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INFLUENCE HOT PLASTIC DEFORMATION ON THE STRUCTURE AND PROPERTIES OF CARBON STEEL OF THE RAILWAY WHEEL

Summary. The study is devoted to the explanation of the influence of hot plastic deformation on the properties of railway wheels. The shape of individual elements of the wheel provides for a different degree of hot compression, which determines the mechanism for the development of the recrystallization at austenite. With a decrease in the degree of the hot deformation, a certain proportion of grains with a low energy of linear stretching are formed in austenite. As a result, of the low mobility of such boundaries, the likelihood of preservation of part of the substructural state of the austenite increases, which should affect the formation of a colony of perlite during the cooling of the carbon steel. Against background preservation and a dependence of strength properties on the dispersion of the pearlite colony, the appearance in austenite of grain boundaries with a low energy of linear tension leads to a qualitative change in the plastic properties of railway wheel steel. The increase in plasticity of carbon steel with an increase in dispersion

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of the pearlite colony is due to a decrease in the effect of solid solution hardening and an increase in the role of the ferrite-cementite interface in the development processes of strain hardening carbon steel. The results obtained can be useful for improving the technology of manufacturing all-rolled railway wheels.

Keywords: railway wheel, carbon steel, mechanical properties, hot deformation, boundary, austenite

1. INTRODUCTION

During the operation of railway transport, the arising static and dynamic stresses at the area of the wheel-rail contact surface are accompanied by irreversible changes in the internal structure of the metal. As a result of the gradual accumulation of damage to the tread surface, their localization leads to the destruction of the center metal of the railway wheel. Moreover, in modern conditions of a progressive increase in intensity of loading of the transport, primarily an increase in load on the wheelset, there is a sharp decrease in the term of operation of the wheels. One of the ways to improve the operational reliability of the railway transport is to increase the crack resistance of the wheel metal by increasing the strength and fatigue characteristics of the metal [4, 16, 19]. Despite the fact that the set properties of the all-rolled railway wheel are determined by the final heat treatment [11, 12], the structural changes during the hot plastic deformation can have a certain effect on the properties of steel. In general, at the manufacture of the railway wheels and tires, depending on the conditions of the hot plastic deformation, simultaneously with strengthening or after a certain pause, processes are developed in the carbon steels aimed at reducing the resistance of the deformation. When the effect of softening exceeds the increase in strength from the hot deformation, conditions of dynamic softening are achieved. The formation of carbon steel's structure and its intricate properties, subsequent to deformation, are virtually identical to the annealed state. On the other hand, at a certain ratio of temperature-speed parameters of the hot reduction, a partial preservation strain hardening effect of the austenite can be used to control the properties of the hot-rolled carbon steels [6]. From the analysis of the influence of structural components on the development of the strengthening and softening processes, either the dominance of a separate phase, its morphology, or the total result for a multiphase system, taking into account the additive influence of the phase components [17], is revealed. Thus, in the case of hot deformation of the carbon steels, in addition to resistance to strain propagation from the presence of the austenite boundaries and subboundaries, it is necessary to take into account additional effects from the solid solution strengthening [17]. As a result, after the completion of hot plastic deformation of the carbon steel, one should expect a certain influence of the structural state of the austenite on the development of the pearlite transformation in comparison with the transformation after annealing. Taking into account that even with thermal hardening of the wheel rim, austenite transformation occurs according to the diffusion mechanism, the influence degree of the hot deformation on the change in internal structure of the austenite should be considered as one of the components by the technology of manufacturing railway wheels.

