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# STRUCTURE AND PROPERTIES OF THE STEEL RAILWAY WHEEL DISC AFTER FORCED COOLING

**Summary**. The technological use of accelerated cooling makes it possible to improve the carbon steel properties of the all-rolled railway wheel disc. The properties' complex depends on the temperature of the accelerated cooling termination. This is determined by the ratio of the carbon atoms emitted from the supersaturated solid solution to the crystal structure defects and dispersion strengthening from carbide phase particles. If the cooling stops at a temperature above 350°C, the decline rate of the strength properties increases. This is caused by the excessive softening effect of the solid solution breakdown and cementite spheroidization during the processes of dispersion hardening.

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**Keywords:** strength, carbon steel, wheel disc, accelerated cooling, microstructure

## 1. INTRODUCTION

Increased operational intensity of railway transport is accompanied by the entirely justified severization of operational safety requirements. The railway wheel is an important structural element of rolling stock. Reliability increases in the operation of railway wheels can be achieved by increasing the property complex of metal by alloying or using heat treatment technologies [1,2]. A disc with the smallest thickness is subjected to complex loads during the wheel operation. This imposes high demands on the property complex of the railway wheel disc. Quite often, when manufacturing the solid-rolled railway wheels, after accelerated cooling of the wheel rim [3], the disc is cooled in air. Developing technical solutions for improving the property complex and, primarily, the combination of strength and ductility characteristics of the metal disc is an important scientific and technical challenge. The use of accelerated cooling of the disc surface is a promising technological solution, which makes it possible to increase the property complex and operational safety of railway wheels under current conditions of increasing specific loads on the wheel set. In [4], the principal possibility of disc thermal hardening by water cooling using nozzle-type devices is shown. Research has indicated that, at a depth of 3-5 mm from the disc surface, the cooling rate reaches 30-35°C/s. Taking into account the increased stability of austenite in the railway wheel steel [5,6], the structure formation near the disc surface may occur according to shifting or intermediate mechanisms [7]. Interrupted cooling of the wheel disc leads to the formation of a microstructural gradient and properties in terms of thickness [4], the level of which is determined by the development of tempering processes from the heated internal volumes of the metal (self-tempering) [8,9]. By considering the continuous nature of change in the cooling rate in relation to the disc cross-section, the influence of these processes will depend on the depth of the layer with respect to the cooling surface [10]. Therefore, the study of structural formation and metal properties in the process of the interrupted cooling of the disc is of interest when estimating the possible increase in the structural strength of the railway wheel.

## 2. RESEARCH MATERIAL AND METHODOLOGY

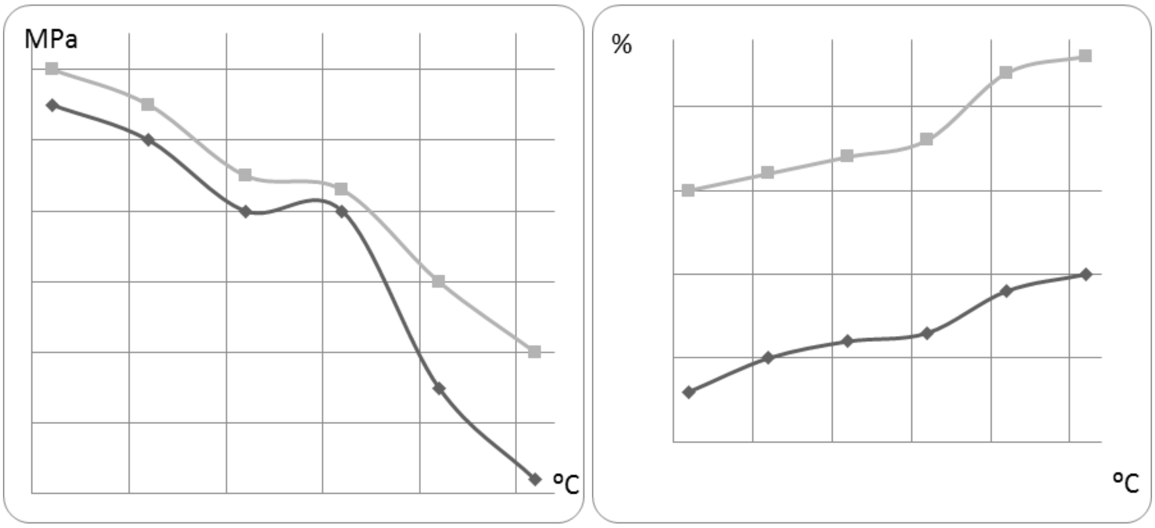
The material for this research was railway wheel steel with the following composition: 0.56% C; 0.66% Si; 0.43% Mn; 0.003% S; 0.012% P; 0.10% Cr. The processes of structural formation in the different layers of the disc were simulated during accelerated cooling by changing the temperature of forced cooling termination. Blanks in the form of rods with a diameter of 9 mm and a length of 100 mm were heated to 830-850ºC, then held at this temperature for 15 min in order to complete the austenite homogenization. They were subsequently cooled with water to achieve a certain temperature, before being cooled in air.

