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МАТЕРІАЛОЗНАВСТВО

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INFLUENCE OF SELF-TEMPERING TEMPERATURE ON STRENGTH OF RAILWAY WHEEL DISK AFTER ACCELERATED COOLING

Purpose. The paper aims at estimation of resource of strength increase for railway wheel disk. **Methodology.** The material for research was carbon steel of railway wheel containing 0.57%C, 0.65%Si, 0.45%Mn, 0.0029%S, 0,014%P, 0,11%Cr. A railway wheel was heated to the temperatures above Ac_3 and was held at this temperature until the completion of austenite homogenization processes and then the disk was cooled at a growing rate to a certain temperature. A temperature interval of completion of the speed-up wheel disk cooling was 200-450 $^{\circ}$C. Structure was studied with the use of research methods under electronic and light microscopes. After accelerated cooling the estimation of metal structure imperfection degree was carried out with the use of X-ray structural analysis method. The stress and yielding limit of carbon steel were determined at tension, at a speed of deformation $10^{-3}s^{-1}$. The microhardness of steel structural components was estimated using the microhardness tester of PMT-3 type. **Findings.** The properties complex of railway wheel carbon steel depending on the temperature of the accelerated cooling termination is determined by the correlation of soften and work-hardening processes development. The effect of work-hardening is based on blocking of mobile dislocations due to a precipitation carbon atoms and dispersion work-hardening from the formed particles of carbidic phase. At the temperatures of the accelerated cooling termination of carbon steel higher than 300-350 $^{\circ}$C the decrease rate of strength properties is determined by the exceeding of total soften effect from disintegration of solid solution, acceleration of spheroidithation and coalescence of cementite particles above the dislocations blocking by the carbon atoms and dispersion work-hardening. **Originality.** Authors proved that the strength level of the railway wheel carbon steel from the temperature of accelerated cooling completion is determined by the influence ratio of the solid solution satiety degree and dispersion

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work-hardening from a carbidic phase. For the temperatures of accelerated cooling termination 200-300 °C a decrease of solid solution satiety degree is a basic factor, which determines the level of the strength characteristic. **Practical value.** When making the whole-rolled railway wheel one can increase the strength limit of disk metal using the accelerated cooling to the middle interval of temperatures, which was successfully proven by authors.

Keywords: dislocations; self-tempering temperature; accelerated cooling; railway wheel disk

Introduction

A complex form of railway wheel elements crossing and their large thickness have for a long time restrained the application of thermal hardening in order to achieve the high strength state in them. In operation of the railway wheel the disk undergoes complicated total loads. On this basis the development of proposals to improve the strength characteristics of railway wheel disk is an important scientific and technical task.

As compared to the other wheel elements the disk has the smallest thickness. Taking into account sufficiently high stability of austenitic phase in the carbon steel of railway wheel [11] one can hope to achieve the cooling rates close to the critical value during the accelerated cooling in metal volumes near the surface of the main heat removal.

State of the problem. During the thermal hardening of the disk for solid railway wheels formation of the structure gradient from the heat removal surface is accompanied by some change in complex of properties [1, 5]. Investigations of structural transformations using the technology of interrupted accelerated cooling determined that a significant influence in the achievement of properties level is caused by the development self-tempering processes [6, 7]. Taking into account the continuous nature of the cooling change rate in different layers of the wheel disc metal depending on their distance from the surface of intense heat removal, the structural condition of the metal should meet the tempering at a certain temperature [4].

Thus, during the interrupted accelerated cooling when the structure gradient on the disk cross section is determined solely by the temperature of cooling termination [2.10], the further metal tempering due to the heating from the internal volumes heat is accompanied by the complex structural changes in the internal structure [4-6]. On this basis, further study of structural changes in the self-tempering process after the accelerated cooling to a certain temperature of cooling termination presents certain practical interest.

Purpose

The article aims to define the strength increase resource of the railway wheel disk.

