Heat treatment as a method of restoring of the material 15Cr12WNiMoV after operational processes

O. *B*. Berdnik, *I*. *N*. Tsareva, and *L*. *A*. Krivina

Institute of Mechanical Engineering Problems of the Russian Academy of Sciences (IPM of RAS) - branch of the FIC of the Institute of Applied Physics of the Russian Academy of Sciences, 603024, Nizhny Novgorod, Russia

Abstract. The article presents the results of studies of the post-operational state of the turbine rotor blade material of the power plant (operating time is about 30000 hours). High-temperature fatigue processes occurring in the heat-resistant steel 15Cr12WNiMoV have been studied. These processes manifested themselves in changing microstructure and mechanical characteristics. Various heat treatment modes were tested to regenerate the structure and restore the mechanical properties of the alloy in order to develop the scientific foundations of the resource-saving technology of turbine blades.

1 Introduction

One of the main units of gas turbine plants is a gas turbine, and the most critical parts with the highest quality operational requirements are turbine rotor blades. They operate under conditions of simultaneous exposure of centrifugal and vibrational loads and erosivity of high-temperature gas flow. The temperature margin ensuring the structural stability of the alloy is 50-100 °C. Often parts operate at the upper-temperature limits, and in emergencies, there may be critical overtemperature, which affects the operation capability of the material. Therefore, the study of processes of high-temperature fatigue and their reversibility is important both from a scientific and practical points of view. It is necessary for the development of modes of reductive heat treatment as part of resource-saving technologies [1, 2].

2 Methods of research

Samples for studying were cut from the most thermally loaded zone (trailing edge) of the first part of the blades made of the martensitic-ferrite grade of the heat-resistant steel 15Cr12WNiMoV. These blades were used at temperatures up to 780 °C for approximately 30000 hours.

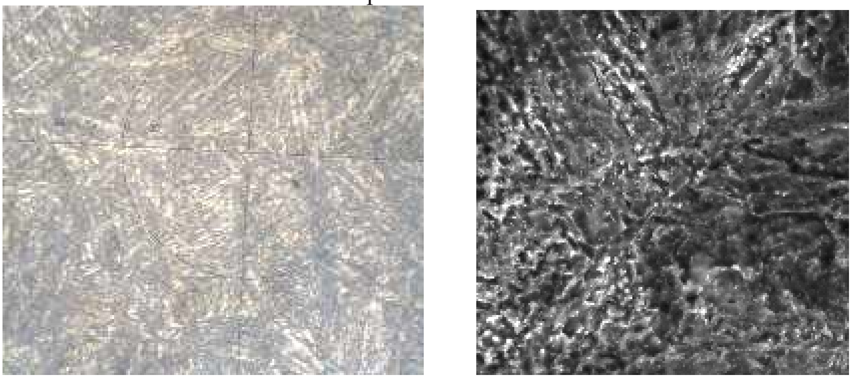
Metal micrographic tests were performed on the micrographic specimens on the «Axio Observer» optical microscope and the «VEGA TESCAN II» electron microscope. Microhardness testings were carried out on a microhardness tester «ПМТ-3» at aт indentation load of 2 N with the State Standard 9450-76 (measurement error was not exceeding 2%). From the experimental microhardness values, the plasticity coefficient of the material was determined by the formula [3]:

$$\delta = 1\text{-}14{,}3\cdot(1\text{-}\nu\text{-}2\nu^2)\cdot(H/E),$$

where H is the average value of microhardness, ν is the Poisson coefficient, E is the elastic modulus (E = 216 GPa for the steel 15Cr12WNiMoV [4]). Mechanical pulling tests were carried out on flat samples on a tension testing machine «У10Т».

3 Research results

Metallographical tests showed that the structure of the material of the blade airfoil after the operation is medium-needled martensite (assessment 5, [4]) (figure 1). The average microhardness of the material after the operation is 2.77 GPa.