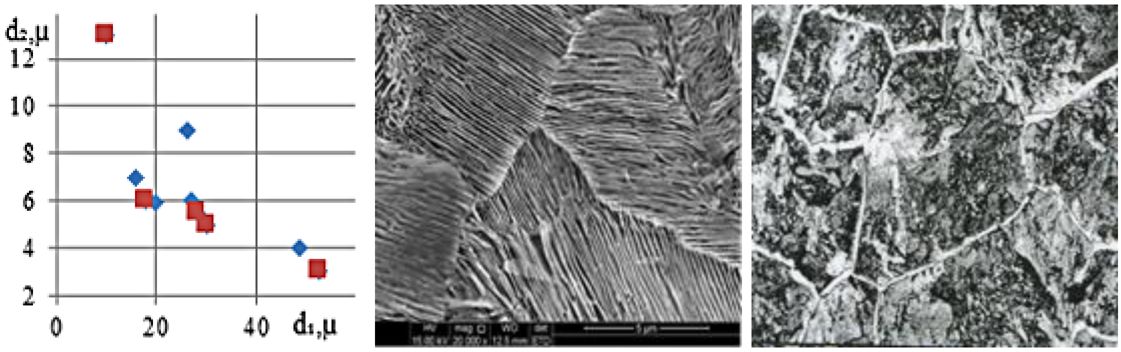
The aim of the work is to evaluate the effect of the structural state of the austenite after hot plastic deformation on the properties of carbon steel of the railway wheel rim is.

2. MATERIAL AND RESEARCH METHODS

The material for research was the carbon steel of the rim railway wheel, with a carbon content of 0.59 %. Other chemical elements met the requirements of regulatory documentation for railway wheels. Heating workpieces for samples to the temperature of hot deformation (1240 °C) was carried out in electric furnaces, preventing oxidation and decarburization of the metal surface. The workpieces were deformed by 20, 40 and 60 %, at a strain rate of about 10-2 s-1. After completion of hot deformation, the workpieces were cooled in air. The structure of the metal was studied under light and electron microscopes. The grain sizes of austenite (d1), pearlite colony (d2) and thickness of the ferrite layer of the pearlite colony (λ) were determined using quantitative metallographic techniques [22]. The yield stress (σy) and strengths (σs), relative elongation (δ) and narrowing (ψ), strain hardening coefficient (n) were determined from the analysis tensile diagrams of the samples at room temperature and a strain rate of 10-3 s-1.

3. RESULTS AND DISCUSSION

The process of manufacturing all-rolled railway wheels is carried out not under conditions of continuous reduction of the workpiece, but in several successive stages separated by a certain technological pause. As a result, at the beginning development of the pearlite reaction, the state of austenite after completion formation of the wheel rim will be depended by total effect on the development processes on structure formation in dynamic and static conditions. This is confirmed by the existence of a certain correlation between the grain sizes of austenite and pearlite colony after cooling of the carbon steel (Fig. 1a). In the case of an unchanged structural state of the austenite, it is rather difficult to explain the existence of the presented relationship.

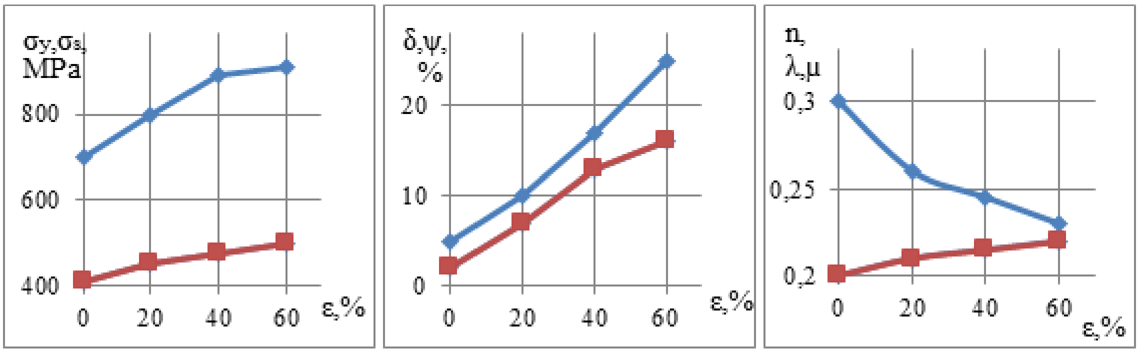


a *b* *c*

Fig. 1. Mutual change the d_1 and d_2 for steels with a carbon content of 0.54 (♦) and 0.56% C (■) [2] – (a). Structures: pearlite colony after annealing – (b) [14] and after 40 % hot deformation of the steel with 0.59 % C – (c). Magnification is 150