Methodology

The material for research was carbon steel of railway wheel containing 0.57%C, 0.65%Si, 0.45%Mn, 0.0029%S, 0,014%P, 0,11%Cr. A railway wheel was heated to the temperatures above Ac_3 and was held at this temperature until the completion of austenite homogenization processes and then the disk was cooled at a growing rate to a certain temperature. A temperature interval of completion of the speed-up wheel disk cooling was 200-450 °C. Structure was studied with the use of research methods under electronic and light microscopes [2]. After accelerated cooling the estimation of metal structure imperfection degree was carried out with the use of X-ray structural analysis method. The stress and yielding limit of carbon steel were determined at tension, at a speed of deformation $10^{-3} s^{-1}$. The microhardness of steel structural components was estimated using the microhardness tester of PMT-3 type.

Findings

Research of the internal structure of heat hardened carbon steel from wheel disc confirmed qualitative correspondence with known experimental data [1, 4]. Metal structure near the surface of the railway wheel disk after rapid cooling to a certain temperature (the temperature of accelerated cooling termination) is to a great degree similar to the structure consisting of martensite tempering products at this temperature [8-10].

The Figure 1 shows the structure of carbon steel samples after accelerated cooling to the temperature 200 C. Analysis of the internal structure shows that one can observe the signs of rail martensite after cold tempering (Figure 1) in the metal volumes near the surface of the main heat removal when the temperature of accelerated cooling termi-

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nation is about 200 C. Similar to the martensite after tempering from the separate heating at the same temperature, thickness of the formed martensite rails was approximately in the range of 0.1 to 0.8 microns. On the edges of the separate rails and their stacks there are the fine carbide phase particles with dimensions of approximately 0.03-0.04 microns. As compared to the bright-field microstructure images, when because of the low dislocation density and specific contrast it is quite difficult to classify the carbide phase, one used the image analysis in a dark field. The images in the dark field, in the cementite reflexes the particles are sufficiently clear. In addition, it was possible to watch the separation of dispersed carbide particles on the dislocation lines in the middle of certain martensite rails and line form, with random orientation (Fig. 1).

Formation of the carbide phase is due to the development self-tempering process during the accelerated cooling.

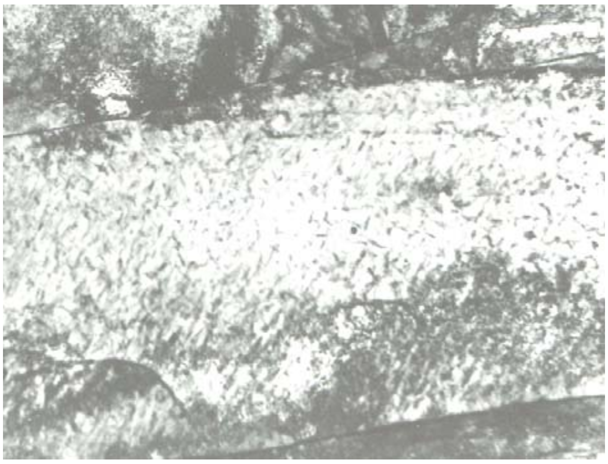

Fig. 1. The steel structure after accelerated cooling to 200 °C. Magnification is 18 000

With further increase of the distance from cooling surface, the metal after structures forming according to the sliding or intermediate mechanisms undergoes the tempering at higher temperatures. The above mentioned influence on the processes of structure formation is similar in nature to the increase of temperature of the accelerated cooling termination.

Fig. 2. The steel structure after accelerated cooling to 400 °C. Magnification is 18 000

The temperature increase of accelerated cooling termination to 400 °C is accompanied by the fully expected qualitative changes in the internal structure of metal (Fig. 2). In the carbon steel structure there are signs of initial stages of the processes similar to polygonization. They include the formation of focuses from the interwoven dislocations and the existence of the certain amount of broken contours from the dislocation groups. The simultaneous presence of cementite globules in the middle of microvolumes of metal with low dislocations density proves not only development, but also termination of polygonization during self-tempering of carbon steel after accelerated cooling. As a result of these processes the structure similar to the modulated one is forming. Some dislocation pits with certain dislocation density in the middle are separated by sufficiently broad walls of dislocations.

The formed dislocation cell structure in form is approaching the polyhedron. The middle part of the dislocation cells is foremost cleared of unbound dislocations. At the same time, there is a significant amount of cementite globules in the structure. Their size is significantly greater in comparison with the self-tempering temperature 200 C (Fig. 1). Moreover, in the heat process from the recessed metal layers after termination of accelerated cooling to 400 °C, it takes place a further carbon depletion of solid solution, increase of the average size of carbide particles and recombination of dislocations that reduces their density (Fig. 2).

