Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 115 **2022**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2022.115.13

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Vakulenko, I.A., Vakulenko, L., Bolotova, D., Kurt, B., Asgarov, H., Çölova, Ö. Influence structure on the plasticity of carbon steel of the railway wheel rim in operation. *Scientific Journal of Silesian University of Technology. Series Transport*. 2022, **115**, 183-192. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2022.115.13.

Igor Alex VAKULENKO[1], Leonid VAKULENKO[2], Dariy BOLOTOVA[3], Bulent KURT[4], Hangardash ASGAROV[5], Ömer ÇÖLOVA[6]

INFLUENCE STRUCTURE ON THE PLASTICITY OF CARBON STEEL OF THE RAILWAY WHEEL RIM IN OPERATION

Summary. When simulating the operating conditions of the rim of a railway wheel, an analysis of change in the structural state from the possible degree of plastic deformation and the heating temperature of steel near the rolling surface was carried out. The development processes of spheroidization and coalescence of cementite during heating of the cold-worked steel change its ability to strain hardening. Substructure changes during heating to temperatures of 500-550°C deformed steel are accompanied by a simultaneous decrease in its ability to strain hardening and the level of plasticity. When heated above 500-550°C, the development of ferrite recrystallization processes provides a gradual transition of the metal from substructure hardening to hardening from grain boundaries with

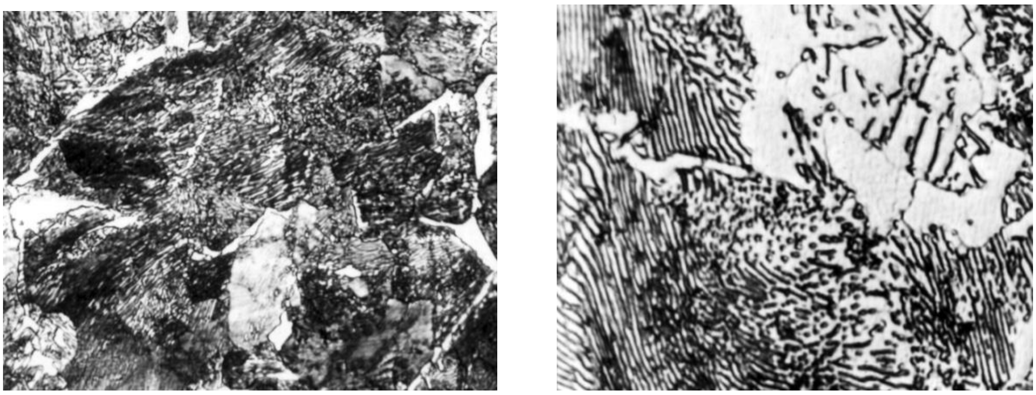
[1] Ukrainian State University Science and Technology, Lazaryan St.,2, Dnipro, Ukraine, 49010. Email: vakulenko_ihor@ukr.net. ORCID: https://orcid.org/0000-0002-7353-1916
2 Management of Prydniprovsk Railway, Yavornytskyi Av., 107, Dnipro, Ukraine, 49054. Email: leon.vakulenko@gmail.com. ORCID: https://orcid.org/0000-0003-2616-740X
3 Dnipro Lyceum of Railway Transport, Universalna St., 7, Dnipro, Ukraine, 49024. Email: dasha.bolotova@i.ua. ORCID: https://orcid.org/0000-0001-6947-3663
4 Engineering and Architecture Faculty Metallurgy and Materials Engineering Department, Nevsehir University, Nevsehir, Turkey. Email: bkurt74@gmail.com. ORCID: https://orcid.org/0000-0002-7245-6774
5 Mechanical Engineering, Karabuk University, Karabük, Turkey. Email: hangardasaskerov@karabuk.edu.tr. ORCID: https://orcid.org/0000-0003-4771-3406
6 Mechanical Engineering, Karabuk University, Karabük, Turkey. Email: omercolova@gmail.com. ORCID: https://orcid.org/0000-0002-4107-4298

large angles of disorientation. It is shown that regardless of the nature of the main structural element, the ability of steel to strain hardening and the level of plasticity after heating are related by a proportional relationship.

