# СТРУКТУРОУТВОРЕННЯ. ОПІР РУЙНУВАННЮ ТА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ

# STRUCTURE FORMATION. RESISTANCE TO DESTRUCTION AND PHYSICAL-MECHANICAL PROPERTIES

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# STRUCTURAL CHANGES DURING THERMAL STRENGTHENING OF THE RAILWAY WHEEL

***Purpose.*** *Justification of mechanism of the structure transformations in the carbon steel of the railway wheel during disk thermal strengthening.*

***Research methods.*** *The material for the study was carbon steel of a railway wheel with a 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 heated to temperatures higher than $Ac_3$, kept at this temperature to complete austenite homogenization process, and disk was rapidly cooled to the specified temperature. Degree defectiveness structure of the metal after accelerated cooling was assessed using technique of X-ray structural analysis. Strength stress, yield stress and relative elongation of the carbon steel were determined at stretching at rate of deformation $10^{-3}$ $s^{-1}$.*

***Results.*** *At accelerated cooling of the carbon steel, the sources of strengthening are the processes of blocking mobile dislocations due to the condensation of carbon atoms on them and dispersion strengthening from the formed particles of the carbide phase. At temperatures of termination of forced cooling of carbon steel above 300…350 °C, the reduction rate of strength properties is determined by the excess of total effect of softening from decomposition of the solid solution, acceleration of spheroidization and coalescence of cementite particles over the blocking of dislocations by carbon atoms and dispersion hardening.*

***Scientific novelty.*** *The level of strength and plasticity characteristics of carbon steel of the railway wheel disc, depending on the temperature end forced cooling, is determined by the ratio of the influence of degree super saturation of the solid solution and the dispersion strengthening by carbide phase.*

***Practical value.*** *For temperatures termination of accelerated cooling of 200…300 °C, degree of super saturation of the solid solution is the main factor that determines the level of strength and plasticity characteristics. When manufacturing an all-rolled railway wheel, the strength limit of the disc metal can be increased by accelerated cooling to the middle range of temperature.*

***Key words:*** *carbon steel, accelerated cooling, tempering, hardening, softening.*

## Introduction

The complex cross-sectional shape of the elements of railway wheel and their considerable thickness have for a long time restrained the use of thermal strengthening in order to achieve a high-strength state in them. During operation of the railway wheel, the disc is subjected to sufficiently complex total loads. Based on this, the development of proposals for increasing strength characteristics of the railway wheel disc is an important scientific and technical task. Compared to other elements of the wheel, the disk has smallest thickness. Taking into account the sufficiently high stability of the austenite phase at carbon steel of the railway wheel, in process of accelerated cooling in the volumes of metal close to the surface of the main heat sink,


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one can hope to achieve cooling rates close to the critic value.

### Analysis of research and publication

During the thermal strengthening of railway wheels, emergence of a gradient of structures from the surface of accelerated cooling is accompanied by a corresponding change in the complex of properties [1, 2]. According to the technology of intermittent accelerated cooling, the level of rolled properties is primarily determined by the development of metal tempering processes from the heat of deeper internal volumes [3, 4]. The continuous nature change in the cooling rate at different distances from the surface of the heat sink determines that the structural state of the metal is largely similar to tempering at the corresponding temperature of individual heating of the steel after quenching [5–7]. Based on this, the temperature gradient along a section of the element railway wheel will correspond to the defined structural state and level of hardness [4, 7].

Taking into account the total contribution components of the microstructure to the overall level of strength characteristics, the final level of the properties will be determined by heating from deeper layers, with a higher temperature. Achieving the required level of strength and hardness in the specified element of the railway wheel will be determined to a greater extent by the temperature at end of accelerated cooling of the surface.

Moreover, the complex shape of the wheel and different cross-sectional thickness of the elements are a limitation to application of accelerated cooling to the temperatures of the beginning of phase and structural transformations by a non-diffusion mechanism [5]. Taking into account the proportional increase stability of austenite with the concentration of carbon, the steels used for manufacture of railway wheels have an increased stability of austenite [8]. As a result of accelerated cooling, one should expect to achieve cooling rates close to the critical value in the volumes of metal near the surface of the main heat sink [6, 10].