Thus, after accelerated cooling termination, the higher distance from the surface of main heat removal the higher temperature of the metal self-tempering.

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In metal volumes, which are close to the middle of the wheel disc the microstructure is formed by force according to the diffusion mechanism.

Analysis of the internal structure of rapidly cooled metal shows that the structure consists of fine differentiated perlite with small amounts of structurally free ferrite spaced on the edges of perlitic colony.

The thickness of the cementite perlite plates is 0.02-0.04 microns and the layers of ferrite to 0.15 microns. Detailed studies revealed that the structurally free ferrite grains in turn consist of sub grains, the size of which varies in the range 1.5-3.5 microns. The metal volumes in the middle of sub grains have high density of interlocked dislocations and focuses with needlelike ferrite form. The existence of these structural components can be considered as the evidence of defined heterogeneity of cooling rate distribution over the disk cross section or it is connected to liquation of chemical elements in steel microvolumes [12].

Based on the results of the known studies [1, 2, 13], given structural state of carbon steel near the surface of the main heat removal consists of structural components that were formed as a result of martensite-bainitic transformation with self-tempering at temperatures of 200-300 $^\circ$C. The steel strength level with the above mentioned structures can vary in the range 1300-1200 MPa depending on the chemical elements concentration within the grade constitution.

Taking into account the continuous nature of the increase in temperature of accelerated cooling termination of metal layers depending on their distance from the surface of forced cooling, the strength level of carbon steel under study will certainly decrease. Herewith the metal structure in the above mentioned layers will consist of different correlation between the focuses of martensite-bainitic structures after self-tempering near the disc surface to ferrite-perlitic structures with different morphology of phase components in the middle.

Given that the strength of carbon steel with martensite structure is primarily determined by the degree of solid solution supersaturation, increase of self-tempering temperature will be accompanied by quite natural development of the processes of its decay. At the same time, as it was described above, the places of disengagement of carbon atoms from the solid solution on dislocations further become globules of carbide phase.

Thus, the development of self-tempering process from the temperature of the forced cooling termination actually determines the correlation between the two processes of steel strengthening: from the supersaturation of solid solution and dispersion strengthening from the carbide phase particles. On this basis, it is necessary to assess the correlation of these influencing factors depending on the self-tempering temperature on the strength characteristics of railway wheel carbon steel.

Analysis of ferrite component microhardness shows that in the process of accelerated cooling and holding at the temperatures forced cooling termination, starting from 200 $^\circ$C one can observe the continuous decrease of the carbon atoms concentration in the solid solution (Fig. 3).

At this, development of the steel softening processes with temperature increase of accelerated cooling termination is to a great extent caused by kinetics of carbon atoms redistribution between the crystal structure defects and the places in the crystalline lattice, defining its tetragonality. One can assess the change in degree of solid solution supersaturation by carbon atoms using the values of ferrite micro hardness (H_μ). According to angular coefficient of dependence $H_\mu = f(t)$, where t is the temperature of accelerated cooling termination for the temperature range 200-300 $^\circ$C, reduction in degree of solid solution carbon supersaturation is caused by high density of defects in the crystal structure and, firat of all, in the dislocations. One can certainly assume that starting from the temperature 350 $^\circ$C almost complete depletion of resource of disengagement of carbon atoms on dislocations is achieved. Confirmation of this statement is a slowdown in the decrease of H_μ value in the temperature range 350-400 $^\circ$C (Fig. 3) and a very small reduction in the width of the X-ray interference (110) (Fig. 4). Then, starting from the 350-400 $^\circ$C temperature we can observe a progressive decrease in the ferrite hardness.

As compared to lower temperature of accelerated cooling termination (200-300 $^\circ$C), the nature of metal softening is caused by the qualitatively different processes of structural transformations.

