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Influence of stress relief annealing on the microstructure and properties of GX12CrMoVNbN9-1(GP91) cast steel

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Summary

The paper presents an effect of stress relief annealing, applied to casts after the repair by welding, on the microstructure and mechanical properties of quenched and tempered martensitic GX12CrMoVNbN9 – 1 cast steel (called GP91). The test pieces being the subject of research were taken out from a test coupon. Heat treatment of GP91 cast steel was carried out at the parameters of temperature and time appropriate for the treatment of multi-ton steel casts, while stress relief annealing was performed at the temperatures of 730 and 750°C. After quenching and tempering GP91 cast steel was characterized by the microstructure of high-tempered martensite with numerous precipitations of carbides of diverse size. Mechanical properties of the investigated cast steel after heat treatment fulfilled the standard requirements. Stress relief annealing contributes to the processes of recovery and recrystallization of the matrix as well as the privileged precipitation of $M_{23}C_6$ carbides on grain boundaries. Changes in the microstructure of the examined cast steel cause deterioration in mechanical properties – the higher the temperature of stress relief annealing, the greater the deterioration.

Key words: heat treatment, microstructure, mechanical properties, martensitic cast steel

1. Introduction

GX12CrMoVNbN9-1(GP91) cast steel belongs to a new group of high-chromium steels and cast steels with 9 ÷12%Cr introduced to the conventional power industry – the so-called martensitic steels (cast steels). GP91 cast steel was formed on the basis of chemical composition of X10CrMoVNb9-1(P/T-91) steel, being a very well examined steel of settled and stable mechanical properties. Application of GP91 cast steel in the power industry enables raising the temperature and steam pressure to the so-called supercritical parameters. The purpose in raising steam parameters is limiting the emission of pollutants into the atmosphere and increasing the efficiency of power units. The growth of steam parameters is the reason why the low-alloy cast steels and steels, used in the power industry so far, can no longer meet high requirements; in modern power units they must be replaced with new materials [1÷ 3].

Steel casts, due to their overall dimensions, great mass and diverse thickness of walls, are subject to the complicated, multi-stage, time- and energy-consuming heat treatment. Forming of microstructure and mechanical properties of GP91 cast steel occurs through hardening from the austenitizing temperature of above 1000°C, with subsequent cooling with air, oil or hardening polymers and finally high tempering at the temperature above 700°C [4, 5]. After the heat treatment on the surface of steel casts some technological defects may appear, such as fractures and deformations. Such defects are being removed mechanically and the cavities which occur afterwards are repaired by welding with electrodes. The chemical composition of weld metal is similar to that of cast material. After the repair through welding the steel casts are subject to heat treatment – stress relief annealing in order to remove welding stresses [6].

The paper presents the results of research on the influence of stress relief annealing at the temperature of 730 and 750^{o}C on the microstructure and mechanical properties of hardened and tempered GX12CrMoVNbN9-1 (GP91) cast steel.

2. Methodology of research

Heat treatment of GP91 cast steel included twelve-hour austenitizing of the test pieces at 1040^{o}C with subsequent cooling with oil. Tempering with twelve-hour holding was carried out at the temperature of 760^{o}C. After tempering the test pieces were cooled in free air. In order to simulate heat treatment after the repair of the cast by welding, the examined cast steel was subject to eight-hour holding at the temperatures of 730 and 750^{o}C. Cooling from the annealing temperature to room temperature was performed at the rate of ~25K/h. Microstructural research was done 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_o = 8mm. Measurement of hardness was taken using the Vickers method with the load of 30kG (294,2N) by means of the Future – Tech FV – 700 testing machine. Impact energy was tested on standard test pieces of the Charpy V type. In the case of the static tensile test and the impact energy measurement, the results presented herein are the mean value of three tests, while the hardness value is the mean of five measurements.

3. Research results and their discussion

3.1.

The subject of research was cast steel of the following chemical composition (%mas.): 0,12%C, 0,49%Mn, 0,31%Si, 0,014%P, 0,004%S, 8,22%Cr, 0,90%Mo, 0,12%V, 0,07%Nb, 0.04%N. The chemical composition of the examined alloy corresponded to that of GX12CrMoVNbN9 - 1 (GP91) cast steel. The standard required chemical composition and mechanical properties of GP91 cast steel are shown in respective Tables 1 and 2.