However, in a more detailed analysis, even at a constant temperature and hot strain rate, a different ratio between degree of deformation and duration of the pause before the onset of pearlite transformation should lead to qualitative differences in the structural state of the austenite. So, at degrees of deformation greater than the critical value, development of the recrystallization will occur according to the mechanism movement boundaries of the austenite grains with large disorientation angles [7]. As a result, d1 will decrease proportionally to the degree of hot deformation. A characteristic feature of the formed structural state is not only the complete replacement of the crystal-geometric characteristics of the austenite but also the purification of the internal volumes of the grains from dislocations. In the case of insufficient thermodynamic stimulus for the development of recrystallization according to the indicated mechanism (when the degree of deformation is close to the critical value), a certain part of the austenite structure will be formed due to the recombination of dislocation. In this case, part of the dislocations that reach the boundaries of austenite grains with large disorientation angles will be annihilated, and the other part will participate in the formation of additional interfaces inside the austenite grains. These boundaries should have not only a lower self-energy, but also a more complex structure (similar to subboundaries).

The appearance of additional boundaries inside austenite grains should be considered one of the factors that can influence the size of a pearlite colony. While dispersion of the pearlite will depend, to a greater extent, on a rate of transformation of the austenite during cooling [1, 9]. The given position is confirmed by the structure formed after hot reduction. Compared to the regular structure of the pearlite colony during cooling of the steel after annealing (Fig. 1b), transformation of the austenite immediately after completion of the hot deformation leads to the formation of a certain proportion of pearlite with a violation of the regular structure (Fig. 1c). It should be assumed that, compared with the pearlite reaction in steel after annealing, these differences in the structure of the pearlite colony after hot deformation should inevitably lead to a qualitative change in the properties. Judging only by the change in strength properties (Fig. 2a), the nature of the dependence on the degree of hot deformation is quite justified.



a *b* *c*

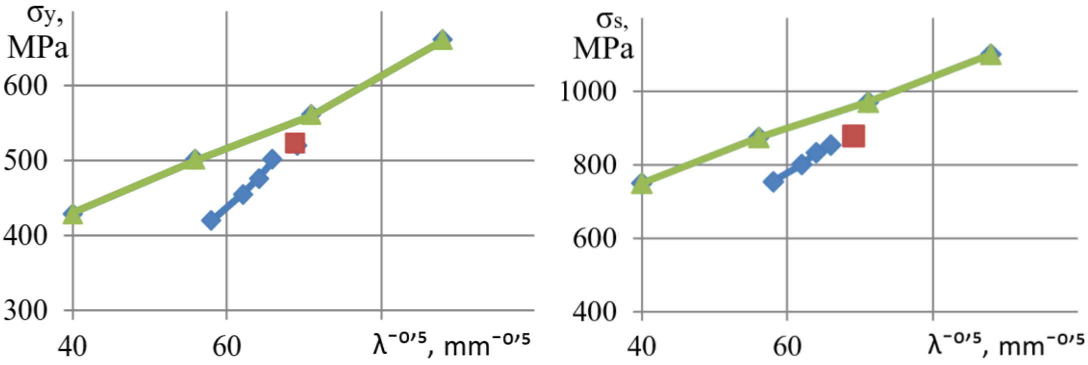
Fig. 2. Influence degree of the hot plastic deformation: (a) on σ_y (■) and σ_s (♦), (b) on δ (■) and ψ (♦), (c) on n (■) and λ (♦) carbon steel