Considering that, the disk of a railway wheel, to have smallest cross-sectional thickness compared to other elements, is subjected to very complex total loads [4, 5, 12]. The formation of a defined structural state and related level of strength of carbon steel of the disc should be considered as one of the critical elements that determines service life of the railway wheel as a whole [4, 7, 13].

### Purpose

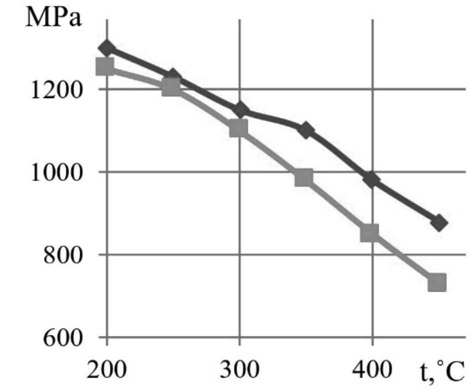
Justification mechanism for the structure transformations in the carbon steel of the railway wheel during disk thermal strengthening.

### Research material and methodology

The material for the study was carbon steel of a railway wheel with a 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 heated to temperatures higher than $Ac_3$, kept at this temperature to complete austenite homogenization process, and disk was rapidly cooled to the specified temperature. The temperature interval at the end of forced cooling of the wheel disc was 200…500 °C. The structure was studied using electron and light microscopes. Degree defectiveness structure of the metal after accelerated cooling was assessed using technique of X-ray structural analysis. Strength stress, yield stress and relative elongation of the carbon steel were determined at stretching at rate of deformation $10^{-3}$ $s^{-1}$. Microhardness phases steel was evaluated using a type PMT-3 microhardness tester.

### Results and their discussion

The effect temperature end of the accelerate cooling the wheel surface on the yield stress and stress strength, relative elongation and microhardness of the carbon steel, is shown in Fig. 1. The analysis of dependence property of the strength indicates a sufficiently complex nature of structure transformations, depending on the temperature of the termination of accelerated cooling. According to known experimental data [1, 3, 6], at the temperatures of intensive cooling up to 300 °C, acceleration process release of carbon atoms from the solid solution is observed.

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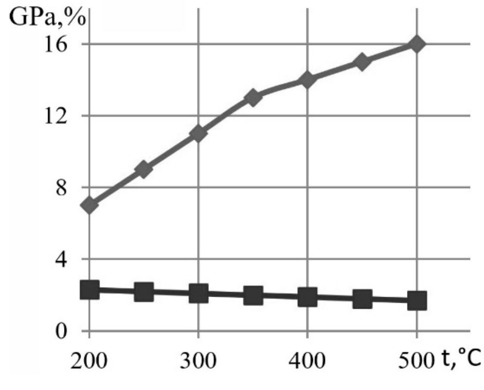


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**Figure 1.** Effect of temperature end of forced cooling on yield stress (■) and strength (♦) – (a); relative elongation (♦) and microhardness (■) – (b) of the carbon steel

Based on this, a change of degradation degree of solid solution is a major factor that determines the level of characteristics of carbon steel strength. A comparative analysis of dependence of yield stress, strength, relative elongation and microhardness ferrite (Fig. 1) on the temperature end


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of accelerated cooling confirms the existence of a well-known correlation between the properties in micro volumes of metal and common strength of the railway wheel. Based on this, it can be considered with a great probability that one of the main factors that determines nature of the dependence degree of thermal strengthening metal of the railway wheel on the temperature end of intensive cooling should be level of super saturation of the solid solution with atoms of the carbon [9, 11].

On other hand, taking into account sufficiently large cross-sections of the metal, for example, at rim of a railway wheel, where it is not possible to achieve a critical cooling rate, the formation of carbide phase will be an indispensable component in obtaining the final structure. Based on this, the presence of cementite particles of different dispersion in the steel structure indicates the need to take into account contribution of processes of dispersion hardening in achieving a certain level strength of properties.