Table 1. Chemical composition of GP91 cast steel, %mass. [7]

	C	Si	Cr	Mo	V	Nb	N
GP91	0.10 ÷ 0.14	0.20 ÷ 0.50	8.0 ÷ 9.5	0.85 ÷ 1.05	0.18 ÷ 0.25	0.06 ÷ 0.10	0.030 ÷ 0.070

In the initial (as-cast) condition the investigated cast steel was characterized by a thick needle microstructure of tempered martensite. In the microstructure of GP91 cast steel in the as-cast state there were areas of lath structure of martensite which were characterized by large density of dislocations, as well as the areas of polygonal substructure (Fig. 1).

Table 2. Required mechanical properties of GP91 cast steel [7]

	$R_{p0.2}$ MPa	TS MPa	El. %	KV J	Creep resistance 100000/600^{o}C, MPa
GP91	min. 450	600 ÷ 750	min. 15	min. 30	86

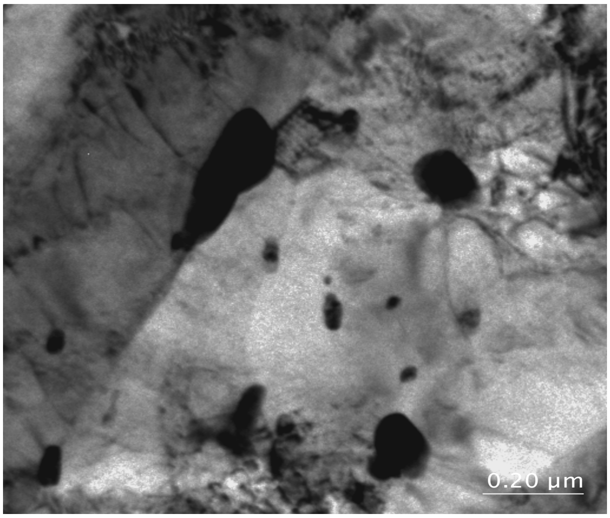

Fig. 1. Microstructure of GP91 cast steel in the as-cast state, thin foil, TEM

The width of martensite laths in the investigated cast steel in the as-cast state amounted to ca. 0.41 ÷ 0.57 µm. In the microstructure on the boundaries of laths and subgrains as well as inside the laths there were many precipitates of diverse morphology observed. Numerous identifications revealed the occurrence of three types of precipitates of different thermodynamic stability in the microstructure: M_3C, $M_{23}C_6$ and NbC.

Table 3. Mechanical properties of GP91 cast steel in cast – state condition at room temperature

	$R_{p0.2}$ MPa	TS MPa	El. %	KV J	HV30
GP91	506	644	20	94	232

Mechanical properties of the examined GP91 cast steel in the as-cast condition are provided in Table 3. They fulfilled the minimum requirements (Table 2 and 3). Strength properties determined for the investigated cast steel in the as-cast state, such as yield strength and tensile strength were higher than the minimum by 12 and 7%, respectively. Plastic properties of the given cast steel, i.e. impact strength and elongation were over

three times as high, by ca. 33%, as the minimum. However, as regards hardness of the examined cast steel in the as-cast state, it amounted to 232HV30 (Table 3).
Detailed description of the microstructure and properties of GP91 cast steel in the as-cast condition is covered by works [8, 9].