However, the simultaneous increase in plasticity indices (Fig. 2b) indicates a different nature of the influence compared to the pearlite reaction in steel after annealing. It should be assumed that one of the reasons for the observed dependence of steel ductility is a certain inheritance of the pearlite structural state of the austenite after hot plastic deformation. The nature dependence λ and coefficient of the strain hardening on the degree of the hot deformation (Fig. 2c) are additional confirmations of the given position. Taking into account that for carbon steels with pearlite structures, the relation $n \sim f(1/\delta_1)$ is satisfied, where δ_1 is the maximum draw during drawing. For steel after hot deformation, a different relation is fulfilled: $n \sim f(\delta, \psi)$, which indicates the possibility of the existence of an additional component to d_1 that influences the properties of the steel. This factor can be partially preserved in elements of the deformed austenite substructure. With an increase in the degree of the hot deformation, the intensity of the development processes of the strain hardening, in addition to the refinement grain of the austenite, should contribute to a decrease in the stability of the austenite at the beginning of pearlite transformation. As a result, under all equal conditions, one should expect a certain effect on the kinetics of pearlite transformation, which is confirmed by the nature dependence of λ on ε (Fig. 2c). For a more detailed analysis of the nature of the influence dispersed by the pearlite colony on the strength properties of hot-rolled steel, a Hall-Petch type relationship was used [1]:

$$\sigma_y, \sigma_s = \sigma_i + k_y \cdot \lambda^{-0,5} \tag{1}$$

where σ_i and k_y are constants.

For dependence σ_y, the value σ_i is called a friction stress of the crystal lattice [1], the yield stress of a single crystal [17], etc. The value k_y is a measure of resistance of the interfacial boundary of a pearlite colony to the propagation of the deformation [1]. Regarding the absolute values of the angular coefficient in relation (1), for dependence on the ferrite grain size of the low-carbon steel and for a complete pearlite structure, there is no consensus. If, according to the data of [17], there is a coincidence of the values k_y for dependence at grain size of the ferrite and λ of the pearlite colony, then in [1], their difference is noted. In general, the construction of the dependence of σ_y and σ_s on λ steels (Fig. 3) indicates the fulfilment of relation (1). On the other hand, in a detailed analysis of the curves, differences found in the values of σ_i and k_y can be associated with the structural state of the austenite before the onset by pearlite transformation. So, for steel after isothermal transformation of the austenite [5], dependence by σ_y from $\lambda^{-0,5}$, mm$^{-0,5}$ (curve ▲) k_y is 2.4 N/mm$^{3/2}$, and for dependence σ_s 3.75 N/mm$^{3/2}$. The observed differences in the values of k_y are due to the development of strain hardening processes in the ferrite gaps of the pearlite colony during metal deformation from the yield strength to the ultimate strength [14]. For hot-rolled steel, the value of k_y reaches higher values. To dependence σ_y,~$f(\lambda^{-0,5})$ k_y is 7.3 N/mm$^{3/2}$, and for dependence σ_s, it increases to 10 N/mm$^{3/2}$.

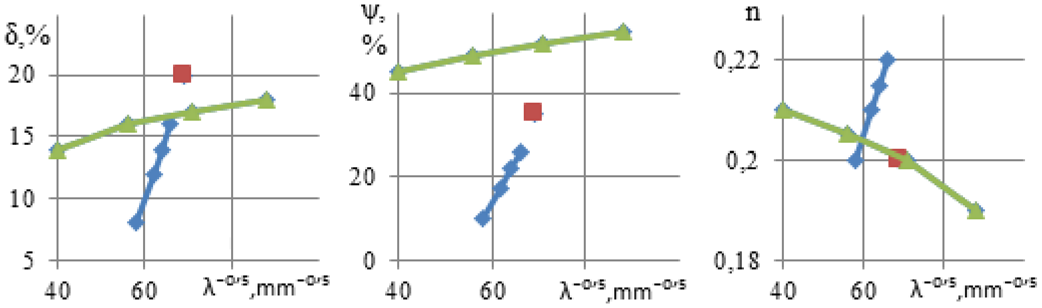


a *b*

Fig. 3. Influence λ on σ_y (a) and σ_s (b) of carbon steel of a railway wheel after manufacturing (■) [2], steel with 0.58 % *C* after isothermal transformation of the austenite at temperatures 550-625 °C of annealed steel (▲) [5] and after hot plastic deformation (♦)

As a result, for steel after hot plastic deformation, the value of k_y exceeds the corresponding values for steel after isothermal transformation of austenite by about three times. At the same time, in absolute values, it approaches the values k_y for low-carbon steels.