Thus, the intermediate release of the carbon atoms from austenite at process of accelerated cooling of carbon steel will be accompanied by a decrease in strength characteristics compared to formation of the martensite. According by influence on strength, the process of carbon release from solid solution during thermal hardening of steel can actually be divided into two components with the opposite character of influence. Thus, in proportion to reducing the degree of tetragonality of the crystalline lattice of ferrite is happening strength characteristics decrease of the steel [9, 11].

At the same time, the formation of the cloud by carbon atoms around dislocation line will lead to braking the movement of dislocations, up to their full blocking [3, 6]. On the other hand, particles formation of the carbide phase of different dispersion by nature of influence on strength is similar to the hardening with given thickness a disk of the railway wheel, it acquires a certain scientific and practical interest to analyse nature of transformed structure and achieving appropriate level of strength characteristics after reaching a certain temperature of cessation of accelerated cooling. At the same time, thickness of the wheel disc is sufficient to approach, at least in volumes close to the surface, the critical cooling rate during thermal hardening.

Detailed analysis of structure of the wheel steel sample after quenching to martensite (Fig. 2) determined existence areas of lath martensite with a high density of dislocations. This confirms possibility of development of the austenite transformation by shear mechanism. The width rails of martensite at range of 0.6…0.8 microns. In individual martensite crystals, simultaneously with thin plates of twining martensite (designation *1*, Fig. 2), discovered presence of very dispersed particles of the carbide phase (designation *2*). According to [3, 8], the presence of a carbide phase at steel structure after quenching indicates on breakdown of the martensite phase at elevated temperatures of austenite transformation.

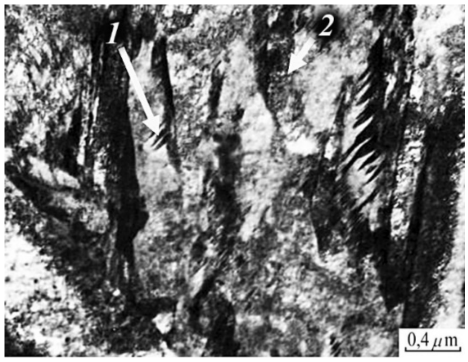


**Figure 2.** Structure of railway wheel steel after hardening to martensite (1 – twins of martensite, 2 – dispersed carbide particles)

On this basis of, already during quenching, development of decomposition processes of martensite indicate development of a complicated influence on the strength properties of steel. The final result consists of the ratio at development of the softening process due to a decrease at degree of tetragonality of the martensite crystal lattice and dispersion hardening due to the presence of a carbide phase in the steel structure. Considering separately effect of cementite particles on the hardening effect, it should be taken into account that in addition to the formed carbide particles during quenching, effect of particles formed during tempering is added.

A comparative analysis of formed structure of the carbon steel after quenching on martensite with one formed as a result of accelerated cooling of the wheel disc indicates existence of a certain coincidence. At the same time, as the temperature of accelerated cooling increases, significant discrepancies should be expected. Structure analysis of the metal layers near surface of the intensive heat sink during cooling of the wheel disc indicates existence of signs of lath martensite when the temperature at end of the accelerated cooling is 200 °C (Fig. 3).

Thickness of the formed laths is almost the same as after separate tempering of martensite at a temperature of 200 °C [2] and is in range of 0.1…0.8 microns. On the borders of individual laths and packages, finely dispersed particles of the carbide phase with sizes of approximately 0.03…0.04 μm are located (Fig. 3*a*). In a larger number of wide laths, very small allocations of cementite particles with random orientation can be observed. The formation of these carbide particles occurs due to release from the heat of the deeper volumes of metal, after termination of the accelerated cooling. With further deepening from the surface of the wheel disk, in addition to the fact that metal undergoes cooling at a lower rate, the final structure is also formed due to the influence of tempering at higher temperatures. At temperature of end of the accelerated cooling up to 200 °C, there are no qualitative changes at structure of the steel. The difference of strength characteristics will be determined to a greater extent by super saturation of the solid solution, and to a lesser extent depend on the allocation of dispersed carbide particles.