The temperature of the accelerated cooling termination ($T_c$) ranged from 200 to 450°C in 50°C intervals. The temperature control was carried out by a chromel-alumel thermocouple. The samples were tested for tension using an Instron machine at the following rate of deformation: $10^{-3}$ $sec^{-1}$. The microstructure was studied using quantitative metallography [10] under the UEMV-100K electron microscope at the accelerating voltage of 100 kV. The parameters of the fine crystalline structure were evaluated by X-ray structural analysis using the DRON-3 diffractometer. The microhardness of structural components was evaluated using the PMT-3 device with loads on the indenter in the range 20-50 g.

## 3. RESEARCH RESULTS AND DISCUSSION

Figure 1 shows changes in the steel properties due to the temperature of the accelerated cooling termination. When analysing Figure 1a, one can see that, as $T_c$ increases from 200 to 450°C, the yield point ($\sigma_{0,2}$) is reduced from 1,250 to 720 MPa, while the ultimate tensile strength ($\sigma_B$) reduces from 1,315 to 880 MPa. The reduction in the level of strength characteristics was accompanied by an increase in the relative elongation (δ) from 7 to 15%, and a narrowing (ψ) from 20 to 28% (Figure 1b). The above-mentioned level of the disc properties exceeded the requirements of certain national standards ($\sigma_B$ – 730-880 MPa, δ and ψ – not less than 6 and 11%, respectively).

The observed combination of strength and ductility characteristics was caused by the structural state of steel, formed in the process of accelerated cooling and during subsequent self-tempering. The conducted electron microscopic studies of the wheel disc metal showed that the identified substructural peculiarities qualitatively coincided with results reported in similar studies on carbon steels subjected to accelerated cooling [11].




a b

Fig. 1. The changes in the steel properties due to the temperature of the accelerated cooling termination. Strength (a): $\sigma_{0,2}$ (♦), $\sigma_B$ (■); and plastic (b): δ (♦), ψ (■) (the characteristics)

It transpires that the mechanical properties of the studied steel, when rapidly cooled to 200-300°C, are largely similar to the properties after martensite quenching (with separate heating) and tempering at these temperatures [9,10]. Figure 2 shows the structure of steel after accelerated cooling to 200-250°C. The analysis presented in this figure shows the presence of not only upper and lower bainite (Figure 2a-b), but also the eutectoid colonies of high dispersion (Figure 3a-b). The differences between the volumes of lower and upper bainite are found in the morphological features of the carbide phase structure. For upper bainite, the characteristic feature is the presence of relatively large elongated cementite particles (Figure

2a), with a primary location along the lath borders of the α-phase. The areas of lower bainite are the metal volumes with dispersed carbide particles located within the lathes (Figure 2b). In this case, the observed image clarity reduction in the lath borders of lower bainite in some microvolumes indicates the increased density of dislocations in the α-phase. The growth in the distance from the cooling surface is accompanied by certain structural changes, starting from the bainitic structures near the disc surface to the ferrite-pearlite phase components with different dispersion and morphology. Compared to the metal located near the surface of intensive cooling (Figure 2), in the volumes lying in the central part of the wheel disc, the microstructure is formed mainly according to the diffusion mechanism (Figure 3). This is indicated by a finely differentiated pearlite structure and the areas of structurally free ferrite located at the boundaries of the pearlite colonies (Figure 3a). The thickness of cementite plates in pearlite is about 0.02-0.04 μ, while the thickness of ferrite layers is no more than 0.15 μ. The morphology change in the carbide phase, starting from thin intermittent plates to dispersed particles of a globular form, shows that the metal is heated to different temperatures after the accelerated cooling termination.

