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Heat treatment of cast steel using normalization and intercritical annealing

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Abstract

The paper presents the influence of heat treatment, normalization with subsequent (α+γ) annealing on the structure and properties of G21CrMoV4-6 (L21HMF) cast steel, long term serviced at the temp. of 540 ^{o}C. Applying of heat treatment ensures obtaining of regenerated ferritic – pearlitic structure with pearlite precipitations mainly on grain boundaries. such a structure formed after slow cooling at two-phase range, ensures a significant impact energy growth with mechanical properties similar to the properties after service. It has also been proved that tempering at temperatures recommended by the norm does not always allow to obtain the required minimum impact energy.

Key words: Heat treatment, Cast steel, Ductility

1. Introduction

Frames and valve chambers of steam turbines of high power are made of Cr - Mo and Cr - Mo – V cast steel. Long term operation of cast elements in creep conditions contributes to deformations, fractures and structure changes, lowering the functional properties [1 ÷ 6].

There is a decrease of impact energy considerably below the minimum required level of 27J, very often reaching 5 ÷ 10J. Together with the impact energy decrease there is also the transition temperature increase, often to the temperature of above 60 ^{o}C. Reduction of the cast properties during long term operation depends to a large extent on its initial steel structure. The optimum initial structure, as private research revealed, is the structure of high tempered bainite; the steel with such a structure has very high mechanical properties and high impact energy. In this structure the impact energy decrease during long term service is lesser in comparison with the initial ferritic – pearlitic or ferritic – bainitic structure [7 ÷ 9].

However, changes in functional properties of the casts, caused by long term service, do not limit the possibility of their further operation, because there aren't any creep changes in the cast steel structure after service. The condition of extending the time of safe operation is applying the process of casts revitalization [10 ÷ 13]. It consists in: heat treatment of the turbine frames for structure regeneration and improvement of crack resistance (increasing impact energy, decreasing transition temperature). For technological reasons massive casts of Cr - Mo - V steel during heat treatment are cooled at low rates, allowing to obtain the ferritic – pearlitic structure. Slow cooling of the steel casts (0.017K/s) from the austenitization temperature counteracts their deformation.

The paper presents the influence of regenerative heat treatment (consisting of normalization and further (α + γ) annealing) on the structure and properties of G21CrMoV 4 – 6 cast steel.

2. Investigated material

The material of research was G21CrMoV4 – 6 (L21HMF) low alloy cast steel with the chemical composition given in table 1. Samples for investigation were taken from the internal frame of turbine serviced for over 186 000 hours at the temp. of 540 ^{o}C and the pressure of 13.5MPa.

Table1.
Chemical composition of the investigated cast steel(wt.%)

C	Mn	Si	P	S	Cr	Mo	V
0.19	0.74	0.30	0.017	0.014	1.05	0.56	0.28

In the post-operational condition the structure of investigated cast steel was ferritic-pearlitic with numerous carbide precipitations on grain boundaries and inside ferrite grains. The carbides precipitated on grain boundaries often formed a continuous grid. Inside pearlite grains some spheroidal and plate carbides were visible – Fig. 1.

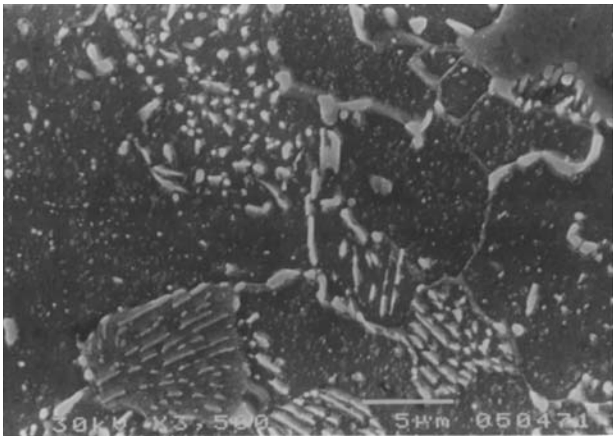

Fig. 1. Structure of G21CrMoV4 – 6 cast steel after operation, nital etched

Identification of precipitates on extraction carbon replicas revealed carbides of different types in the cast steel. On ferrite grain boundaries there were $M_{23}C_6$ carbides visible, while inside ferrite grains there were four kinds of carbides: $M_{23}C_6$, VC and Mo_2C and complex of precipitates defined as „H – carbide" – Fig. 2.

