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STRENGTH PROPERTIES OF CARBON STEEL OF RAILWAY WHEEL AFTER THE SPEED-UP COOLING

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МІЦНІСНІ ВЛАСТИВОСТІ ВУГЛЕЦЕВОЇ СТАЛІ ЗАЛІЗНИЧНОГО КОЛЕСА ПІСЛЯ ПРИСКОРЕНОГО ОХОЛОДЖЕННЯ

Purpose. The work is directed at elaboration of softening effect of carbon steel of a railway wheel after the speed-up cooling to the different temperatures.

Methodology. Material for the research was carbon steel of a disk railway wheel with content of 0.57 % C, 0.65 % Si, 0.45 % Mn, 0.0029 % S, 0.014 % P, 0.11 % Cr. Specimens as plates 3 mm thick were exposed to heating up to the temperatures higher than Ac_3, the subsequent speed-up cooling was halted after achieving certain temperatures (200–450 °C). A structure was studied with the use of electronic and light microscopes. The estimation of degree of the structure defect after the speed-up cooling was carried out with the use of method of *x*-ray analysis. The strength and yield stresses of carbon steel were determined under tension. Speed of deformation at mechanical tests was 10^{-3} s^{-1}. The microhardness of structural constituents of steel was estimated using the apparatus a PMT-3 type.

Findings. The research results of the structural state and properties of carbon steel of a railway wheel are presented depending on the temperature of self-tempering after the irregular cooling. Within the investigated temperature interval of self-tempering, permanent soften character of carbon steel with growth of the temperature of completion of the forced cooling of wheel is conditioned by the correlation of qualitatively different processes structural transformations.

Originality. The net effect of softening the metal by reducing the degree of supersaturation of solid solution, reducing the dislocation density and coalescence of cementite particles exceeds the strengthening due to the presence of fine carbide particles in the structure.

Practical value. According to studies it is determined that in order to increase fracture toughness, the disc-rolled railway wheel can be subjected to accelerated cooling to temperatures of 300–350 °C without substantial metal embrittlement.

Keywords: *structure, carbon steel, railway wheels drive, temperature, self-tempering*

Introduction. In modern conditions of steady increase in the intensity of industrial development, the safety problems of railway transport operation are of particular relevance. One of the directions to increase the operational safety of rolling stock is the use of metallic materials with high level of properties for the production of support elements. The use of thermal and thermomechanical treatments for manufacturing the high strength rolled metal has become widespread over the last few decades.

A complex form of section of the railway wheel elements and their considerable thickness have restrained the application of thermal hardening to achieve the high strength condition in carbon steels for a long time. While in operation, the railway wheel disk undergoes a complicated total load. On this basis, the development of proposals to improve the strength characteristics of the railway wheel disk is an important scientific and technical challenge.

Compared with other wheel elements, the disk has the smallest thickness. Taking into account the sufficiently high stability of austenitic phase in the carbon steel of the railway wheel, one can expect to achieve the cooling rates of critical values during accelerated cooling in the metal volumes near the surface of heat-removal.

Problem solution. During the thermal hardening of the solid wheel disk the formation of structure gradient from the surface of heat-removal is accompanied by certain change in the complex of properties [1]. The article represents a change in structural component morphology and the corresponding complex of properties that is achieved. Investigation of processes of structural transformations using the technology of intermittent hardening determined that a significant influence while achieving the level of properties is caused by the development of self-tempering processes [2]. The work shows that the processes of structural transformations after the termination of accelerated cooling are caused by heating from the heat of metal volumes that are distant from the cooling surface. Taking into account the continuous nature of change in the cooling rate of the wheel disk depending on the distance of the intense heat-removal surface, the structural condition of the metal corresponds to the tempering at a certain temperature [3].

During the intermittent hardening, when the structure gradient on the disk section depends on the temperature of accelerated cooling termination, the further metal tempering by heating from the heat of internal volumes is accompanied by complex structural changes in the internal structure [1–3]. The results of the research show the qualitative agreement with the structures of systemic research of thermally hardened carbon steels [4]. Thus, the additional study of structural changes in the process of self-tempering after accelerated cooling to a certain temperature is of some interest concerning the clarification of the nature of a softening effect of the carbon steel and determining the resource of increase in wheel disc strength without metal embrittlement.