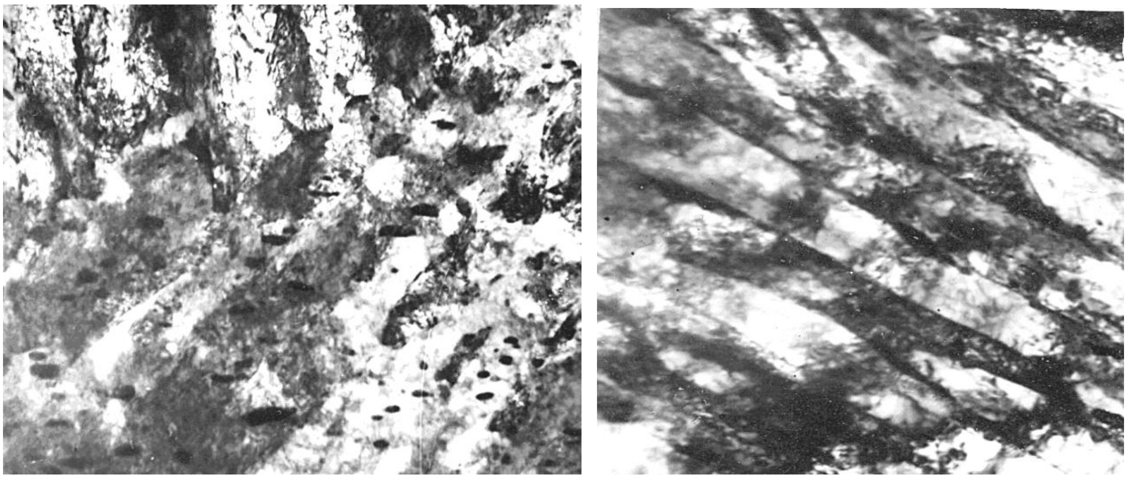


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Fig. 2. The microstructure of steel after accelerated cooling to 200-250°C: upper bainite (a), lower bainite (b) (magnification: 18,000)

During detailed analysis, the division of areas of structurally free ferrite (Figure 3b) into subgrains with dimensions of 1.5-3.5 μ can be found. The form of subgrains varies from a polyhedron with a high dislocation density to needle-like formations. The presence of ferrite of a different morphology is explained by differences in cooling rates due to disc thickness and the possible liquation of chemical elements in the metal microvolumes [8].

A further increase in the temperature of the accelerated cooling termination to 400°C is followed by the somewhat expected qualitative changes in the microstructure. The formation of complex dislocation tangles, which occur as broken contours in the dislocation complexes, corresponds to the occurrence of signs of the development of polygonization processes (Figure 4a). In other microvolumes of ferrite, the presence of cementite particles of a globular form is observed within the areas with a low dislocation density (Figure 4b). This fact indicates the completion of polygonization. The simultaneous behaviour of these processes leads to the formation of a rather complex modulated structure. Individual cells, with a specific dislocation density inside them, are sufficiently separated from wide dislocation walls (Figure 4b). In general, the formed cellular dislocation structure resembles a polyhedral form;

the central part of the cells is largely cleared from unbound dislocations. However, a certain number of cementite particles, with sizes greater than that after self-tempering at 200°C, can be found in the structure. Thus, the nature of the influence of the self-tempering temperature increase on the metal structure is based on the progressive reduction in the degree of solid solution supersaturation by carbon atoms, the increase of the average size of carbide particles and the recombination of dislocations reducing their density.

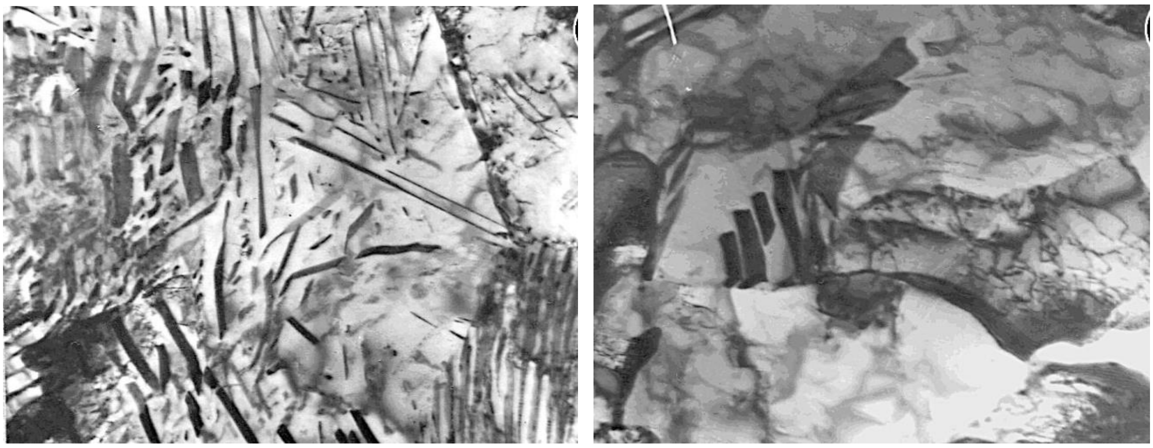

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Fig. 3. The microstructure of metal in the axial part of the disc (magnification: 12,000)

The structural state of railway wheel disc steel near the surface of accelerated cooling is caused by the development of bainite transformation with self-tempering in the temperature range 200-300°C, which leads to the achievement of the level of strength properties as follows: 1,320-1,200 MPa [4].

