MICROSTRUCTURE AND MECHANICAL PROPERTIES OF GX12CrMoVNbN9 – 1 CAST STEEL AFTER HEAT TREATMENT

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Abstract

The paper presents results of research on the influence of heat treatment on the microstructure and mechanical properties of high-chromium martensitic GX12CrMoVNbN9-1 (GP91) cast steel. The heat treatment applied to GP91 cast steel included hardening from the austenitizing temperatures of 1010, 1040, 1070, 1100°C and tempering at the temperature of 700, 730, 760 and 780°C. Apart from the investigation on mechanical properties, performed research included microstructural examination by means of OM and TEM as well as the identification of precipitates. GP91 cast steel was examined in the as-cast state as well as after the thermal strengthening. It has been proved that GP91 cast steel in the as-cast state is characterized by a coarse grain microstructure of self-tempered martensite with numerous precipitations of carbides of the following type: M23C6, M3C and NbC. In the as-cast state the examined cast steel met the standard required properties. Thermal strengthening of GP91 cast steel contributed to the obtainment of fine-grained microstructure of high-temperature tempered martensite with numerous M23C6 and MX precipitates of diverse size. Investigation on mechanical properties has revealed that heat treatment of GP91 cast steel most of all contributes to the growth of plastic properties, i.e. impact strength and reduction of area. Strength properties, due to long times of holding at the temperatures above 700°C, stay on the level of a cast steel in the as-cast state. The highest strength properties GP91 cast steel achieves, regardless of the tempering temperature, after hardening from the austenitization temperature of 1040°C.

Keywords: 9%Cr cast steel, heat treatment, microstructure, mechanical properties

1. INTRODUCTION

The necessity of limiting the emission of CO₂, SO₂ and NOₓ into the atmosphere, with regard to global legal regulations, forces lowering fuel consumption and increasing the reliability of power devices. One of the ways to achieve it is increasing the thermal efficiency of power units by raising the parameters of steam – temperature and pressure. Applying high steam parameters in the power units was achieved by introducing new materials into the power industry. Some of the newly introduced materials are the so-called martensitic steels (cast steels). This new group of materials includes GX12CrMoVNbN9 – 1 (GP91) cast steel which was developed on the basis of chemical composition of P91 steel and was meant to replace the low-alloy cast steels: Cr – Mo – V and Cr – Mo used so-far. Through appropriate matching of the chemical composition and applying quenching and tempering as the heat treatment, GP91 cast steel can work at the temperatures higher by 30 – 50°C when compared with the low-alloy cast steels [1, 2].

Stability of the microstructure under creeping conditions is one of the basic criteria laid to creep-resisting alloys. Heat treatment of those alloys should on one hand provide the most favourable morphology of the structure constituents in the aspect of its strengthening and on the other hand it should provide the distribution of alloying elements between the matrix and precipitation of secondary phases. This ensures high stability of microstructure and proper creep resistance. Matching of the austenitizing parameters must guarantee maximum saturation of austenite with alloying elements providing high-temperature creep resistance, however, the excessive growth of austenite grain is unacceptable as it has a negative influence on impact strength and decrease in plastic properties [3, 4]. The aim of performed research was to determine the influence of heat treatment on the microstructure and mechanical properties of GX12CrMoVNbN9 – 1
(GP91) cast steel. Heat treatment applied to the examined GP91 cast steel included austenitizing at the temperatures of 1010, 1040, 1070 and 1100°C as well as high-temperature tempering after quench hardening at the temperatures of 700, 730, 760 and 780°C.

2. METHODOLOGY OF RESEARCH

Microstructural research was performed by means of JOEL JEM – 3010 high-resolution transmission electron microscope using thin foils. The tests were carried out on test pieces in the as-cast state and after heat treatment at the assumed parameters of temperature and time. Mechanical properties were examined according to the currently obeyed standards. The static tension test was made by means of the MTS – 810 testing machine on test pieces with their initial gauge diameter of \( d_0 = 8 \text{mm} \). Measurement of hardness was taken using the Vickers method with the load of 30 kG (294,2N), by means of the Future Tech FV – 700 testing machine. Tests of impact energy were carried out on standard test pieces of the Charpy V type. In the case of static tensile test and impact energy measurement, the presented results are the mean value of three tests, while the hardness value is the mean of five measurements.

Heat treatment of GP91 cast steel covered twelve-hour austenitizing of test pieces at the temperatures of: 1010, 1040, 1070 and 1100°C with subsequent cooling with oil. Twelve-hour tempering of test pieces was carried out at four temperatures: 700, 730, 760 and 780°C. After tempering the test pieces were air-cooled.