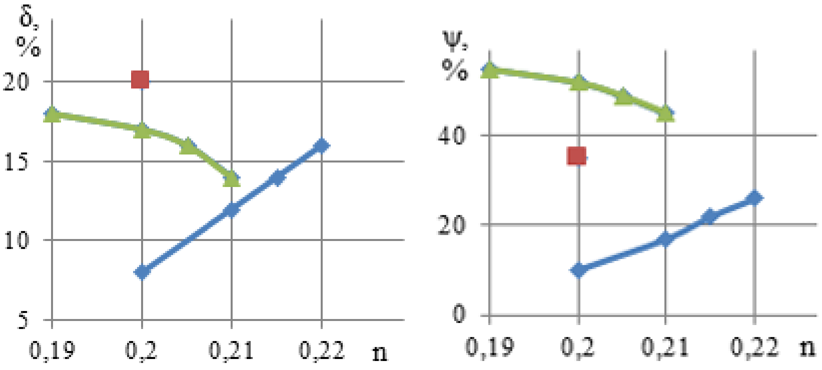
Another characteristic (σ_i) also indicates qualitative differences in the structural state of austenite and their probable inheritance during the formation of a pearlite colony. Moreover, values of the strength characteristics of the carbon steel of the railway wheel, which, after hot plastic deformation and thermal hardening of the rim (designation ■), fit quite well on the dependence for hot plastic deformation (curve ♦, Fig. 3). As a result of extrapolation of the curve (♦) up to intersection with the ordinate axis, the obtained values of σ_i are close to the friction stress of the ferrite crystal lattice after annealing of the low-carbon steel [1, 17]. In carbon steel after isothermal transformation, as a result of differences in the degree of super cooling of the austenite during the formation of a pearlite colony, ferrite can have a certain degree of the super saturation with carbon atoms. Based on this, the value of σ_i, quite justifiably, should exceed the similar characteristic of the hot-deformed state, reaching values at the level of 200…230 MPa (Fig. 3a). Therefore, increasing the friction stress of the ferrite crystal lattice should be considered one of the ways to increase the strength properties of the steel. Like the yield and strength limits, the plasticity characteristics and strain hardening exponent also illustrate a certain dependence on λ (Fig. 4). The observed dependence characteristics of the plasticity on the dispersion of the pearlite colony of carbon steel qualitatively coincide with the known experimental data [1, 17], according to which a decrease in λ contributes to an increase in plasticity of the metal. On the other hand, the nature dependence n on dispersion of the pearlite colony (Fig. 4c) indicates qualitative differences in the development of strain hardening processes, which is confirmed by the dependencies δ, ψ on n (Fig. 5). As for most steels with pearlite structures, including after isothermal transformation of the austenite, the relations $(\delta, \psi) \sim f(1/n)$ [13], (curve ▲, Fig. 5) are observed. For steel after hot plastic deformation, the dependence changes its sign to the opposite one: $(\delta, \psi) \sim f(n)$ (curve ♦, Fig. 5).



a *b* *c*

Fig. 4. Influence of λ on δ (*a*), ψ (*b*) and n (*c*) carbon steel of a railway wheel after manufacturing (■) [2], steel with 0.58 % *C* after isothermal transformation of austenite at temperatures of 550…625 °C (▲) [5] and after hot plastic deformation (♦)