Keywords: carbon steel, strain hardening, plastic deformation, temperature, cementite, ferrite

1. INTRODUCTION

In the process of interaction of the railway wheel with the rail, the metal along the rolling surface is subjected not only to significant plastic deformations with a high degree of non-uniformity of distribution but also to significant thermal effects. Analysis of known experimental data [1-3] indicates differences in the kinetics of structural changes during the operation of railway wheels, after thermal strengthening to different levels (Figure 1a). For a thin layer by the rim of the railway wheels, the development processes of strain hardening during rolling are accompanied by a different rate of accumulation of defects in the crystal structure in the phase components of the carbon steel [4,5]. Considering that the structure of the steel of the wheel consists of grains of ferrite and pearlite colonies (Figure 1b), the development of strain hardening processes in them, with a simultaneous temperature effect during deceleration of the rolling stock, can change the complex of properties of steel to a wide range. For ferrite regions, the differences in the crystallographic slip systems between adjacent grains, the frequency of the boundaries encountered [4], and the formation of dislocation cellular structures form the basis for the increase of the strength of the metal after cold plastic deformation. The presence of dispersed carbide particles of various sizes and morphology (Figure 1b) in the steel structure is an additional obstacle to moving dislocations. In proportion to the decrease in distance between the cementite particles, an increase in the resistance of the metal to deformation is achieved [6,7].



a b

Fig. 1. Structure of the steel of the rim railway wheel after accelerated cooling to a temperature of 650˚C: (a) near the rolling surface; (b) at a distance of 25 mm. Magnification is: (a) 800; (b) 1000

In comparison with known mechanisms of strain hardening in large plastic deformations, the development of this phenomenon in the area of the initiation of plastic flow deserves some attention. In this case, it is of certain theoretical and practical interest to trace the relationship between the evolution of the structure and the development of strain hardening processes in deformed carbon steels with different structural states. The aim is to assess the effect of the structure of carbon steel on the strain hardening parameters in the area of nucleation and propagation of plastic deformation.

2. MATERIAL AND METHODS

The material for this study was the carbon steel of a railway wheel (0.61% C) and the concentration of the rest of the chemical elements was within the requirements of regulatory documents. Samples of cylindrical shape, 3 mm in diameter, after obtaining the required structural state in steel, were tested with tension, as shown in the deformation diagram. The steel was examined after two treatments. The quenching for martensite, tempering at 650°C, plastic deformation by drawing on 30, 60, and 80% (I), and isothermal decomposition of austenite at 550°C, plastic deformation of 30 and 80% (II). After (I) and (II), the steel final annealing at 400-680°C. The structural studies of metal were carried out using electron and light microscopes. The structure of the steel after treatment (I) and (II) is illustrated in Figures 2a and b. The dislocation density was estimated using X-ray structural analysis techniques by measuring [8] the width of a line of the X-ray interference (211) (B_{211}). The bearing elongation of the sample was used as parameter ductility of the steels under study. The strain hardening characteristics were determined from the analysis of tension curves plotted in logarithmic coordinates. Strain curves were obtained by tension samples on an Instron type testing machine, at a strain rate of 10^{-3} s^{-1}. To assess the effect of strain hardening, methods of analysis of strain curves are used. In appearance, the deformation curves of metallic materials can be divided into two types: with a section of intermittent flow *A-C* (Figure 2c) and without it (Figure 2d). Plastic deformation, accompanied by degenerated sections *A-C*, changes the curve. Various analytical dependencies are used to describe the patterns of change in the deformation curves. One of them is the Ludwik ratio [9]:

$$\sigma = \sigma_0 + K \cdot \varepsilon^m, \quad (1)$$

where σ_0 - stress of irreversible motion of dislocations [10], *K* constant, *m* - exponent. To determine σ_0, *K* and *m*, the deformation curve is plotted in logarithmic coordinates (Figures 2c and d). The value of σ_0 is determined from the extrapolation area of uniform strain hardening (*CD*) to zero plastic deformation (sector *BC* Figure 2d) [7]. In the absence area of *A-C* on the deformation curve, the limit of elasticity of the carbon steel was accepted as σ_0. Point *D* on the curve by the deformation scale (ε_n) corresponds to moment formation in a dislocation cell of the structure. The values *K* are the stress when $\varepsilon = 1$. There is no consensus on the physical meaning of *K*. The specified characteristic is called the coefficient of plasticity [11], less often strength [7], etc. The exponent *m* is defined as a tangent of inclination angle α (Figure 2c) by the ratio (1):

$$m = \Delta lg\, (\sigma - \sigma_0)/\Delta\varepsilon \quad (2)$$

At the same time, exponent *m* is not sensitive to the structural changes of the metal during plastic deformation in the *CD* section.

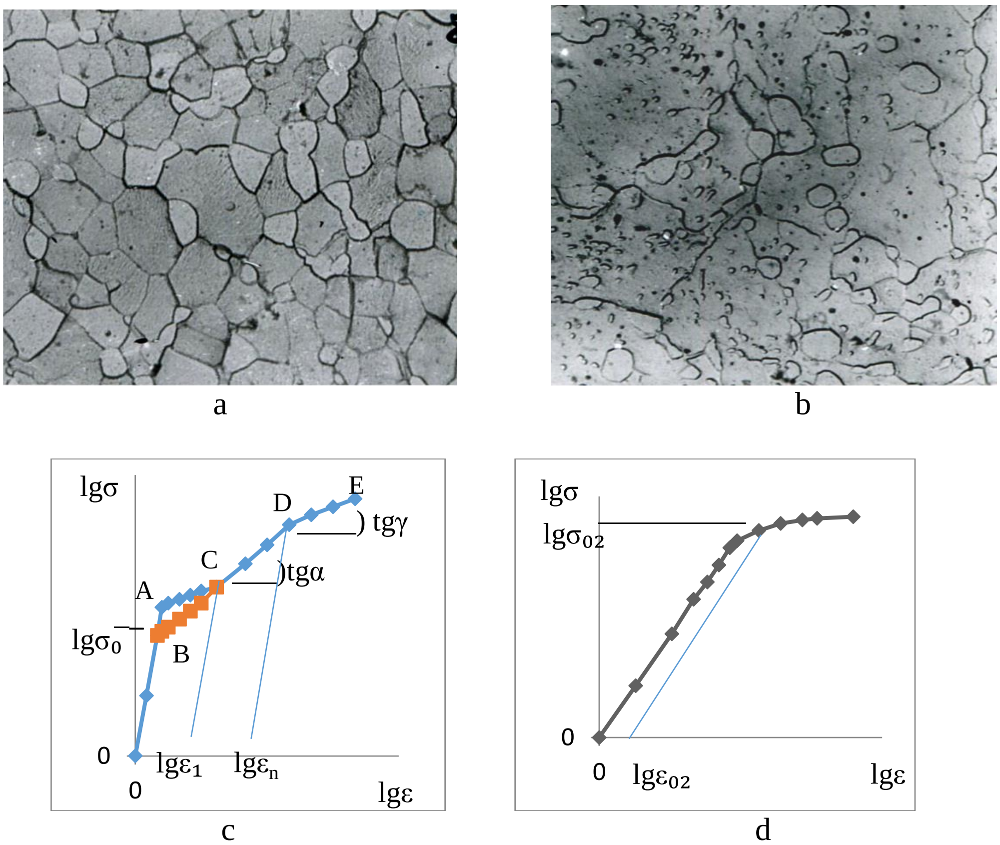
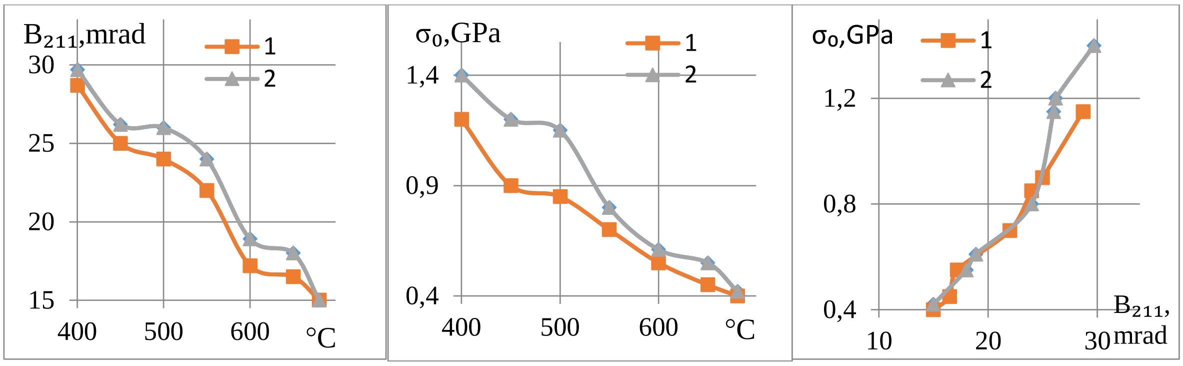