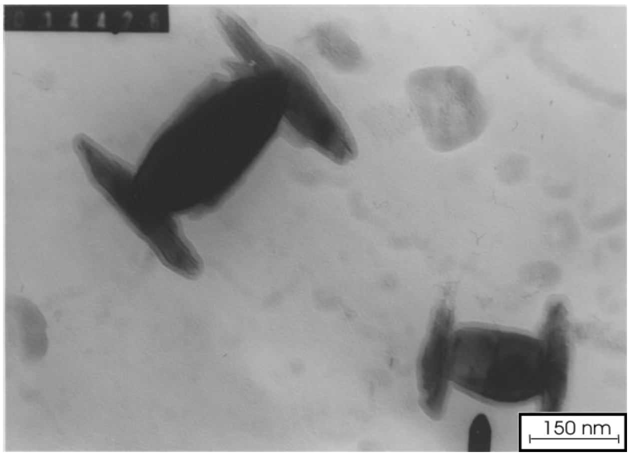

Fig. 2. „H – carbide" in the investigated cast steel, carbon extraction replica, TEM

Apart from changes in the morphology of precipitates during cast steel operation, there is also segregation of phosphorus to grain boundaries taking place. Phosphorus in steels and cast steels, which are long term serviced at elevated temperatures, is one of the most detrimental admixtures. Segregation of phosphorus to grain boundaries during long term operation decreases impact energy and raises transition temperature, the more intensely, the greater the content of this admixture in the cast steel. Concentration of phosphorus on grain boundaries can be revealed by selective etching of metalographic specimen with picric acid. This reagent "attacks" micro-areas enriched with phosphorus. The measure unit of phosphorus concentration is depth or/and width of the etched grain boundaries [4,6, 7] . Fig. 3 presents segregation of phosphorus on grain boundaries in the investigated cast steel after service.

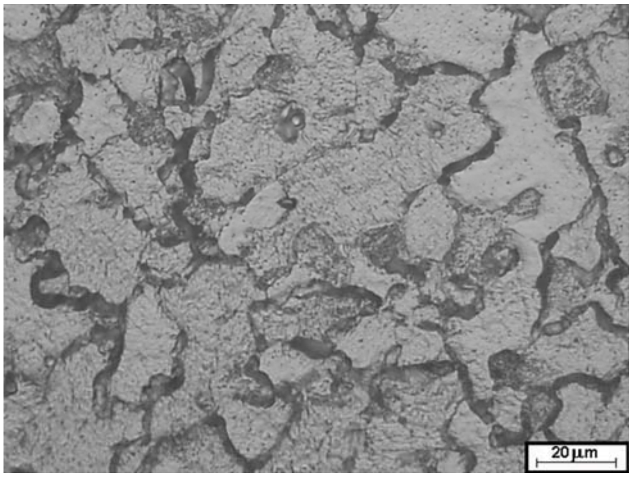

Fig. 3. Phosphorus segregation on grain boundaries in the investigated cast steel after operation, picral etched

Long term operation didn't cause a large decrease of mechanical properties. Tensile strength and hardness met the requirements for new casts [14], and the yield point value was lower by 15 MPa than the value required for new casts (Table 2).

Table 2.
Structure and mechanical properties of cast steel after service

	TS MPa	YP MPa	El %	KV J	HV30
after exploatation	545	305	26	10	156
according to Polish Standard*	500 ÷ 670	min. 320	min. 20	min. 27	140 ÷ 197**

*- PN - 89/ H - 83157; ** - hardness according to Brinell

3. Research results and their description

The basis for determining the optimum heat treatment parameters is determining of the critical temperatures A_{c1} and A_{c3}, which amounted to 775 and 903 °C, respectively (for the investigated G21CrMoV4-6 cast steel). Heat treatment of the investigated cast steel consisted in austenitization of the samples at the temperature of 910 °C for 3 hours and cooling at the rate of v_{8-5} ~ 0.017 K/s. Low cooling rate (v_{8-5} ~ 0.017 K/s) from the austenitization temperature, which was applied for the samples, is required for the technological reasons in order to avoid deformations of massive steel casts. Next, the samples were subjected to two-phase annealing for four hours at the temp. of 780 ÷ 840 °C.

Private research [15] proved that temperatures of tempering recommended by the norm for the investigated cast steel, very often contribute to obtaining of the impact energy below the required minimum of 27J (Table 3).

Table 3.
Structure and mechanical properties of cast steel after regenerating heat treatment

Parameters of heat treatment	TS MPa	YP MPa	El %	KV J	HV30
910 °C/3h/0.017K/s + 720 °C/4h	558	336	27	26	153
910 °C/3h/0.017K/s + 800 °C/4h	552	316	31	42	162
910 °C/3h/0.017K/s + 840 °C/4h	550	324	28	42	164
according to Polish Standard*	500 ÷ 670	min. 320	min. 20	min. 27	140 ÷ 197**

*- PN - 89/ H - 83157; ** - hardness according to Brinell

The research results prove that privileged carbide precipitation on grain boundaries, which occurs during few hours' high tempering, is the cause of brittleness (Fig. 4). Applying of two-phase annealing instead of tempering after normalization prevents precipitation of numerous carbides on grain boundaries and decreases segregation of phosphorus on boundaries. Width of border films enriched with phosphorus (examples of boundaries with little phosphorus segregation are marked with arrows) was significantly smaller after heat treatment in comparison with the width of etched boundaries after service (Fig. 3 and 5).