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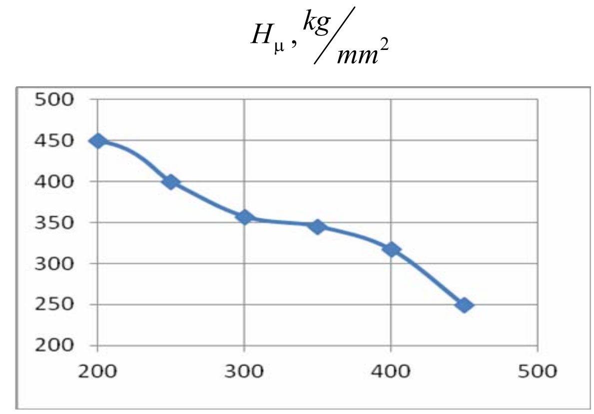
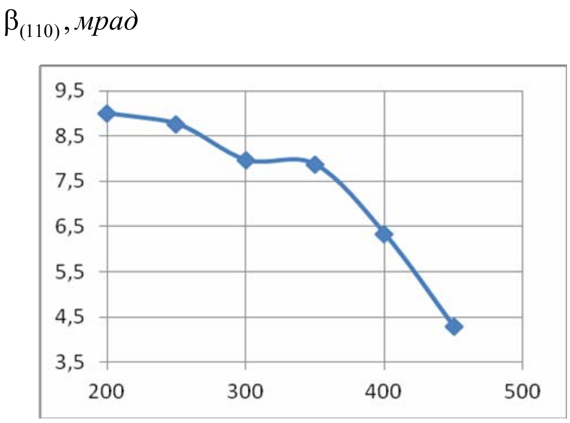


Self-tempering temperature, °C

Fig. 3. Dependence of ferrite microhardness on the self-tempering temperature of the carbon steel after accelerated cooling



Self-tempering temperature, °C

Fig. 4. Dependence of expansion of x-ray photography interference (110) of ferrite on the carbon steel after accelerated cooling

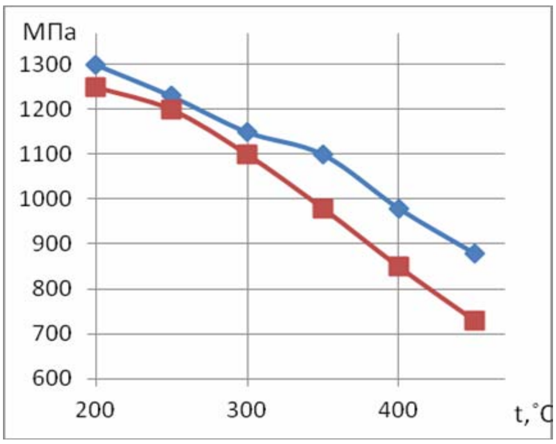
Indeed, as show the works [2, 3, 9], starting from the tempering temperature 350 °C carbon steels after martensite quenching already have a certain amount of fine particles of carbide phase. On this basis, the carbon depletion of solid solution will take place due to direct diffusion of carbon atoms from solid solution for carbide particles. This is to a great extent confirmed by the rapid decline in the expansion of X-ray interference (110) (Fig. 4). The correlation between these processes of structural transformations in rapidly cooled carbon steel is determined solely by the temperature of forced cooling termination and is confirmed by the strength change (Fig. 5).

The dependence nature analysis of the stress and yielding limits confirms the complex nature of structural transformations depending on the temperature of metal accelerated cooling termination. We can observe corresponding decrease in strength characteristics for the temperatures 200-300 °C, due to reducing in degree of solid solution supersaturation.

Almost equidistant run of dependency curves for σ_B and σ_T (Fig. 5) shows that the main influencing factor is the supersaturation degree of solid solution by carbon atoms in the process of accelerated cooling and the strengthening from the the development of strain hardening has much lesser influence. This is caused by the fact that the development of strain hardening processes is greatly exaggerated by the effect of metal softening due to the carbon depletion of solid solution (Fig.3, 4).

On the other hand, the process of carbon atoms release from the solid solution has dual effect on the strength properties of metal. Thus, the disengagement of carbon atoms from the octahedral sites of ferrite crystal lattice on the dislocations will further promote their strengthening [3, 9, 14]. According to the nature of influence on the hardness this process relates to the strengthening.

Reducing the carbon concentration in ferrite contributes to the appearance of additional quantities of cementite dispersed particles (Fig. 2). This should improve the strength properties due to the processes of dispersion strengthening.