Objectives. The work is aimed to clarify the nature of a softening effect of the railway wheel carbon steel after accelerated cooling to different temperatures.

Material and methodology of the research. The material for the research was the carbon steel of the railway wheel with the content of 0.57 % C, 0.65 % Si, 0.45 % Mn, 0.0029 % S, 0.014 % P, and 0.11 % Cr. The railway wheel was subjected to heating to the temperatures above Ac_3, holding at that temperature for completion of the austenite homogenization process and accelerated cooling of the disk to the specified temperature. Temperature range of the accelerated cooling termination for the wheel disc was 200–450 °C.

The samples for the research in the form of plates 3 mm thick were cut off from the wheel disk. The structure was studied using electron and light microscopes [4]. The work quite efficiently states the methodology of studies using an electron microscope. Evaluation of the degree of the defective structure of metal after accelerated cooling was performed using the methodology of X-ray structural analysis [5]. The given work represents the results of the research concerning the determination of parameters of a fine crystalline structure of carbon steels with structures which are formed by sliding and intermediate mechanisms. The strength ($\sigma_в$) and yield (σ_T) limits of carbon steel were determined during stretching. The deformation rate during mechanical testing was 10^{-3} sec^{-1}. Microhardness of steel structural components was evaluated using microhardness tester of PMT-3type.

Explanation of scientific results. The conducted research of the internal structure of thermally hardened carbon steel of the wheel disc confirmed the qualitative agreement with the known experimental data [1–3]. The metal structure near the surface of the wheel disk after accelerated cooling to a certain temperature (the temperature of accelerated cooling termination) was to a large extent similar to the structure consisting of martensite tempering products at this temperature [1].

Fig. 1 shows the structure of carbon steel samples after accelerated cooling to the temperature of 200 °C. The analysis of the internal structure shows that in the metal volumes near the surface of the main heat removal one can observe the existence of signs of lath martensite after low-temperature tempering when the temperature of accelerated cooling termination is about 200 °C (Fig. 1, *a*). Indeed, making a comparative analysis of martensite tempering from another heating at the same temperature, one can find a lot in common. The thickness of the formed martensite lathes observed in the foil plane had the value in the range of approximately from 0.1 to 0.8 microns. With the certain difficulties on the edges of separate lathes and their stacks, the location of fine particles of carbide phase with the dimensions of approximately 0.3–0.04 microns was found. As compared to the bright-field microstructure images, when due to the high dislocation density and specific contrast it is quite diffi-

a

b

Fig. 1. The structure of the investigated steel after accelerated cooling to 200 °C with signs of martensite lath (a) and small carbide particles randomly oriented dashed shape (b). Zooming of 18,000

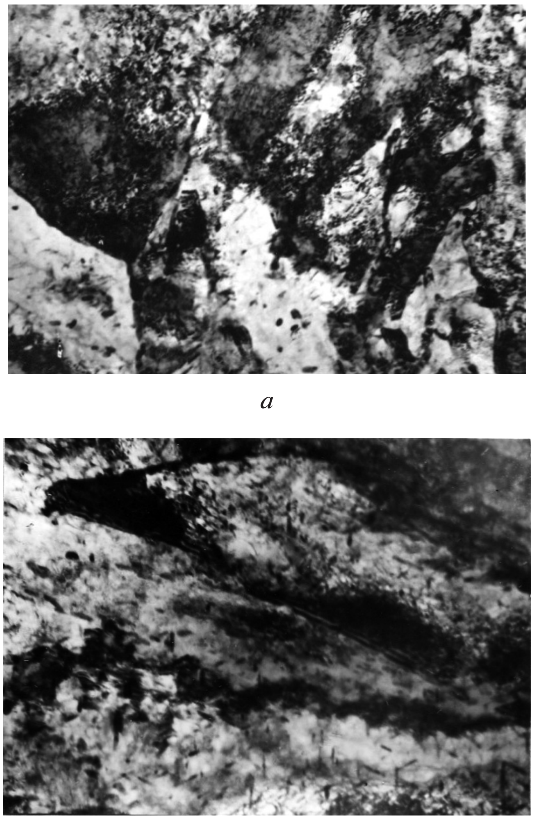
cult to classify the carbide phase, the image analysis in a dark field was used. In the images in the dark field, the particles were detected distinctively in the cementite reflexes. This made it possible to observe the selection of a number of highly dispersed carbide particles on the dislocation lines in the middle of separate martensite lathes.