The values for the steel of a railway wheel do not fit into any curve at all (point ■). The observed differences in nature of the dependencies δ, ψ vs. n can be associated with structural features of austenite before pearlite reaction, and for railway wheel steel, the effect of thermal hardening of the rim is also added. A detailed analysis of the austenite structure will be used to explain the observed differences in strain hardening capacity of carbon steels with a pearlite structure. First of all, this is an assessment of the dihedral angles and boundary shapes of the austenite grains. Compared to austenite after annealing, when the grains of a convex shape are separated by straight boundaries with predominantly triple junctions [6], the structure after hot deformation has certain differences (Fig. 6). In addition to the formation of twins, the austenite structure consists of a significant number of grains, not only with dangling boundaries (designation 1), but also with fragments (designation 2), which indicate a qualitative difference from ordinary boundaries with large disorientation angles [3, 10].



a *b*

Fig. 5. Effect of n on δ (a) and ψ (b) for carbon steel of a railway wheel after manufacturing (■) [2], annealed steel with 0.58 % *C* after isothermal transformation of austenite at temperatures of 550…625 °C (▲) [5] and after hot plastic deformation (♦)

From the calculation of the sum of angles, their number in the grain junction [8, 15], and the deviations in shape of the boundaries from the rectilinear (2), it follows from the results of [20] that such boundaries have their own energy approximately an order of magnitude lower than that of a conventional boundary. As a result of low linear tension [13], these boundaries are low-moving during hot plastic deformation [20, 21], and their presence at the austenite structure can have a certain effect on the pearlite transformation [13]. Based on this, one of the reasons for the qualitative change in the ability to strain harden the carbon steel with a structure after hot plastic deformation should be considered the formation of grain boundaries with a low self-energy in austenite. The low mobility of such boundaries ensures the preservation of part of the hot-deformed austenite substructure at the time of the pearlite transformation. In general, the formed pearlite colonies outwardly remain similar to those obtained during isothermal transformation of the steel after annealing (Fig. 1b, c).

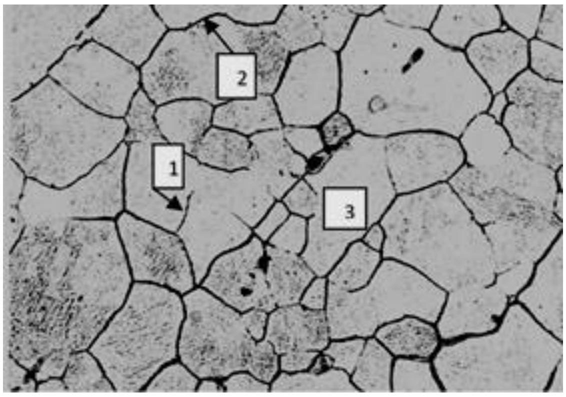


Fig. 6. The structure of the austenite of the carbon steel after 20% hot plastic deformation, magnification 150

However, differences found in the austenite structure of carbon steel (Fig. 6) lead to changes in conditions for the initiation and propagation of plastic deformation in pearlite (σ_i, k_y and n) and associated properties of the steel (Fig. 3, 4).

Indeed, lower values of σ_i in the steel after hot deformation (Fig. 3a) indicate a decrease in the role of the solid solution strengthening in the ferrite of the pearlite. As a result, the required level of resulting stress to maintain conditions for the onset propagation of the plastic deformation should be, quite justifiably, compensated by an increase in the resistance of the ferrite-cementite interface to the movement of dislocations. The fulfilment of the indicated relationship between the hardening of the solid solution and the role interfacial boundaries of the pearlite colony in the region of uniform strain hardening is confirmed by the change at a value of n (Fig. 4c). A similar effect was found in [21], where a change in the proportion of such boundaries (with a low linear tension) during various temperature-deformation treatments affects the properties of steels. Considering that for all-rolled railway wheels intended for cargo transportation, the predominant structural state of the steel is pearlite structures with varying dispersion, considering influence the structural state of austenite on the pearlite transformation can be useful for developing measures to improve the safety of operating railways. Take into account the significant cross-sectional dimensions of the railway wheel elements and the impossibility of creating isothermal conditions for pearlite transformation, the discovered effect of the formation of low-mobility boundaries in austenite during hot melts is observed. The above provisions are confirmed by the results in Figs. 3 and 4. The observed increase in properties of the carbon steel rim after thermal hardening with separate heating, with a complete elimination of the effect of the hot deformation of austenite, indicates a resource for an additional increase in the properties. Indeed, the implementation of accelerated cooling of steel to pearlite transformation temperatures in the intervals between hot reductions at the manufacture of certain elements of a railway wheel will improve its complex properties.

