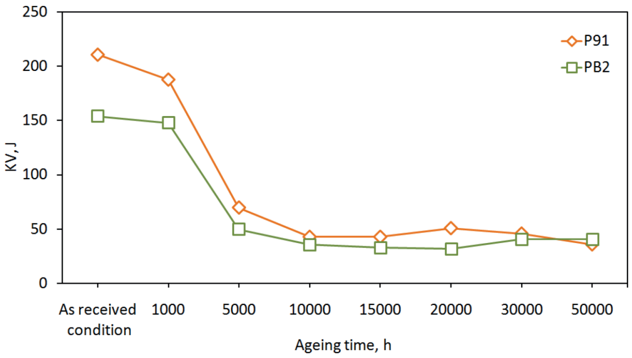

Fig. 5. Influence of ageing time at 620°C on impact energy KV of steels P91 and PB2

Rys. 5. Wpływ czasu starzenia w temperaturze 620°C na energię łamania KV stali P91 i PB2

The decrease in impact energy KV of the tested steels should be associated primarily with the intensification of precipitation processes (separation and growth of the Laves phase, increase in the amount and size of $M_{23}C_6$ carbides), but also with the progressive disappearance of lath/subgrain microstructure.

The higher stability of $M_{23}C_6$ carbides and the Laves phase in the PB2 steel as compared to the P91 steel [7], is understood as their slower increase in size over time, translated into a decrease in the properties of this steel. The beneficial effect of boron on the slowing down of the coagulation process of $M_{23}C_6$ carbides and the Laves phase precipitates was also demonstrated [5, 6, 17]. Nevertheless, the obtained results of tests of mechanical properties showed a similar tendency for the tested steels as in the case of other steel grades used in the power industry, i.e. a significant decrease in the ductility of these steels with a slight reduction in strength properties and hardness.

4. SUMMARY

The aim of the study was to present the effect of long-term isothermal ageing for up to 50,000 hours and temperature of 620°C on the mechanical properties of the P91 (X10CrMoVNb9-1) and PB2 (X13CrMoCoVNbNB9-2-1) steels.

As-received, the investigated steels were characterised by high mechanical properties. The long-term effect of temperature and time through changes in the microstructure contributed to a slow decrease in strength properties and hardness of the tested steels. The slight decrease of these properties was accompanied by a significant decrease in impact energy. At the initial period of ageing, for up to 5,000 hours, a very rapid decrease in it was observed, while longer annealing times resulted in a relatively slowly progressing decrease of this parameter.

A slower decrease in mechanical properties during long-term ageing was observed for steel PB2. This indirectly indicates the beneficial impact of microalloying boron which, by reducing the increase of $M_{23}C_6$ carbides and Laves phase precipitates, contributed to the inhibition of the rate of changes in the microstructure.

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