Self-tempering temperature, °C

Fig. 5. Dependence of strength stress (♦) and yield limits (■) on the self-tempering temperature of carbon steel after accelerated cooling

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At the slight increase in tempering temperature or holding time under isothermal conditions, the development of carbide phase spheroidization process has the opposite effect. During formation of the more equilibrium cementite globules their number decreases. At the same time, the transition of carbon atoms from the solid solution to the carbide particles is accompanied by a decrease of internal pressures. This is proved by the increase in reflexes contrast on microdiffraction photos [2, 9] and reduction in expansion of X-ray interferences of the ferrite (Fig. 4).

When the tempering temperature increases to 400 °C the structural studies revealed early signs of dislocations redistribution and slight decrease in their density, which is associated with this (Fig. 2). Participatory development of these processes explains the permanent effect of carbon steel softening during increase of the termination of accelerated cooling temperature for carbon steel in the range 200-450 °C (Fig. 5).

According to the obtained results the complex nature of the influence of carbon steel structural transformations, depending on the temperature range of forced cooling termination was determined. The total effect of metal softening from the reducing in degree of solid solution supersaturation by carbon atoms, reducing the dislocation density and cementite particle coalescence exceeds the strengthening effect from the presence in the structure of fine carbide particles. At low temperatures (300 °C) of cooling termination, the main source of steel strengthening are the processes solid solution supersaturation by carbon atoms. The increase in temperature of accelerated cooling termination is accompanied by the indispensible increase in self-tempering effect from the metal volumes that are buried from the surface of cooling. The level of strength properties of carbon steel is determined by the compliant influence from the development of processes of dislocations interaction with the carbon atoms at the decay of solid solution and dispersion strengthening from the formation of additional particles of cementite.

Analysis of the dependence of carbon steel strength properties (Fig. 5) showed that in the manufacturing process of all-rolled railway wheels in order to improve the spalling resistance the disk can be subjected to accelerated cooling to the temperatures 300-350 °C without significant metal embrittlement.

Originality and practical value

1. The level of strength characteristics of railway wheel carbon steel from the temperature of the forced cooling termination is defined by the influence correlation from the solid solution supersaturation and dispersion strengthening of carbide phase.
2. For the temperatures of accelerated cooling termination 200-300 °C the reduction in degree of solid solution supersaturation is the key factor in determining the strength characteristics level.

During manufacture of all-rolled railway wheel one can increase the strength limit of the metal disk by the accelerated cooling to the medium temperature range.

Conclusions

1. Under conditions of carbon steel accelerated cooling the processes of mobile dislocations blocking due to the carbon atoms release and the dispersion strengthening from the formed particles of carbide phase are the sources of strengthening.
2. At the temperatures of forced cooling termination above 300-350 °C the rate of decrease in strength properties is determined by the excess of total softening effect from the breakdown of solid solution, spheroidization aped-up and the cementite particles coalescence over the dislocation blocking by carbon atoms and dispersion strengthening.

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ВПЛИВ ТЕМПЕРАТУРИ САМОВІДПУСКА НА МІЦНІСТЬ ДИСКА ЗАЛІЗНИЧНОГО КОЛЕСА ПІСЛЯ ПРИСКОРЕНОГО ОХОЛОДЖЕННЯ

Мета. Робота спрямована на визначення ресурсу підвищення міцності диску залізничного колеса. **Методика.** Матеріалом для дослідження була вуглецева сталь залізничного колеса зі змістом 0,57 % C, 0,65 % Si, 0,45 % Mn, 0,0029 % S, 0,014 % P, 0,11 % Cr. Залізничне колесо піддавали нагріву до температур вище Ac_3, витримували при цій температурі для завершення процесу гомогенізації аустеніту та прискорено охолоджували диск до визначеної температури. Температурний інтервал закінчення примусового охолодження диску колеса складав значення 200–450 $^\circ$C. Структуру вивчали за методиками досліджень із вико-