A detailed analysis of structural changes from the temperature of the accelerated cooling termination ($T_c$) indicates the development of two competing processes: reducing the degree of solid solution supersaturation by carbon atoms and dispersion hardening from the carbide phase particles. The nature of the microhardness change ($H_\mu$) of the ferrite component shows that, with an increase in the temperature of the accelerated cooling termination (starting from 200°C), a continuous decrease in the concentration of carbon atoms in the solid solution is observed (Figure 5a). On this basis, it should be assumed that the development of steel softening processes with the $t_t$ increase will, to a greater extent, depend on the carbon atoms' transfer from the solid solution to the defects in the crystal structure than on the contribution of the dispersion strengthening of ferrite. On the basis of the angular coefficient of dependence $H_\mu = f(T_c)$, the reduction degree in solid solution supersaturation by carbon atoms can be qualitatively judged. At the same time, ferrite has a sufficiently high density of crystalline structure defects, especially the dislocations, as evidenced by the change behaviour of the line width of the X-ray interference of ferrite $\beta_{(110)}$ (Figure 5b.). The comparison of microhardness values (Figure 5a) and $\beta_{(110)}$ makes it possible to determine the intervals with a qualitatively different nature of structural changes in the metal during self-tempering. It is supposed that, at the temperature of self-tempering, i.e., 350°C, the point of almost full exhaustion of the evolution resource of carbon atoms from the solid solution on dislocations (acceleration of a reduction in the values $H_\mu$ and $\beta_{(110)}$ at temperatures above 350°C) is achieved.

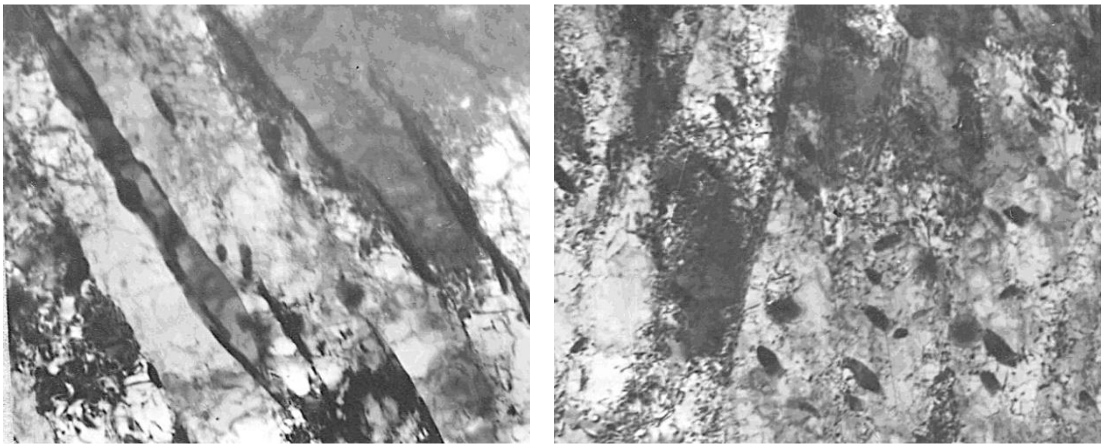

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Fig. 4. The microstructure of steel after accelerated cooling to 400°C (magnification: 18,000)

Similar results were obtained when analysing the nature of hardening for most of the mix of rolled stock after accelerated cooling. In [9,10], it is shown that, starting from temperatures of 350°C and above, in the structure of carbon steel, one can already find a certain number of fine particles of the carbide phase. On this basis, the carbon depletion of the solid solution will take place due to the direct diffusion of carbon atoms from the solid solution for carbide particles, which, to some extent, is confirmed by the change nature of the metal strength properties (Figure 1a). A detailed analysis of the curve rate indicates that the main factor of hardening during accelerated cooling is the degree of solid solution supersaturation by carbon atoms, while the dispersion strengthening has a lesser influence. On the other hand, the process of carbon depletion of the solid solution has a dual nature of influence on the strength properties. The evolution of carbon atoms from the octahedral interstices in the crystalline lattice of ferrite on dislocation, which contributes to their further consolidation [9], leads to hardening. At the same time, a reduction in the concentration of carbon atoms in the solid solution, which leads to softening, further increases the amount of dispersed cementite particles. Dispersion hardening from these particles will enhance the strength characteristics of the metal. On the other hand, the transition of the carbon atoms from the solid solution to the carbide particles is accompanied by a reduction in internal stresses, which is evidenced by an increase in the contrast of the reflexes of microdiffraction images [7, 10] and a reduction in the broadening of X-ray ferrite interferences (Figure 4b).