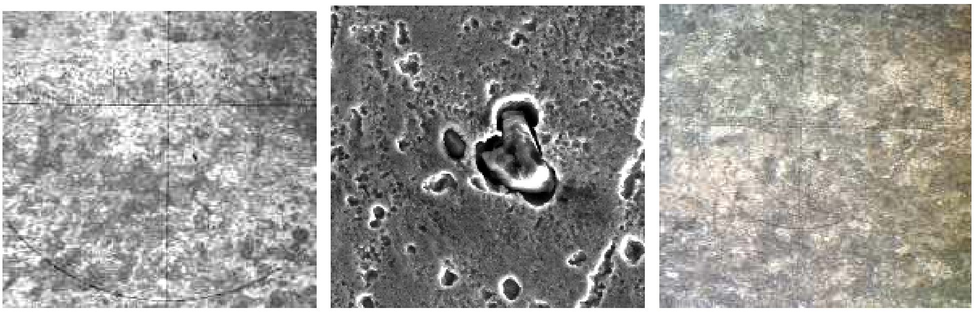
a b

Fig. 1 - Microstructure of the steel 15Cr12WNiMoV after the operation: a - x500, b- x10000

According to the reference data [5], the following heat treatment mode is recommended for the steel 15Cr12WNiMoV during fabrication: oil quenching from 1050 °C, tempering at 700-720 °C. Following heat treatment modes have been proposed for regenerative heating of the microstructure and restoring the mechanical properties of the material: 1 - quenching at T=1000 °C for 1,5 hours; 2 -ageing at T = 700 °C for 5 hours, air cooling; 3 - ageing at T = 740 °C for 5 hours, air cooling; 4 -ageing at T = 600 °C for 5 hours, air cooling; 5 - ageing at T = 700 °C for 5 hours, air cooling; 6 -ageing at T = 700 °C for 5 hours, air cooling, then ageing at T = 700 °C for 5 hours, furnace cooling; 7 - ageing at T=740 °C for 5 hours, air cooling, then ageing at T = 700 °C for 5 hours, furnace cooling; 8 - ageing at T=600 °C for 5 hours, air cooling, then ageing at T = 700 °C for 5 hours, furnace cooling; 9 - ageing at T=700 °C for 5 hours, air cooling, then tempering at T = 700 °C for 5 hours, furnace cooling.

The microstructure of the material after the heat treatment is shown in figures 2 - 5. After the heat treatment in mode 1, the structure of fine-needled martensite (assessment 3, [4]) is formed (figure 2a). Numerous separations of the carbide phase (chromium carbides) with a particle size of 2 to 3 μm were revealed, the size of individual particles reaches is about 10 μm (figure 2b), a thin carbide network is also observed (figure 2c). The mean microhardness of the material is 2.6 GPa.

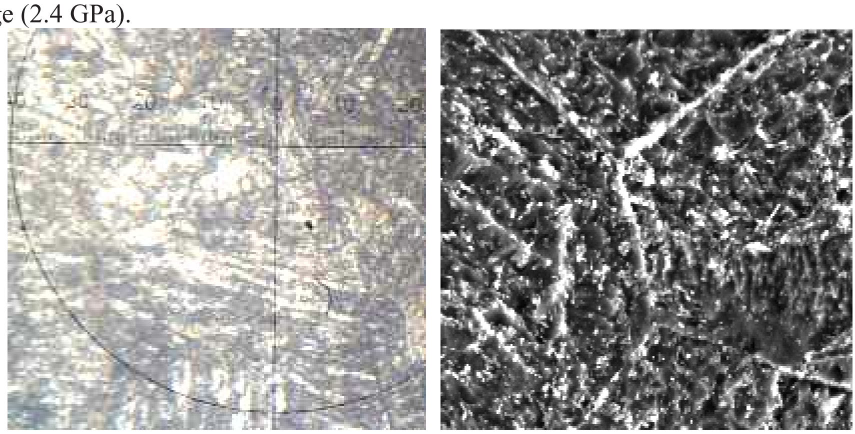
Fine-needled (sorbitic) martensite of tempering is preserved in the structure (figure 2c) after additional tempering at 700 °C (holding for 5 hours) and furnace cooling (mode 5). The microhardness of the material is 2.0 GPa.



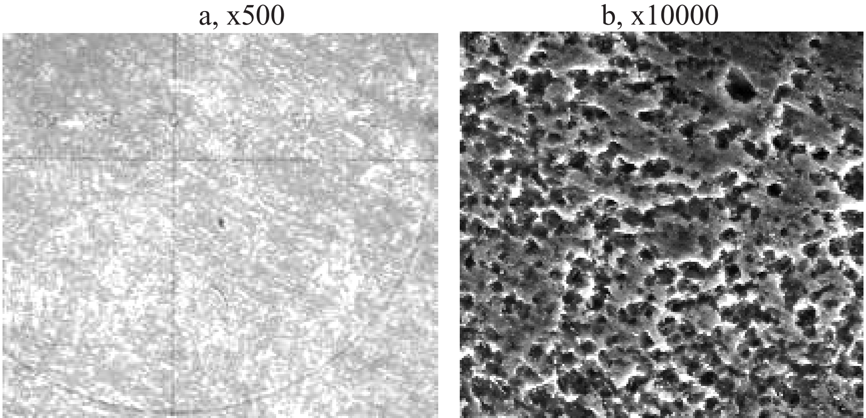
a, x500 b, x5000 c, x500

Fig. 2 - Microstructure of the steel 15Cr12WNiMoV after the heat treatment in mode 1 (a, b) and mode 5 (c)