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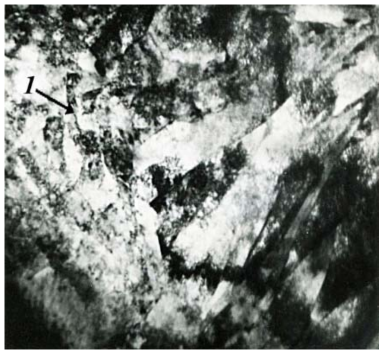
**Figure 3.** Structure carbon steel of a disk wheel after completion of accelerates cooling at a temperature of 200 °C. Magnification is 19000

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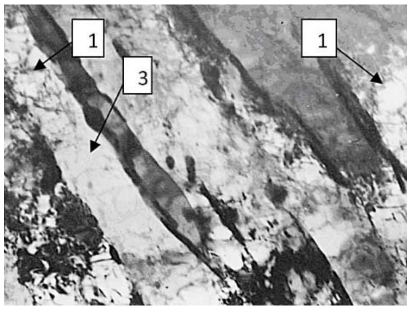


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**Figure 4.** Structure carbon steel of the disk a railway wheel after completion accelerated cooling at a temperature of 300 °C (*a*), 400 °C (*b*). Magnification is 19000

In comparison with volumes of metal, the structure of which is formed at temperatures of 200 °C, a temperature increase of only 50…100 °C has a certain effect on the strength and plasticity of the carbon steel (Fig. 1). An increase in the temperature at the end of forced cooling to 300 °C (Fig. 4) indicates a qualitative change of steel structure.

The development of dislocation recombination processes within individual micro volumes of the metal leads to emergence of a dislocation structure similar to a cell structure. This violates the general orientation (marked by arrow *1*, Fig. 4*a*), which is inherent in the lath structure of ferrite (Fig. 3). Compared to 200 °C, an increase at temperature of ended intensive cooling should have a certain effect on the growth process of the martensite phase. Indeed, when steel is cooled to a temperature of 300 °C, a partial change at shape of martensite crystals is observed. As a result, relatively small cells (Fig. 4*a*) and oriented at a certain angle to the lath ferrite formed at a temperature of 200 °C appear. In terms of shape, dislocation cells approach a polyhedron (designation *1*, Fig. 4*a*).

The body of the cells themselves has already been largely cleared of unconnected dislocations. At the same time, in individual volumes of metal, one can observe the existence of cementite particles, which differ in size from those formed at a lower temperature at end of accelerated cooling. Further increase at temperature of termination of accelerated cooling of the wheel disk is accompanied by qualitative changes at structure of carbon steel. Fig. 4*b* shows microstructure of the metal layers, which corresponds to the temperature at which forced cooling ends at 400 °C.

A detailed analysis of the structure discovers the signs of the initial stages of processes similar to polygonization. This is confirmed by the existence contours of groups dislocations with partially broken boundaries (marked by arrow *1*, Fig. 4*b*) in ferrite cells, which in shape resemble previously formed bainite crystals. Moreover, the location of dispersed cementite particles in volumes with a low dislocations density (arrow *2*, Fig. 4*b*) should be considered as confirmation of development, and in some places and completion of polygonalization after stopping accelerated cooling of steel. At the result of that, a formed structure is a similar to modular, when individual dislocation cells, with a determined density of dislocations in the middle, are distinguished from a wide enough walls out of dislocations.

Further development of recombination of dislocations, against background of a decrease in their total number, leads to appearance of a dislocation cellular structure, which in the form is already approaching polyhedron (Fig. 4*b*). Body of dislocation cells itself is largely cleared of unbound, chaotically arranged dislocations. Although there are still volumes with an increased dislocations density, the movement of which is blocked by presence of very dispersed carbide particles. Thus, the greater the distance of the volume of metal from the surface of the intensive heat sink, the higher the temperature at which transformation of the austenite proceeds. An increase at disk cooling temperature to 500 °C is accompanied by a further increase at size of cementite particles and a transformation of the dislocation structure.