One can observe that most of the broad lathes have small dashed disengagement of cementite with random orientation (Fig. 1, *b*). These carbide particles were formed by virtue of the self-tempering process during accelerated cooling of the metal.

As the distance from the cooling surface increases, the metal with the structures formed by sliding or intermediate mechanisms undergoes tempering at higher temperatures. The above mentioned influence on the processes of structure formation is similar in its nature to the increase in temperature of accelerated cooling termination. Taking into account the fact that there are no qualitative changes in the metal structure, the differences in the steel strength level can only be caused by increase in thickness of the martensite lathes. As compared to the metal volumes that were subjected to the low-temperature tempering (to 200 °C), increase in temperature of accelerated cooling termination only by 50–100 °C can lead to increase in the thickness of the martensite lathes up to 3–4 times.

Fig. 2 shows the metal structure when the temperature in carbon steel volumes corresponds to the cooling termination at the level of about 400 °C. Under these conditions, in carbon steel there are signs of initial stages of processes similar to polygonization. Examples include the formation of groups of dislocations which are very similar to the dislocation modulated structure. Separate dislocation pits, with certain dislocation density in the middle are separated by sufficiently broad walls of dislocations that are interlaced. The structure also includes a certain amount of broken contours of dislocation groups. The simultaneous presence of cementite globules in the middle of metal microvolumes with low dislocation density proves not only development, but also the termination of polygonization during self-tempering of carbon steel after accelerated cooling. The formed dislocation cell structure in form is approaching to polyhedron, with thinner subboundaries (Fig. 2). The body of dislocation cells is largely cleared from unbound dislocations.

There is a significant quantity of cementite globules in the volumes of ferrite structural elements. Their average size is significantly greater in comparison with the self-tempering temperature of 200 °C (Fig. 1, *a*).



a

b

Fig. 2. The structure of the investigated steel after accelerated cooling to 400 °C with signs of dislocation pit substructure (a) and recombination of dislocations (b). Zooming of 18,000

Moreover, in the process of heating from the buried metal layers after termination of accelerated cooling to 400 °C, further carbon depletion of solid solution occurs as well as increase in the average size of carbide particles. As compared to the cooling termination temperature of 200 °C, at the temperature of 400 °C recombination of dislocations and, consequently, reduction of their density is observed (Fig. 2, *b*).

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

In metal volumes, which are close to the middle of the wheel disc, the microstructure is formed by force according to the diffusion mechanism. The 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 plates in perlite is 0.02–0.04 microns and the thickness of ferrite layers is up to 0.15 microns.

Detailed studies revealed that the structurally free ferrite grains in their turn consist of sub grains, the size of which varies in the range of 1.5–3.5 microns. At this, the metal volumes in the middle of sub grains have high density of interlocked dislocations. Moreover, except the polyhedral form of ferritic grains in separate microvolumes, the formation of Widmanstatten ferrite can be observed. 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 with the liquation of chemical elements in the steel microvolumes.

Based on the results of the known studies [2, 4, 5], the 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 °C.

The steel strength level with the above mentioned structures can vary in the range of 1300–1200 MPa depending on the chemical elements concentration within the grade composition.

Taking into account the continuous nature of the increase in the 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 a martensite structure is primarily determined by the degree of solid solution supersaturation, increase in 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 carbon atoms disengaging from the solid solution on dislocations further become the globules of carbide phase.

Thus, the development of self-tempering process from the temperature of the forced cooling termination actually determines the correlation between 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.