3.2. Microstructure and properties of GP91 cast steel after heat treatment

Heat treatment (hardening from the austenitizing temperature of 1040^oC and high-tempering at the temperature of 760^oC) of the GP91 cast steel allowed to obtain a fine-lath microstructure of high-tempered martensite. An example of microstructure of GP91 cast steel after heat treatment is illustrated in Fig. 2. Austenitizing of GP91 cast steel at the temperature of 1040^oC contributed to the austenite grain size reduction in comparison with the as-cast state. Mean diameter of former austenite grain after hardening from the temperature of 1040^oC amounted to ca. 25μm. This influenced the obtainment of fine-lath microstructure of martensite after hardening. The austenite grain size reduction has a beneficial effect on mechanical properties of the cast steel in two ways: it raises the yield strength and impact strength and at the same time lowers the nil ductility transition temperature.
High temperature of tempering and long time of holding contributes to the precipitation of numerous carbides of diverse size. Moreover, high tempering temperature leads to the intensification of the processes of recovery and recrystallization of the matrix, which is revealed first of all by a decrease in density of dislocations and an increase in the width of martensite laths and their decay in favour of the polygonized ferrite grains. As practice shows [2 ÷ 4], long holding times and high temperature of tempering of high-chromium cast steel are necessary in order to obtain a microstructure with high thermodynamic stability. This is what provides long and safe operation time of the casts at elevated temperatures.
The microstructure of the examined cast steel after quenching and tempering was characterized by lath substructure of martensite of high dislocation density and also by the polygonal grains of ferrite. Between martensite laths, as well as the subgrains, the dislocation boundaries occurred. The lath microstructure of martensite and polygonized ferrite were alternating with each other (Fig. 2). Identifications of precipitates performed for the GP91 cast steel after heat treatment revealed the occurrence of two precipitation types in the microstructure – $M_{23}C_6$ carbides and nitrides, carbonitrides of the MX (NbC, VX) type. In the given cast steel there were two types of MX precipitates observed: niobium-rich carbonitrides with their shape resembling a sphere – NbX and lamellar carbonitrides, vanadium-rich nitrides of the VX type. Large amounts of $M_{23}C_6$ carbides of diverse size were located mostly on grain boundaries of former austenite and on the boundaries of subgrains/martensite laths. Only some sparse carbides of this type were revealed also inside the subgrains of ferrite. Fine dispersive precipitates of the MX type were seen on the dislocations inside laths and on lath boundaries as well as on subgrain boundaries (Fig. 2).

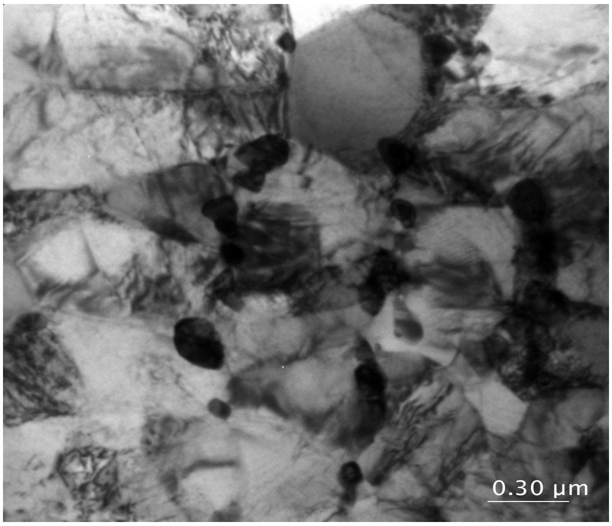

Fig. 2. Microstructure of GP91 cast steel after quenching and tempering, thin foil, TEM

Single MX precipitates were also noticed on the boundaries of initial austenite grains. After heat treatment the mean diameter of $M_{23}C_6$ carbides amounted to 158nm, while for the MX precipitates - 22nm. Carbides of the $M_{23}C_6$ type precipitated on the boundaries of subgrains/laths of martensite play a significant role – by stabilizing the subgrain microstructure of martensite they inhibit the movement of dislocation boundaries. Whilst the fine dispersive precipitations of MX on the dislocations inside martensite laths provide high creep resistance by anchoring and inhibiting the movement of dislocations.

Table 4. Mechanical properties of GP91 cast steel after heat treatment

	TS MPa	$R_{p0.2}$ MPa	El., %	KV, J	HV30
GP91	640	488	24	151	201

Table 4 includes mechanical properties of GP91 cast steel after quenching and tempering. Heat treatment of the examined cast steel contributed to the obtainment of mechanical properties required by the standard. The strength properties, i.e. apparent yield strength $R_{p0.2}$ and tensile strength were higher than the required minimum by the respective 8% and 7%. Quenching and tempering of the investigated cast steel caused a considerable increase in plastic properties. The elongation was higher than the required minimum by ca. 60%, while impact strength was over 5 times as high.

High plastic properties of the cast steel designed for long-lasting service at elevated temperatures are essential because – as proved in the course of an independent research [10], as well as in the literature data [11] – during the service the fall of impact strength runs faster than the fall of strength properties.