Analysis of the structure (Fig. 5) shows the presence, as at 400 °C, of closed and broken dislocation contours. In


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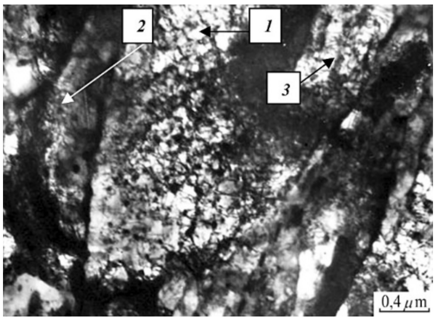
addition, there are other features at structure of the metal, in comparison with the lower temperature of completion of accelerated cooling.

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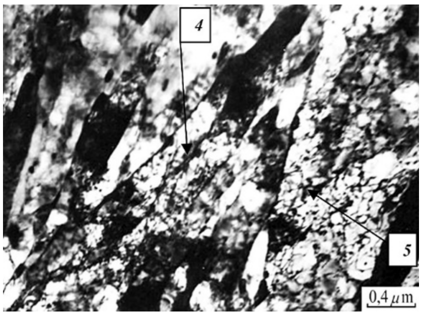


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**Figure 5.** Structure at steel of the railway wheel disc after accelerated cooling to a temperature of 500 °C

Qualitative changes include the appearance of large areas consisting of subgrains with practically the same length of axes (Fig. 5, *a*, designation *1*) and ferrite layers with a reduced density of dislocations around dispersed cementite particles (arrow designation *1*, Fig. 5*a*). Along with this, the structure still has a certain number of micro volumes in which formation of sub-boundaries is just beginning (Fig. 5*a*, designation *2*). Based on this, the polygonization process should be considered practically complete in a sufficiently significant part of the metal. Moreover, as a result of the sequential development of structural transformations during accelerated cooling to a temperature of 500 °C and heating from a deeper hot layers, a structure is formed, which to a large extent resembles a modular one. Indeed, according to external signs, the formed micro volumes of metal have a certain alternation, similar to modular structures. A fairly significant part of the structure is separate dislocation cells with a certain density of dislocations in the middle (designation *2*, Fig. 5, *a*), which are separated from each other by walls of interconnected dislocation groups (designation 3, Fig. 5*a* and designation *4*, Fig. 5*b*).

It should be taken into account occurrence of an additional strengthening effect from the appearance particles of the carbide phase as a result of heating the metal after termination forced cooling of the steel. Along with this, simultaneously with the appearance of dispersed particles during tempering, the processes of spheroidization and coalescence of cementite particles formed during cooling at lower temperatures acquire certain acceleration [3].

Based on this, reducing the number particles of the carbide phase, which made it difficult to move both individual dislocations and their groups at lower cooling termination temperatures will contribute to reducing the resistance process of transforming sub-boundaries into boundaries with large disorientation angles. As a result separation of the specified boundaries from the blocking points (carbide phase), processes of cleaning certain volumes of the ferrite matrix from dislocation groups will gain further acceleration (designation *5*, Fig. 5*b*). As a result, there are sufficiently large volumes of metal with practically no sub-boundaries, with evenly spaced particles of the carbide phase in the middle.

According to the structures (Fig. 4–5), it is possible to determine location of the particles mainly on the sub-boundaries during tempering and in the internal volumes, during formation of martensite crystals, although they have almost the same diameter. This is due to the cyclical change stages growth and dissolution of carbide particles depending on their location. The growth of particles occurs when they are located along grain boundaries and dissolve at middle of the grain [3]. The nature of changes of microhardness of ferrite and the width of the X-ray interference line (110) (Fig. 6) indicate a continuous decrease at concentration of carbon atoms in the solid solution, starting from the cooling temperature of 200 °C.