The analysis of ferrite component microhardness shows that in the process of accelerated cooling and holding at the temperatures of forced cooling termination starting from 200 °C, one can observe the continuous decrease in the carbon atoms concentration in the solid solution (Fig. 3, *a*). At this, the development of the steel softening processes with temperature increase of accelerated cooling termination is to a great extent caused by kinetics of carbon atoms redistribu-

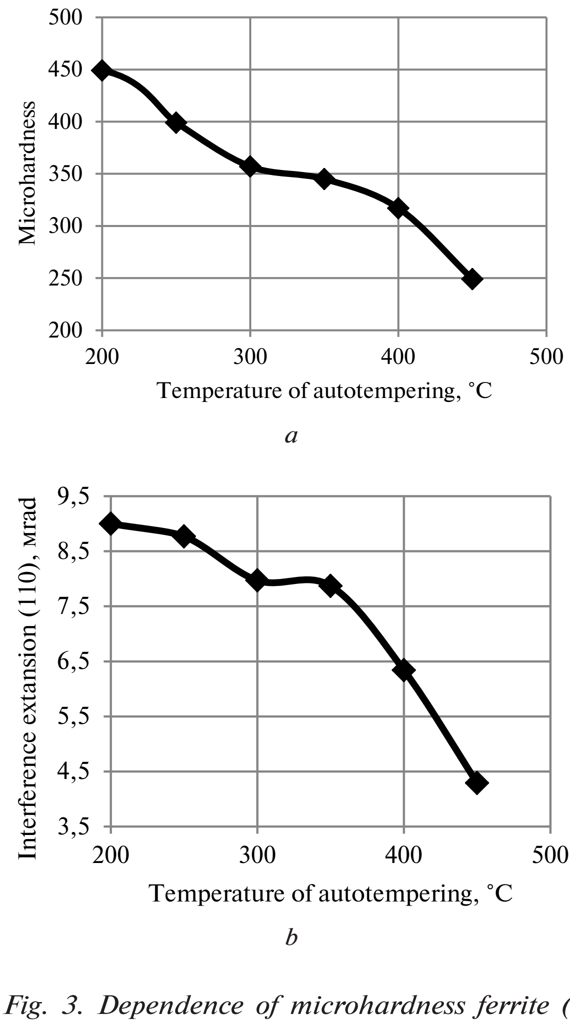


Fig. 3. Dependence of microhardness ferrite (a) and X-ray interference extension (110) ferrite (b) on the self-tempering temperature of rapidly cooled carbon steel

tion between the crystal structure defects and the places in the crystalline lattice, defining its tetragonality. One can assess the change in the 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 of 200–300 °C, the defined reduction in degree of solid solution carbon supersaturation is caused by high density of defects in the crystal structure and, first of all, in the dislocations. Moreover, one can certainly assume that starting from the temperature of 350 °C almost complete depletion of resource of disengagement of carbon atoms on dislocations is achieved. A confirmation for this statement can be a certain slowdown in the decrease of H_μ value in the temperature range of 350–400 °C (Fig. 3, *a*) and a very small reduction in the width of the X-ray interference (110) (Fig. 3, *b*).

Then, starting from the temperatures of 350–400 °C a progressive decrease in the ferrite hardness is observed. As compared to the lower temperature of accelerated cooling termination (200–300 °C), the nature of metal softening is caused by the qualitatively different processes of structural transformations.

Indeed, as it is shown in the works [4–6], starting from the tempering temperature of 350 °C carbon steels already have a certain amount of fine carbide phase particles after martensite quenching. On this basis, the carbon depletion of solid solution will occur due to direct diffusion of carbon atoms from solid solution for carbide particles. To a great extent confirmed this is by the rapid decline in the expansion of X-ray interference (110) (Fig. 3, *b*).

The correlation between these basic 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. 4).

Analyzing the type of dependence of the stress and yielding limits confirms the complex nature of structural transformations depending on the temperature of metal accelerated cooling termination. It can be observed the corresponding decrease in strength characteristics for the temperatures 200–300 °C, due to reduction in degree of solid solution supersaturation.

Almost equidistant run of dependency curves for $\sigma_в$ and σ_T (Fig. 4, 5) shows that the main influencing factor should be considered the degree of supersaturation of the solid solution by carbon atoms in the process of accelerated cooling while the strengthening from the development of strain hardening has much less influence. This is caused by the fact that the development of strain hardening processes is greatly exceeded by the effect of metal softening due to the carbon depletion of the solid solution (Fig. 3, *a, b*).

On the other hand, the process of carbon atoms disengaging from the solid solution has dual effect on the strength properties of metal [5]. Thus, the disengagement of carbon atoms from the octahedral sites of ferrite crystal lattice on the dislocations will further promote their strengthening [6]. The work [6] determined a change mechanism for the complex of properties after accelerated cooling and tempering at certain temperatures using a large experimental material. According to the nature of influence on the hardness this process relates to the strengthening. Decrease in carbon concentration in ferrite contributes to the appearance of additional quantities of cementite dispersed particles (Fig. 2, *b*). This should improve the strength properties due to the processes of dispersion strengthening.