3.3. Microstructure and properties of GP91 cast steel after annealing

The microstructure of GP91 cast steel after stress relief annealing is illustrated in Fig. 3. Regardless of the annealing temperature, the GP91 cast steel after annealing was characterized by a microstructure similar to that of quenched and tempered cast steel, i.e. the microstructure of high-tempered martensite with many precipitations.

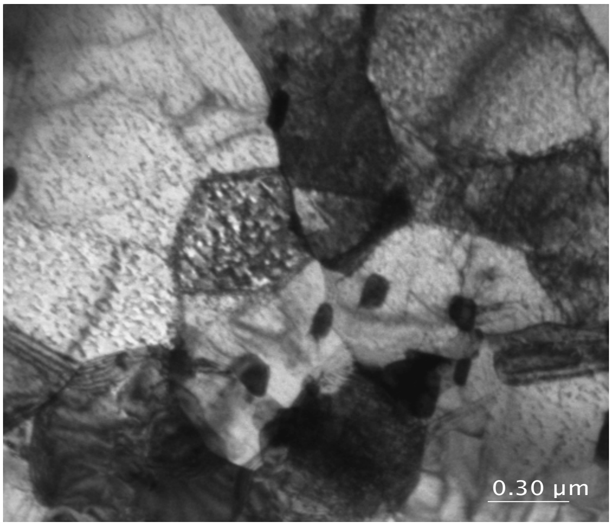

Fig. 3. Microstructure of GP91 cast steel after stress relief annealing, thin foil, TEM

Similarly as in the state after quenching and tempering, in the microstructure there were the areas of lath martensite observed being characterized by large density of dislocations, as well as the areas of polygonized ferrite. Similarly, in both: quenched and tempered state and cast steel after annealing, the occurrence of two precipitation types was disclosed: $M_{23}C_6$ carbides and nitrides, MX carbonitrides. After annealing at the temperature of 750°C the mean diameter of $M_{23}C_6$ carbides was 142nm. Stress relief annealing, however, did not influence the size of MX precipitates in any significant way. At the same time, annealing of the examined cast steel for many hours at the temperature above 700°C leads to a decrease in:

- the dislocation strengthening through the fall of dislocation density, as a result of the occurring processes of recovery and recrystallization of the matrix,
- the solid solution strengthening by alloying elements, as a result of the matrix depletion in atoms of the carbide forming elements: chromium and molybdenum;
- precipitation strengthening through the process of coagulation of $M_{23}C_6$ carbides.

Additionally, high temperature and long time of stress relief annealing lead to the privileged precipitation of carbides on grain boundaries.

Results of research on mechanical properties of the quenched and tempered GP91 cast steel after annealing are shown in Fig.4.

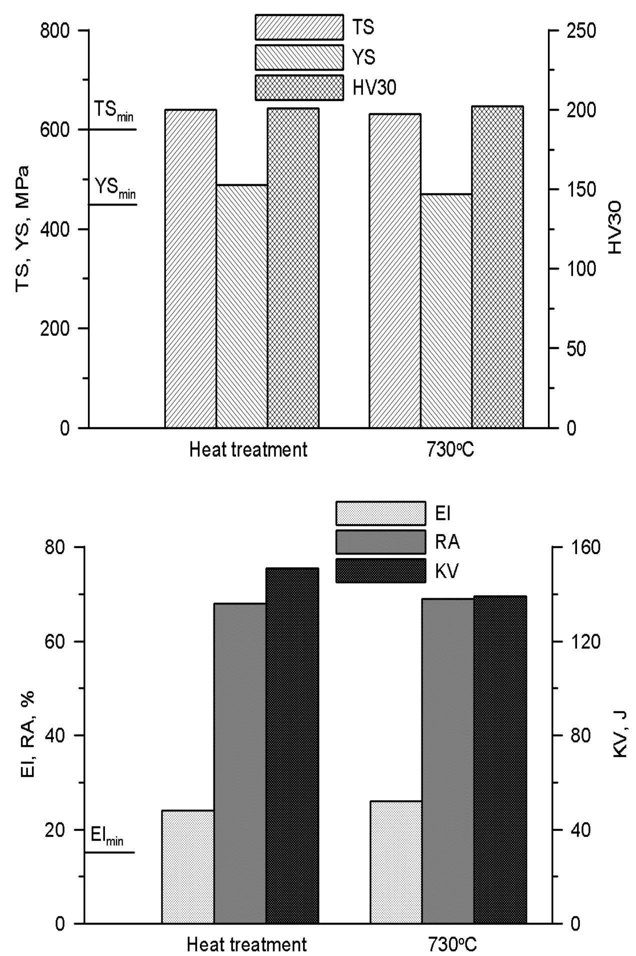

Fig. 4. Influence of stress relief annealing at the temperature of 730°C on the properties of GP91 cast steel.