Applied heat treatment within the entire range of annealing allowed to obtain ferritic – pearlitic structure in the investigated cast steel – Fig. 6. Characteristic feature of the structure of cast steel regenerated by heat treatment was precipitation of almost entire pearlite on ferrrite grain boundaries.

Slow cooling after the process of two-phase annealing, which provides for obtaining of ferritic – pearlitic structure, ensures impact energy level of ~ 40J, with the mechanical properties approximate to the properties after service (Fig. 7, Table 2 and 3).

Fig. 4. Structure of the investigated cast steel after normalization and high tempering, nital etched

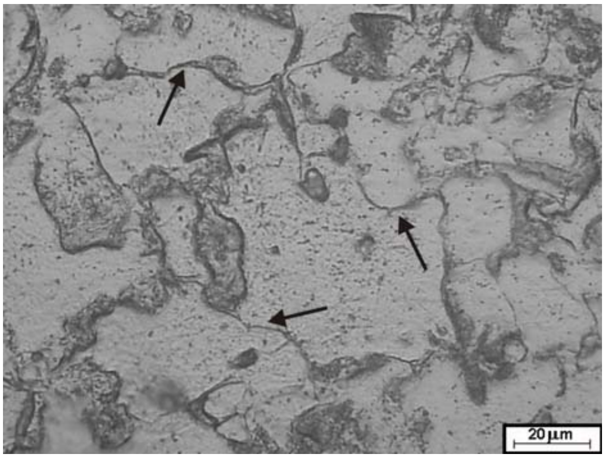

Fig. 5. Segregation of phosphorus on grain boundaries after annealing at 780 °C temperature; picral etched

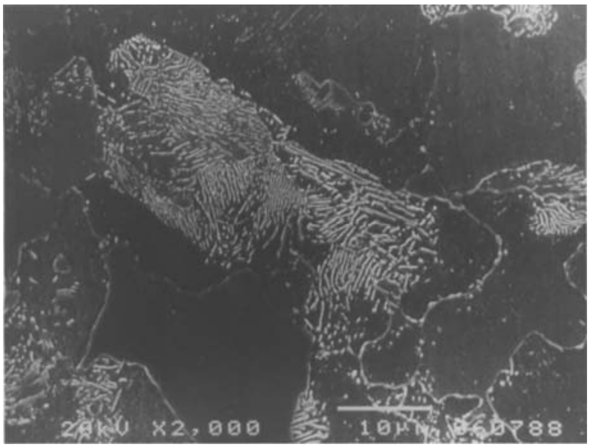

Fig. 6. Structure of the cast steel after normalized and α+γ annealing, nital etched

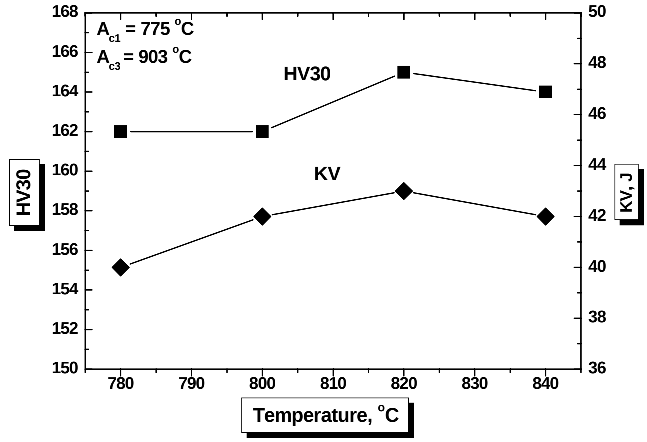

Fig. 7. Influence of the α + γ annealing on the change of impact energy and hardness after normalized annealing of the cast steel

4. Conclusions

1. Tempering after normalized annealing does not always ensure obtaining of required impact energy KV > 27J in regenerated casts. The main cause of cast steel brittleness after few hours' high tempering is privileged carbide precipitation on ferrite grain boundaries.
2. Regenerative heat treatment – normalized annealing with subsequent two-phase annealing – allows to obtain ferritic – pearlitic structure with pearlite precipitated mostly on ferrite grain boundaries.
3. Ferritic – pearlitic structure, formed after slow cooling, ensures a significant increase of impact energy with the mechanical properties similar to the properties after service.

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