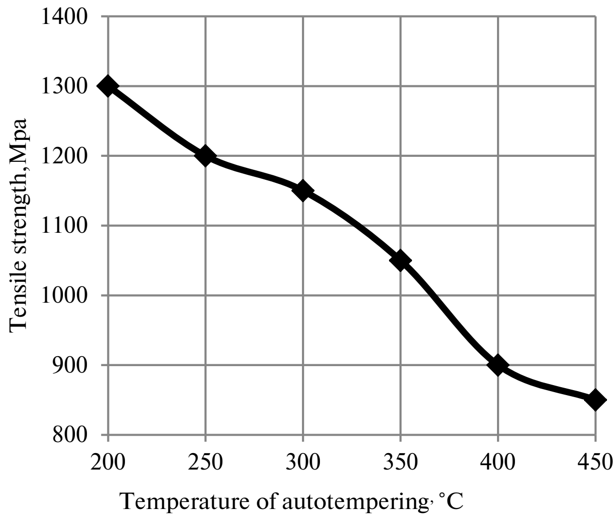


Fig. 4. The dependence of the strength limit on the temperature of self-tempering rapidly cooling carbon steel

With the slight increase in tempering temperature or holding time under isothermal conditions, the development of carbide phase spheroidization process has the opposite effect. When forming the cementite particles with more equal axes the decrease in their number occurs. At the same time, the transition of carbon atoms from the solid solution to the carbide particles is accompanied by a decrease in internal pressures. This is proved by the increase in reflex contrast on microdiffraction photos [4, 5] and reduction in expansion of X-ray interferences of the ferrite (Fig. 3, *b*).

When the tempering temperature increases to 400 °C the structural studies reveal early signs of dislocations redistribution and slight decrease in their density, which is associated with this (Fig. 2). Combined development of these processes explains the permanent effect of carbon steel softening during increase in the temperature of accelerated cooling termination for carbon steel in the range of 200–450 °C (Fig. 4).

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 supersaturation of the solid solution with carbon atoms, reducing the dislocation density and cementite particle coalescence exceeds the strengthening effect from the presence of fine carbide particles in the structure.

At low temperatures (up to 300 °C) of cooling termination, the main source of steel strengthening is the supersaturation of the solid solution with carbon atoms. The increase in temperature of accelerated cooling termination is accompanied by the indispensible increase in self-tempering effect for the metal volumes that are buried from the cooling surface. 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.

The analysis of dependence of carbon steel strength properties (Fig. 4, 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.

Conclusions.

1. A complex of properties of carbon steel railway wheels depending on the temperature of accelerated cooling termination is determined by correlating the development of softening and strengthening processes.

2. Sources of the strengthening effect include processes of blocking mobile dislocations due to the allocation of carbon atoms and dispersion strengthening particles formed from carbide phase to them.

3. The rate of decrease in strength properties at temperatures of suspension of forced cooling of carbon steel above 300–350 °C is determined by excess of cumulative effect mitigation of solid solution collapse, accelerating spheroidization and coalescence of cementite particles of carbon atoms blocking dislocation and dispersion strengthening.

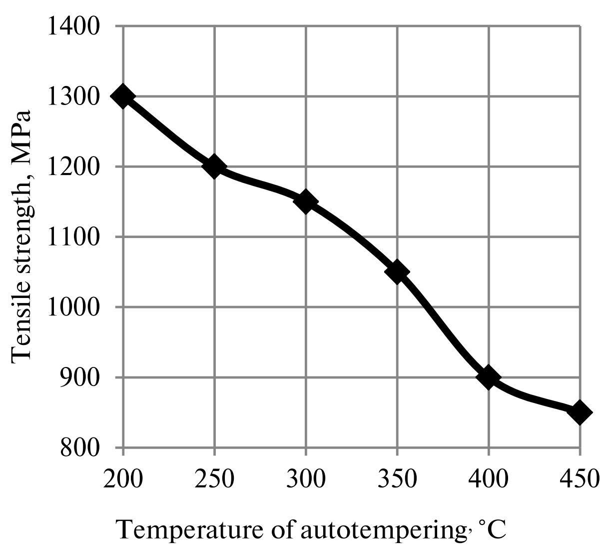


Fig. 5. The dependence of the limit temperature fluidity self-tempering rapidly cooling carbon steel

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Мета. Вивчення природи ефекту пом'якшення вуглецевої сталі залізничного колеса після прискореного охолодження до різних температур.