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ристанням електронного та світлового мікроскопів. Оцінку ступеня дефектності структури металу після прискореного охолодження здійснювали з використанням методики рентгенівського структурного аналізу. Межі міцності та плинності вуглецевої сталі визначали при розтяганні зі швидкістю деформації $10^{-3}c^{-1}$. Мікротвердість структурних складових сталі оцінювали, використовуючи мікротвердомір типу ПМТ-3. **Результати.** Комплекс властивостей вуглецевої сталі залізничного колеса в залежності від температури припинення прискореного охолодження визначається співвідношенням розвитку процесів пом'якшення та зміцнення. Джерелами ефекту зміцнення є процеси блокування рухомих дислокацій за рахунок виділення на них атомів вуглецю та дисперсійного зміцнення від сформованих частинок карбідної фази. При температурах припинення примусового охолодження вуглецевої сталі вище за 300–350 $^{\circ}$C темп зниження властивостей міцності визначається перевищенням сумарного ефекту (пом'якшення від розпаду твердого розчину, прискорення сфероїдизації та коалесценції частинок цементиту) над блокуванням дислокацій атомами вуглецю та дисперсійним зміцненням. **Наукова новина.** Авторами доведено, що рівень характеристик міцності вуглецевої сталі залізничного колеса від температури закінчення примусового охолодження визначається співвідношенням впливів від пересичення твердого розчину та дисперсійного зміцнення від карбідної фази. Для температур припинення прискореного охолодження 200–300 $^{\circ}$C зниження ступеню пересичення твердого розчину є основним чинником, що визначає рівень характеристик міцності. **Практична значимість.** При виготовленні суцільнокатаного залізничного колеса підвищити межу міцності металу диску можна прискореним охолодженням до середнього інтервалу температур, що успішно доведено в роботі.

Ключові слова: дислокації; температура самовідпуску; прискорене охолодження; диск залізничного колеса

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ВЛИЯНИЕ ТЕМПЕРАТУРЫ САМООТПУСКА НА ПРОЧНОСТЬ ДИСКА ЖЕЛЕЗНОДОРОЖНОГО КОЛЕСА ПОСЛЕ УСКОРЕННОГО ОХЛАЖДЕНИЯ

Цель. Работа направлена на **о**ценку ресурса повышения прочности диска железнодорожного колеса. **Методика.** Материалом для исследования была углеродистая сталь железнодорожного колеса с содержанием 0,57 % C, 0,65 % Si, 0,45 % Mn, 0,0029 % S, 0,014 % P, 0,11 % Cr. Железнодорожное колесо нагревали до температур выше Ac_3, выдерживали при этой температуре для завершения процессов гомогенизации аустенита и ускоренно охлаждали диск до определенной температуры. Температурный интервал окончания принудительного охлаждения диска колеса составлял 200–450 $^{\circ}$C. Структуру изучали с использованием методик исследований под электронным и световым микроскопами. Оценку степени дефектности структуры металла после ускоренного охлаждения осуществляли с использованием методики рентгеновского

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структурного анализа. Пределы прочности и текучести углеродистой стали определяли при растяжении, со скоростью деформации $10^{-3} c^{-1}$. Микротвердость структурных составляющих стали оценивали, используя микротвердомер типа ПМТ-3. **Результаты.** Комплекс свойств углеродистой стали железнодорожного колеса в зависимости от температуры прекращения ускоренного охлаждения определяется соотношением развития процессов разупрочнения и упрочнения. Эффект упрочнения основан на блокировке подвижных дислокаций за счет выделения на них атомов углерода и дисперсионного упрочнения от сформированных частиц карбидной фазы. При температурах прекращения принудительного охлаждения углеродистой стали выше 300–350 $^{\circ}$ С темп снижения прочностных свойств определяется превышением суммарного эффекта (разупрочнения от распада твердого раствора, ускорения сфероидизации и коалесценции частиц цементита) над блокировкой дислокаций атомами углерода и дисперсионным упрочнением. **Научная новизна.** Авторами доказано, что уровень характеристик прочности углеродистой стали железнодорожного колесав от температуры окончания принудительного охлаждения определяется соотношением влияния степени пресыщения твердого раствора и дисперсионным упрочнением от карбидной фазы. Для температур прекращения ускоренного охлаждения 200–300 $^{\circ}$ С снижение степени пресыщения твердого раствора является основным фактором, который определяет уровень характеристик прочности. **Практическая значимость.** При изготовлении цельнокатаного железнодорожного колеса повысить предел прочности металла диска можно ускоренным охлаждением до среднего интервала температур, что успешно доказано в работе.

Ключевые слова: дислокации; температура самоотпуска; ускоренное охлаждение; диск железнодорожного колеса

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