High stability of microstructure in the investigated cast steel slightly influenced the decrease in strength properties by 2÷5% in the given cast steel after annealing at the temperature of 730 and 750°C. An insignificant decrease in strength properties occurred along with the considerable fall of impact strength KV, by 8 ÷ 18%. Higher temperature of annealing contributed to a major decrease not only in the strength properties, but also impact strength. The remaining plastic properties of the examined cast steel, i.e. elongation and the percentage reduction of area, practically did not change. Similar phenomenon of decreasing in the values of yield strength and tensile strength in high-chromium cast steels as the time of tempering/annealing extends, was noted in the work [9, 10]. Despite the reduction in strength properties and impact strength, the investigated cast steel after stress relief annealing met all of the requirements established by the standard [7].

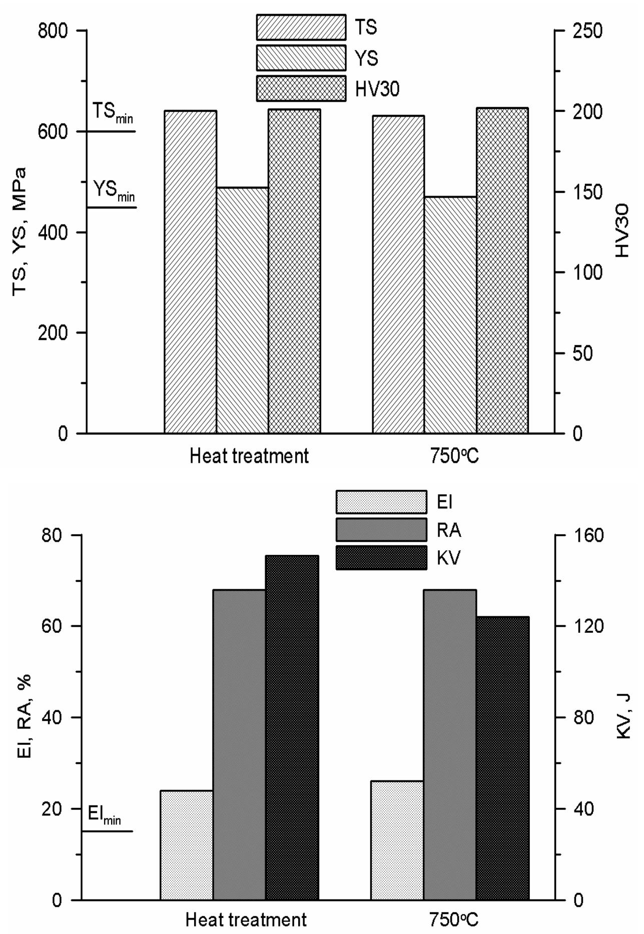

Fig. 5. Influence of stress relief annealing at the temperature of 750°C on the properties of GP91 cast steel.

Summary

The aim of the performed research was to determine the influence of stress relief annealing at the temperatures of 730 and 750°C, applied after the casts' repair by welding, on the microstructure and mechanical properties of GP91 cast steel. The tests have proved that annealing applied to the quenched and tempered GP91 cast steel first of all contributes to the processes of recovery and recrystallization of the matrix, which is recognized by the decay of lath microstructure of tempered martensite and leads to the privileged precipitation of carbides on grain boundaries. Changes in the microstructure of GP91 cast steel result in a slight decrease in strength properties and quite a significant drop in impact strength. During the service, as a result of degradation of the cast steel microstructure, its impact strength decreases faster than its strength properties. Therefore – if possible – it is recommended to apply the lowest temperatures of annealing and the shortest times of this treatment after the repair by welding.

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