Методика. Матеріалом для дослідження була вуглецева сталь диску залізничного колеса із змістом 0,57 % C, 0,65 % Si, 0,45 % Mn, 0,0029 % S, 0,014 % P, 0,11% Cr. Зразки у вигляді пластин товщиною 3 мм піддавали нагріву до температур вище Ac_3, подальше прискорене охолодження припиняли після досягнення визначеної температури (200–450 °C). Структуру вивчали з вико-

ристанням електронного та світлового мікроскопів. Оцінку ступеня дефектності структури після прискореного охолодження здійснювали з використанням методики рентгенівського структурного аналізу. Межі міцності й плинності вуглецевої сталі визначали при розтяганні. Швидкість деформації при механічних випробуваннях складала 10^{-3} $с^{-1}$. Мікротвердість структурних складових сталі оцінювали, використовуючи мікротвердомір типу ПМТ-3.

Результати. Наведені результати дослідження структурного стану та комплексу властивостей вуглецевої сталі залізничного колеса в залежності від температури самовідпуску після переривчастого охолодження. У досліджуваному інтервалі температур самовідпуску, перманентний характер пом'якшення вуглецевої сталі при збільшенні температури закінчення примусового охолодження колеса обумовлений співвідношенням якісно різних процесів структурних перетворень.

Наукова новизна. Сумарний ефект пом'якшення металу від зниження ступеня пересичення твердого розчину, зменшення щільності дислокацій і коалесценції цементитних частинок перевищує рівень зміцнення від присутності у структурі дрібнодисперсних карбідних часток.

Практична значимість. Визначено, що, з метою підвищення тріщиностійкості, диск суцільнокатаного залізничного колеса можна піддавати прискореному охолодженню до температур 300–350 °C без суттєвого окрихнення металу.

Ключові слова: *структура, вуглецева сталь, диск залізничного колеса, температура, самовідпуск*

Цель. Определение природы эффекта разупрочнения углеродистой стали железнодорожного колеса после ускоренного охлаждения до разных температур.

Методика. Материалом для исследования была углеродистая сталь диска железнодорожного колеса с содержанием 0,57 % C, 0,65 % Si, 0,45 % Mn, 0,0029 % S, 0,014 % P, 0,11 % Cr. Образцы в виде пластин толщиной 3 мм подвергали нагреву до температур выше Ac_3, дальнейшее ускоренное охлаждение прекращали после достижения определенной температуры (200–450 °C). Структуру изучали с использованием электронного и светового микроскопов. Оценку степени дефектности структуры после ускоренного охлаждения осуществляли с использованием методики рентгеновского структурного анализа. Пределы прочности и текучести углеродистой стали определяли при растяжении. Скорость деформации при механических испытаниях составляла 10^{-3} $с^{-1}$. Микротвердость структурных составляющих стали оценивали, используя микротвердомер типа ПМТ-3.

Результаты. Приведены результаты исследования структурного состояния и прочностных свойств углеродистой стали железнодорожного колеса в зависимости от температуры самоотпуска после прерывистого охлаждения. В исследуемом интервале температур самоотпуска, перманентный характер разупрочнения углеродистой стали с ростом температуры окончания принудительного охлаждения колеса обусловлен соотношением развития качественно разных процессов структурных превращений.

Научная новизна. Суммарный эффект разупрочнения металла от снижения степени пресыщения твердого раствора, уменьшения плотности дислокаций и коалесценции цементитных частиц превышает уровень упрочнения от присутствия в структуре мелкодисперсных карбидных частиц.

Практическая значимость. Определено, что, с целью повышения трещиностойкости, диск цельнокатанного железнодорожного колеса можно подвергать ускоренному охлаждению до температур 300–350 °C без существенного охрупчивания металла.

Ключевые слова: *структура, углеродистая сталь, диск железнодорожного колеса, температура, самоотпуск*

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