4. CONCLUSIONS

1. For the carbon steel rim of the railway wheel, proportionally to the increase in dispersion of the pearlite colonies from the degree of hot plastic deformation, a simultaneous increase in strain hardening coefficient, strength and plastic properties is observed.
2. The formation of grain boundaries with a low linear energy of the tension in hot-worked austenite is one of the reasons for the appearance of disturbances with regularity in the structure of pearlite.
3. In the pearlite of the carbon steel after hot deformation, the work hardening coefficient and ductility are related by the proportional relation.
4. Compared with the pearlite transformation of the annealed steel, the increase in plasticity after hot deformation is due to a decrease in the contribution from solid solution hardening and an increase in the role of the ferrite-cementite interface in the development of strain hardening processes.
5. The results obtained can be useful for improving the technology of manufacturing all-rolled railway wheels.

References

1. Бабич В.К., Ю.П. Гуль, И.Е. Долженков. 1972. *Деформационное старение стали*. Москва: Металлургия. [In Russian: Babich V.K., Yu. P. Gulj, I.E. Dolzhenkov. 1972. *Deformation aging of steel*. Moskow. Metallurgiya].

2. Бабаченко О.І., Г.А. Кононенко. 2023. „Тріщиностійкість залізничних коліс". Монографія, Київ, Україна: Наукова думка. [In Ukrainian: Babachenko A.I., G.A. Kononenko. 2023. "The cracking resistance of railway wheels". Monograph, Kiïv, Ukraine: Naukova dumka]. DOI: https://doi.org/10.15407/978-966-00-1824-2.
3. Brandon D.G. 1966. „The structure of high-angle grain boundaries Structure de joints de grains a grands angles". *Acta Metallurgica* 14(11): 1479-1484. ISSN: 0001-6160. DOI: https://doi.org/10.1016/0001-6160(66)90168-4.
4. Gao Guhui, Rong Liu, Yusong Fan, Guian Qian, Xiaolu Gui, R.D.K. Misra, Bingzhe Bai. 2022. „Mechanism of subsurface microstructural fatigue crack initiation during high and very-high cycle fatigue of advanced bainitic steels". *Journal of Materials Science & Technology* 108: 142-157. ISSN: 1941-1162. DOI: https://doi.org/10.1016/j.jmst.2021.08.060.
5. Gensamer M., E.B. Pearsall, W.S. Pellini, J.R. Low. 1942. "The tensile properties of pearlite, bainite, and spheroidite". *Trans. Amer. Soc. Met.* XXX: 983-1020.
6. Gleiter H., B. Chalmers. 1972. *High-angle grain boundaries. Progress in Materials Science*. Oxford, New York, Toronto, Sydney, Braunschweig: Pergamon Press.
7. Хесснер Ф., С. Хофман. 1982. "Миграция большеугловых границ зерен". В*: Рекристаллизация металлических материалов*: 71-103. Под редакцией Ф. Хесснера. Москва: Металлургия. [In Russian: Haessner F., S. Hoffman. 1982. "Migration of high-angle grain boundaries". In: *Recrystallization of metallic materials*: 71-103. Edited by F. Haessner. Moskow. Metallurgiya].
8. Herring A.C. 1951. *Physics of Powder Metallurgy*. New York. McGraw-Hill Book Co.
9. Hillert Mats. 1975. „Diffusion and interface control of reactions in alloys". *Metallurgical Transactions A* 6: 5-19. DOI: https://doi.org/10.1007/BF02673664.
10. Lee K.T., J.A. Szpunar. 1995. „The role of special grain boundaries during the grain growth in Fe-3%Si". *Canadian Metallurgical Quarterly* 34 (3): 257-263. ISSN: 0008-4433. DOI: https://doi.org/10.1016/0008-4433(95)00011-L.
11. Liu Man, Jun Wang, Qi Zhang, Haijiang Hu, Guang Xu. 2021. „Optimized Properties of a Quenching and Partitioning Steel by Quenching at Fine Martensite Start Temperature". *Metals and Materials International* 27: 2473-2480. ISSN: 2005-4149. DOI: https://doi.org/10.1007/s12540-020-00726-5.
12. Liu Miao, Yusong Fan, Xiaolu Gui, Jie Hu, Xi Wang, Guhui Gao. 2022. „Relationship between Microstructure and Properties of 1380 MPa Grade Bainitic Rail Steel Treated by Online Bainite-Based Quenching and Partitioning Concept". *Metals* 12(2): 330. ISSN: 2075-4701. DOI: https://doi.org/10.3390/met12020330.
13. Luo C.P., G.C. Weatherly. 1989. "The crystallography of heterogeneous nucleation in a Ni-45 wt% Cr alloy". *Acta Metallurgica* 37(3): 791-801. ISSN: 0001-6160. DOI: https://doi.org/10.1016/0001-6160(89)90006-0.
14. Masoumi Mohammad, Edwan Echeverr, André Tschiptschin, Hélio Goldenstein. 2019. „Improvement of wear resistance in a pearlitic rail steel via quenching and partitioning processing". *Scientific Reports* 9(7454): 1-12. ISSN: 2045-2322 (online). DOI: https://doi.org/10.1038/s41598-019-43623-7.
15. Murr L.E. 1975. *Interfacial Phenomena in Metals and Alloys*. New York. Addison-Wesley Publ. Company.