At higher temperatures of the accelerated cooling termination, a progressive decrease is observed in the ferrite microhardness and the corresponding decrease in the value of $\beta_{(110)}$, alongside well-defined qualitative changes in the internal structure of the metal corresponding to them. As the temperature increases to 400-450°C, the intensive development of the polygonization process is started, especially in the areas of bainite.

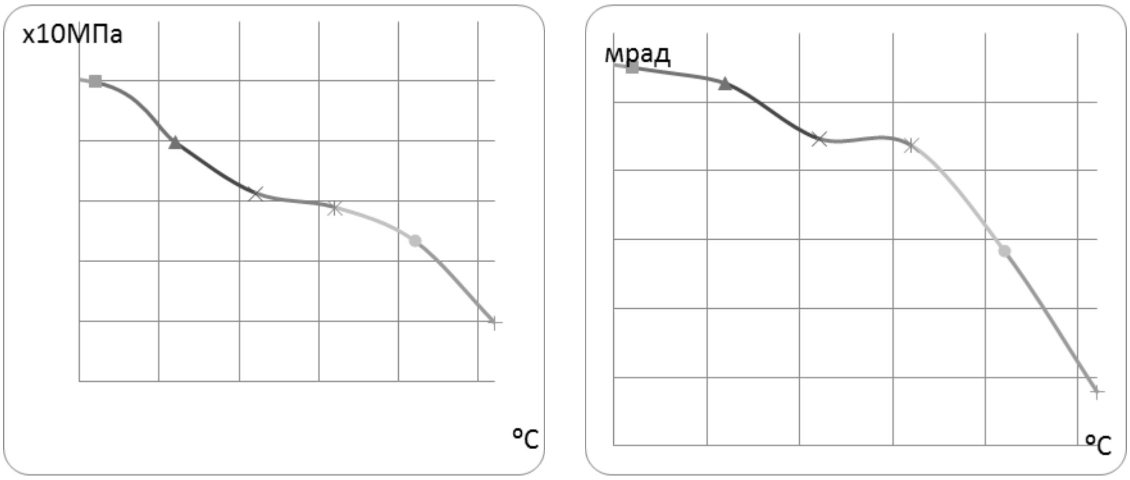


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Fig. 5. Influence of the accelerated cooling end temperature on ferrite microhardness (a) and the $\beta_{(110)}$ of ferrite (b)

The formation of cells of a polygonal form is accompanied by the emergence of boundaries with a different degree of perfection. In the middle of the cells, the dislocation density is significantly reduced, compared to the lower temperature of the cooling termination. In some microvolumes, the metal redistribution of dislocations leads to the initial stages of the “spillage” of boundaries with small angles of disorientation. In the pearlite colonies, the spheroidization and coalescence of cementite are accelerated. The simultaneous development of these phenomena explains the observed change behaviour in the property complex of wheel disc metal at different distances from the surface of accelerated cooling (Figure 1). According to these results, the effect of softening from reducing the degree of solid solution supersaturation by carbon atoms, as well as reducing the dislocation density and coalescence of cementite particles, exceeds the strengthening effect from the presence of fine carbide particles in the structure.

Thus, the accelerated cooling termination at temperatures of up to 300°C, the level of steel strength properties is determined by the combined effect from the processes of carbon atoms’ evolution from the solid solution for dislocations and dispersion hardening of cementite from the formation of an additional quantity of cementite particles. The analysis of the obtained results indicates that the use of accelerated cooling of the disc to 350-400$^{o}$C, when manufacturing the all-rolled railway wheel, will make it possible to improve the strength characteristics of metal without reducing the ductility properties, as compared to air cooling. The existing regulatory requirements (Standard EN 13262: 2004, Steel ER 9) confirm the relevance of technical solutions aimed at improving the strength properties of the railway wheel disc.

## 4. CONCLUSIONS

Firstly, accelerated cooling of the surface of the railway wheel disc to a temperature in the range of 350-400$^{o}$C enhances the strength characteristics of the metal, as compared to cooling in air. Secondly, the level of strength properties of the metal disc is regulated by the temperature of the accelerated cooling termination after achieving the desired effect from the development of hardening and softening processes.

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