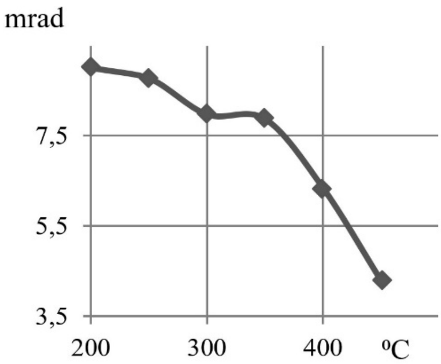


**Figure 6.** Variation broadening (110) X-ray interference of ferrite depending on temperature termination accelerated cooling of the wheel disc

The strength of steel (Fig. 1) depending from temperature of the finish of accelerated cooling will be determined by the compensation from preservation of a certain amount of blocked dislocations, continuous softening of steel from decrease degree of super saturation of solid solution. Already from temperatures 300…350 °C, a significant exit of carbon atoms from a solid solution and their deposition on the dislocations is one of main factor preservation their amount.

As a result, the decrease in $H\mu$ will slow down (Fig. 1*b*), as evidenced by the violation of the monotonic course of the curve (Fig. 6). The received explanation is confirmed by a certain amount of experimental data. Thus, according to [2, 4, 6], starting from the separate heating temperature of 350 °C in carbon steels after quenching to martensite, there is already a certain amount of finely dispersed particles of the carbide phase.


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Based on this, the depletion of the solid solution of carbon will occur due to the directed diffusion of carbon atoms from the supersaturated solid solution to the carbide particles, which is confirmed by the accelerated decrease in the broadening of X-ray interference (110) (Fig. 6).

## Conclusions

1. The level of strength and plasticity characteristics of carbon steel of the railway wheel disc, depending on the temperature end forced cooling, is determined by the ratio degree super saturation of the solid solution and the dispersion strengthening by carbide phase.
2. When manufacturing all-rolled railway wheel, the strength of the disc metal can be increased by accelerated cooling to the middle temperature range
3. Under conditions of accelerated cooling of the carbon steel, the sources of strengthening are the processes of blocking mobile dislocations due to the condensation of carbon atoms on them and dispersion strengthening from the formed particles of the carbide phase.
4. At temperatures of termination of forced cooling of carbon steel above 350 °C, the rate reduction of strength properties is determined by the excess total effect of softening from decomposition of the solid solution, acceleration of spheroidization and coalescence of cementite particles over the blocking of dislocations by carbon atoms and dispersion hardening.

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# СТРУКТУРНІ ПЕРЕТВОРЕННЯ ПРИ ТЕРМІЧНОМУ ЗМІЦНЕННІ ДИСКУ ЗАЛІЗНИЧНОГО КОЛЕСА

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***Мета роботи****. Обґрунтування механізму структурних перетворень при термічному зміцненні диску залізничного колеса.*

***Методи дослідження****. Матеріалом для дослідження була вуглецева сталь залізничного колеса зі вмістом 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. Оцінку ступеня дефектності структури металу після прискореного охолодження здійснювали з використанням методики рентгенівського структурного аналізу. Границі міцності, плинності і відносне видовження вуглецевої сталі визначали при розтяганні зі швидкістю деформації $10^{-3}$ с$^{-1}$.*

***Отримані результати****. За умов прискореного охолодження вуглецевої сталі, джерелами зміцнення є процеси блокування рухомих дислокацій за рахунок виділення на них атомів вуглецю і дисперсійного зміцнення від сформованих частинок карбідної фази. При температурах припинення примусового охолодження вуглецевої сталі вище за 300...350 °C, темп зниження властивостей міцності визначається перевищенням сумарного ефекту пом'якшення від розпаду твердого розчину, прискорення сфероїдизації і коалесценції частинок цементиту над блокуванням дислокацій атомами вуглецю і дисперсійним зміцненням.*

***Наукова новизна****. Рівень характеристик міцності і пластичності вуглецевої сталі диску залізничного колеса в залежності від температури закінчення примусового охолодження визначається співвідношенням впливу від пересичення твердого розчину і дисперсійного зміцнення від карбідної фази.*

***Практична цінність****. Для температур припинення прискореного охолодження 200...300 °C, зниження ступеню пересичення твердого розчину є основним чинником, що визначає рівень характеристик міцності і пластичності. При виготовленні суцільнокатаного залізничного колеса підвищити границю міцності металу диску можна прискореним охолодженням до середнього інтервалу температур.*

***Ключові слова:*** *вуглецева сталь, прискорене охолодження, відпуск, зміцнення, пом'якшення.*

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