3. MATERIAL FOR INVESTIGATION

The material under investigation was a cast steel of the following chemical composition (% mass): 0.12C, 0.49Mn, 0.31Si, 0.014P, 0.004S, 8.22Cr, 0.90Mo, 0.12V, 0.07Nb, 0.04N. The chemical composition of the examined alloy corresponded to that of GX12CrMoVNbN9-1 (GP91) cast steel (see Table 1).

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10 ( \div ) 0.14</td>
<td>max 0.50</td>
<td>0.20 ( \div ) 0.50</td>
<td>max 0.03</td>
<td>max 0.03</td>
<td>8.0 ( \div ) 9.5</td>
<td>0.85 ( \div ) 1.05</td>
<td>0.18 ( \div ) 0.25</td>
<td>0.06 ( \div ) 0.10</td>
<td>0.030 ( \div ) 0.070</td>
</tr>
</tbody>
</table>

4. THE RESEARCH RESULTS AND THEIR DISCUSSION

4.1. The GP91 cast steel – the as-cast state

In the as-cast state the examined cast steel GP91 was characterized by a coarse-needle microstructure of autotempered martensite with numerous precipitations of carbides (Fig. 1). The microstructure of the investigated cast steel in the as-cast condition revealed the presence of both: lath structure of martensite with high density of dislocations as well as polygonal substructure of ferrite. There were three types of precipitates occurring in the microstructure of the given cast steel in the as-cast state: \( M_2 C \), \( M_23 C_6 \) and NbX. The NbX precipitates, which precipitated directly from the liquid, constitute an inhibiting factor for the grain growth. The \( M_2 C \) carbides are a metastable phaze in the examined cast steel precipitating according to [6] already after ca. 0.29s at the temperature of 690°C. Apart from NbX, stable precipitate in the given cast steel is also the \( M_23 C_6 \) carbide. According to the data [7] precipitation of \( M_23 C_6 \) carbide in P92 steel is finished after ca. 100s at the temperature of 770°C, after ca. 400s at the temperature of 730°C and after ca. 2000s at the temperature of 700°C.
The Table 2 presents mechanical properties of GP91 cast steel in the as-cast state including the requirements laid for this cast. Strength properties of the examined cast steel, i.e. tensile strength and yield strength were higher than the required minimum respectively by 7 and 2%.

![Image of GP91 cast steel microstructure](image)

**Fig.1.** Microstructure of GP91 cast steel in the as-cast condition: a) SEM, b) TEM, thin foil

Plastic properties – impact strength and elongation exceeded the required minimum, respectively: over 3 times and by ca. 33%. Hardness of the examined cast steel in the as-cast condition amounted to 232HV30, whereas the reduction of area – 58% (Table 2).

**Table 2.** Mechanical properties of GP91 cast steel in cast – state condition and their mechanical requirement

<table>
<thead>
<tr>
<th></th>
<th>TS, MPa</th>
<th>R_p0.2, MPa</th>
<th>El., %</th>
<th>RA, %</th>
<th>KV, J</th>
<th>HV30</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP91</td>
<td>644</td>
<td>506</td>
<td>20</td>
<td>58</td>
<td>94</td>
<td>232</td>
</tr>
<tr>
<td>Acording to [5]</td>
<td>600 ÷750</td>
<td>min. 450</td>
<td>min. 15</td>
<td>---</td>
<td>min. 30</td>
<td>---</td>
</tr>
</tbody>
</table>

4.2. Microstructure and properties of GX12CrMoVNB91 (GP91) cast steel after heat treatment

Heat treatment of the examined cast steel (quench hardening and high-temperature tempering) contributed to the obtaining of fine-lath microstructure of high-tempered martensite by reducing austenite grain size. The purpose in applying high temperature of austenitizing in the heat treatment was dissolving the majority of carbides in the matrix, which had a good influence on hardenability due to saturation of austenite with alloying elements. However, during austenitizing of the examined cast steel the dissolution of carbides in the matrix is not complete. Part of the precipitates rich in niobium, i.e. precipitations of NbX, remain undissolved, successfully inhibiting the growth of austenite grain, which favourably influences the later properties of the examined cast steel. Oil hardening after the process of austenitizing contributes to the achievement of the microstructure of lath autotempered martensite. High temperature at the beginning of martensite
transformation, amounting to 386°C for the investigated cast steel, is high enough for the carbon diffusion to occur. This results in the precipitation of \( M_2C \) carbides inside martensite laths already during cooling to the room temperature. Moreover, in the GP91 cast steel microstructure after quench hardening there was small quantity of retained austenite observed (Fig. 2). The microstructure of GP91 cast steel after different variants of heat treatment was comparable and characterized by both: lath substructure of high-tempered martensite with high dislocation density as well as polygonal grains of ferrite. The said microstructures alternated with each another. Typically microstructure of GP91 cast steel after heat treatment is shown in Fig. 3.