Heat treatment in mode 2 leads to the appearance of coarse-needled martensite in the microstructure (assessment 7-8, [4]) (figure 3a) with carbide inclusions (measuring about 0.5-1 μm) uniformly distributed along the metallographic specimen (figure 3b). The microhardness of the material is 2.4 GPa. Heat treatment in mode 6 is accompanied by fine crushing of martensite to 6 assessment [4] (medium-needled martensite with a needle length of 10 μm) (figure 3c, d). The microhardness of the material after tempering does not change (2.4 GPa).



a, x500 b, x10000



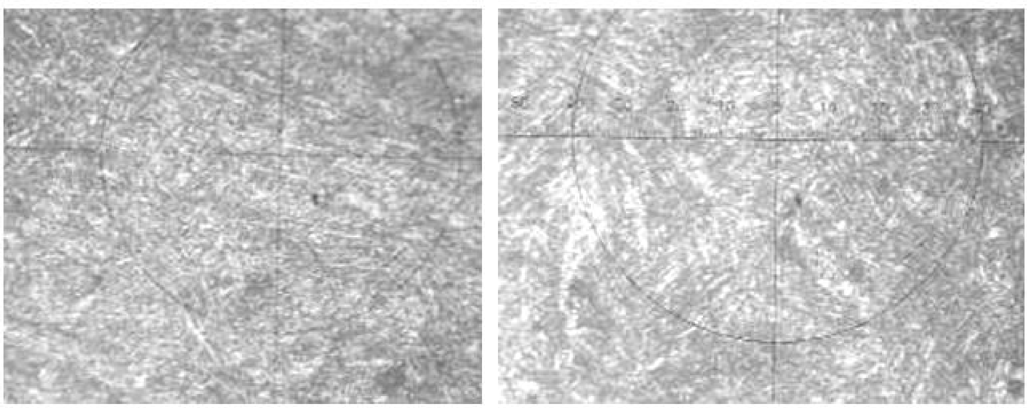
c, x500 d, x10000

Fig. 3 - Microstructure of the steel 15Cr12WNiMoV after the heat treatment in mode 2 (a, b) and in mode 3 (c, d)

After the heat treatment in mode 3, fine-needled martensite or secondary sorbite with the saved martensite orientation in it (needle length: 2.0-4.0 μm) is formed in the structure, which corresponds to assessment 3-2 (figure 4a). The microhardness of the material is 3.2 GPa The application of an additional tempering in mode 7 leads to the growth of needles of martensite (to 8 μm) (figure 4). The Microhardness of the material is 2.85 GPa.

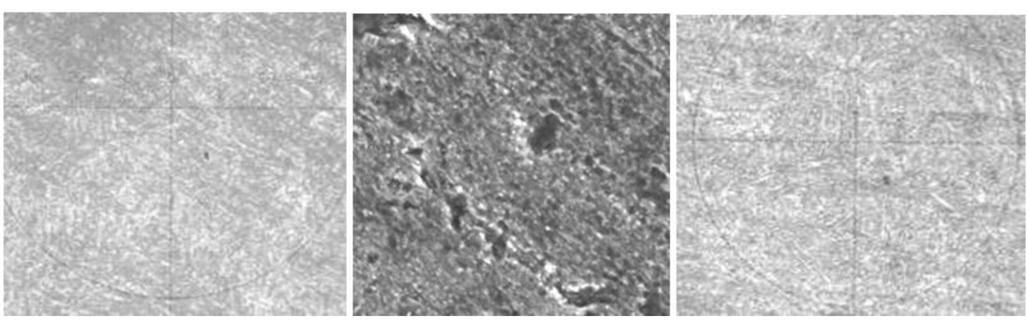
Heat treatment in mode 4 leads to the formation of medium-needled martensite (assessment 6-7, [4]) (figure 5a, b). The microhardness of the material is 3.0 GPa. Tempering at 700 °C for 5 hours (furnace cooling) in mode 8 leads to the formation of tempered martensite (figure 5c) and, as a result, to a slight decrease in the microhardness of the material to 2.7 GPa.