16. Pereira Henrique Boschetti, Luiz Henrique Dias Alves, Andrei Bavaresco Rezende, Paulo Roberto Mei, Hélio Goldenstein. 2022. „Influence of the microstructure on the rolling contact fatigue of rail steel: Spheroidized pearlite and fully pearlitic microstructure analysis". *Wear* 498-499: 204299. ISSN: 0043-1648. DOI: https://doi.org/10.1016/j.wear.2022.204299.
17. Pickering F.B. 1978. *Physical metallurgy and the design of steels*. Applied science publishers LTD.
18. Qiu Jiajia, Min Zhang, Zhunli Tan, Guhui Gao, Bingzhe Bai. 2019. „Research on the Microstructures and Mechanical Properties of Bainite/Martensite Rail Treated by the Controlled-Cooling Process". *Materials* 12(19): 3061. ISSN: 1996-1944. DOI: https://doi.org/10.3390/ma12193061.
19. Seo Jung-Won, Hyun-Moo Hur, Seok-Jin Kwon. 2022. „Effect of Mechanical Properties of Rail and Wheel on Wear and Rolling Contact Fatigue". *Metals* 12(4): 630. ISSN: 2075-4701. DOI: https://doi.org/10.3390/met12040630.
20. Sukhomlin G.D., A.V. Andreeva .1983. „Particular properties of $\Sigma = 3^n$ boundaries in F. C. C. polycrystals. I. Crystallographical parameters and grain boundary faceting during annealing". *Physica status solidi (a)* 78: 333-341. ISSN: 1862-6319. https://doi.org/10.1002/pssa.2210780139.
21. Сухомлин Г.Д. 2013. „Специальные границы в феррите низкоуглеродистых сталей". *Металлофиз. новейшие технол* 35(9): 1237-1249. [In Russian: Sukhomlin G.D. 2013. „Special boundaries in ferrite of low-carbon steels". *Metallophysics and Advanced Technologies* 35(9): 1237-1249]. ISSN: 2005-4149. DOI: https://doi.org/10.1007/s12540-020-00726-5.
22. Standard test methods for determining average grain size$_1$. 2004. E 112-96.

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