Fig. 2. Microstructure of GP91 cast steel after hardening, TEM, thin foil

Long times of tempering for the examined cast steel resulted in the processes of recovery and polygonization as well as the intense processes of precipitation mainly on grain boundaries of former austenite grain. The process of matrix recrystallization in the given cast steel was inhibited by anchoring subgrain boundaries by the carbide particles which precipitated on them, as a result of which only the processes of recovery and matrix polygonization occurred. The boundaries of former austenite grains are privileged areas for the precipitation of \( M_{23}C_6 \) carbides.

Fig. 3. Microstructure of GP91 cast steel after heat treatment: 1040°C/12h/oil + 760°C/12h/air, a) SEM; b) TEM – thin foil

High-angle boundaries of former austenite grain are characterized by high energy and they are the areas of privileged precipitation of secondary phases from the supersaturated solid solution, while stable boundaries favour the growth of carbides. On the boundaries of grains and laths the occurrence of \( M_{23}C_6 \) carbides was
revealed, whereas inside the laths and on boundaries of subgrains there were precipitations of the MX type observed. In the investigated cast steel two morphologies of MX precipitates were seen: spheroidal precipitates mostly rich in niobium – NbX and lamellar precipitates mostly rich in vanadium – VX. The mean diameters of precipitates depending on the parameters of heat treatment amounted for the M_23C_6 carbides - from 97 to 159nm and for MX precipitates - from 18 to 25nm. The M_23C_6 carbides precipitated on the boundaries of grains/ subgrains/ laths of martensite play a crucial role, as they stabilize the subgrain microstructure of martensite inhibiting the movement of dislocations. Fine dispersion precipitates of the MX type precipitating on the dislocations inside martensite laths provide high creep resistance by anchoring and inhibiting the dislocation movement. Detailed description of the microstructure of the investigated cast steel in the as-cast state as well as after the heat treatment is presented in work [8, 9].

Fig. 4. Tempering effect on mechanical properties of GX12CrMoVNbN9-1 (GP91) cast steel (depending on austenitizing temperature)

Influence of heat treatment on mechanical properties of GP91 cast steel is presented in Fig. 4. The research performed on mechanical properties of GP91 cast steel have proved that the highest properties: strength ones (R_p0.2, TS, HV30), as well as plastic ones (KV, EI.) were obtained regardless of the temperature of tempering for the test pieces hardened from the austenitizing temperature of 1040°C. It seems like the above temperature of austenitizing allows to obtain high mechanical properties after tempering in the examined
cast steel by providing appropriate alloy level of austenite and favourable dislocation substructure of the matrix. Within the whole range of tempering temperatures 700 ÷ 780°C mechanical properties of the investigated cast steel meet the minimum requirements. Low temperature of tempering – 700°C – allows to obtain very high strength properties on the upper level of their values. Tensile strength reaches the level of at least 700MPa, the yield strength value is higher than 580Mpa, whilst hardness amounts to 240 ÷ 260HV30. High strength properties are accompanied by low impact strength and elongation, on the level of 36 ÷ 70J and 17 ÷ 19%, respectively. Increase in the tempering temperature to 760°C results in the reduction of strength properties - yield strength by 17 ÷ 28%, tensile strength by 9 ÷ 14% and hardness by 16 ÷ 25% (depending on the temperature of austenitizing). Fall of the strength properties occurs along with an increase in plastic properties – impact strength (KV >120J) and elongation strength (A>20%). The value of impact strength (for most of the austenitizing temperatures) reaches its maximum at the temperature of 760°C. Further raising the temperature of tempering up to 780°C contributes to a slight decrease in impact strength by ca. 8% (for the austenitizing temperatures of 1040 and 1100°C). High temperature of tempering is required in order to provide high stability in the microstructure of a cast steel designed for long-lasting service at elevated temperatures. High tempering temperature allows to obtain high plastic properties, especially impact strength KV > 100J, maintaining the strength properties above the required minimum. High plastic properties of a cast steel designed for long-term operation at elevated temperatures are necessary, since – as proved by the independent study [10], as well as literature data [11] – during operation the decrease in impact strength runs faster than in the case of strength properties.

SUMMARY

The tests were carried out on high-chromium martensitic GX12CrMoVNbN9-1(GP91) cast steel designed for work under supercritical parameters. Performed research has proved that GP91 cast steel with its microstructure of partly autotempered martensite is characterized by the required mechanical properties already in the as-cast state. Heat treatment (quench hardening and high-temperature tempering) of the examined cast steel results in obtaining a microstructure of tempered martensite with numerous precipitates. The tests of mechanical properties have revealed that the given cast steel achieves the optimum mechanical properties after quench hardening from the austenitizing temperature to 1070°C and after tempering within the temperature range of 760±10°C. High tempering temperatures of the hardened GP91 cast steel provide very high impact energy with lower strength properties, whereas lower temperatures of tempering provide high strength properties with lower impact energy.

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