According to the results of metallographical tests, the optimal heat treatment mode (ageing at 740 °C for 5 hours, air cooling and tempering at 700 °C for 5 hours, furnace cooling), which contributes to the formation of a stable microstructure of the medium-needled martensite, was chosen. Microhardness of the material after ageing at 740 °C for 5 hours with air cooling is 2.4 GPa and doesn't change after the repeated tempering.



a b

Fig. 4. The microstructure of the steel after the heat treatment: in mode 3 (a) and in mode 7 (b), x500



a, x500 b, x10000 c, x500

Fig. 5. The microstructure of the steel 15Cr12WNiMoV after the heat treatment in mode 4 (a, b) and in mode 8 (c)

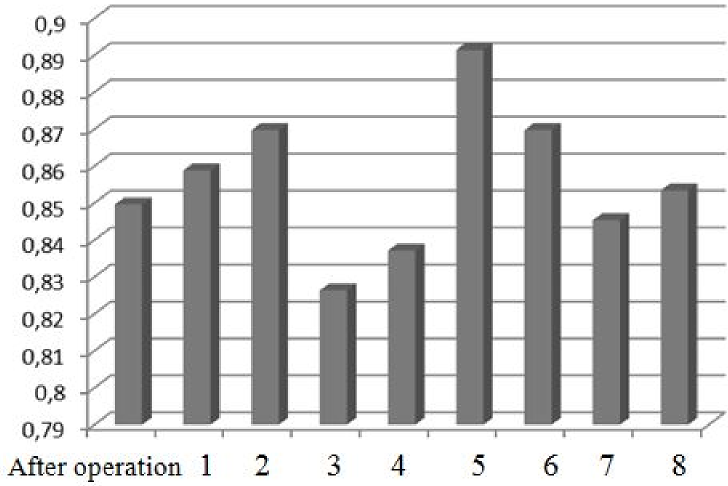


Fig. 6. Plasticity coefficient of the steel 15Cr12WNiMoV after the operation and the following heat treatment

Using the experimental values of the microhardness, theoretical estimates of the plasticity coefficient (δ), were made (Fig. 6). This coefficient characterizes the ability of the material to perceive elastic and plastic deformations. To ensure a sufficient level of plasticity of the long-lived metal material, the plasticity coefficient must be at least δ = 0,8. In the hardness range H^{min} =2.0 GPa; H^{max} =3.2 GPa plasticity coefficient is within acceptable range: from δ = 0.89 to δ = 0.82. The average hardness value will meet this plasticity criteria.

Table 1 shows the results of tests of mechanical properties of steel samples 15Cr12WNiMoV after the operation and reductive heat treatment. Changing the microstructure during the long-term operation leads to an increase in resistance to rupture by 1.33 times (from 740 MPa to 940-1030 MPa) and a decrease in flow limit by 2.1 times (from 590 MPa to 280 MPa). The difference between the values of these limits diminishes severely. The material is in a hardened condition with low ductility (percentage of elongation below the normalized value). The probability of the brittle fracture increases.

Table 1. The results of tests of mechanical properties of steel samples.

Material condition	resistance to rupture $\sigma_в$, MPa	flow limit, $\sigma_{0,2}$, MPa	percentage of elongation, δ, %	contraction ratio, ψ, %
According to literature data	≥740	≥590	≥ 15	≥ 45
After the operation	940	280	11	44
After the heat treatment (oil quenching 1050 °C, tempering at 700 - 720 °C) [6]	690	510	18	57
After the heat treatment in mode 2	770	455	15	49
After the heat treatment in mode 5	755	460	15	53

Using the heat treatment in modes 2 and 5, it was possible to restore the strength characteristics of the steel for 170 MPa ($\sigma_в$ =770 MPa). A significant increase (180 MPa) of the flow limit ($\sigma_{0.2}$ = 460 MPa) was achieved (but the value 1.28 times below than the normalized value).

4 Conclusion

The material after the operation for 30000 hours is in a hardened condition with unsatisfactory mechanical characteristics due to the changes in microstructure (dispersion of martensite and carbide phase distribution). The use of reductive heat treatment leads to the regenerative heating of the microstructure and the restoration of mechanical properties ($\sigma_в$ =755 MPa; $\sigma_{0.2}$=460 MPa; δ=15 %; ψ=53 %).

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