Fig. 2. Structure of the carbon steel after final annealing at 650°C by: (a) – (I); (b) – (II). Strain curve in the logarithmic coordinates with a sector of the discontinuous deformation: (c) – (A-C); (d) – without it. Magnification is 4000 x 2

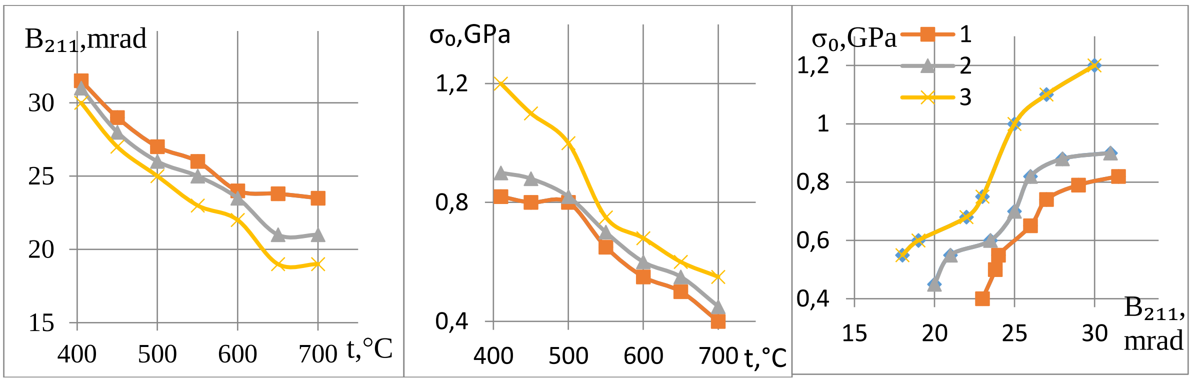
3. RESULTS AND DISCUSSION

During the operation of a railway wheel, a thin layer of carbon steel close to the rolling surface undergoes significant plastic deformation with a high degree of uneven distribution. When decelerating the rolling stock, deformed metal of the wheel can be heated up to high temperatures at the beginning of the phase transformations. Based on the development of polygonization and recrystallization processes in the ferrite [12, 13], spheroidization and coalescence of cementite particles [1], after treatments (I) and (II), the structural state of cold-deformed metal will change qualitatively. The observed changes in the nature of strain hardening of the metal will determine conditions for the formation of damage to the rolling surface of railway wheels. The morphology and uniformity distribution of cementite particles in steel have a significant effect on the nature of the development of the strain hardening processes. The formation of certain unevenness at the distribution of cementite during the isothermal decomposition of austenite in the temperature range of pearlite transformation, after plastic deformation, and annealing is inherited by the steel structure (Figure 2b). A more detailed study of the structure reveals significant differences in the sizes of neighboring ferrite grains of carbon steel. Considering the dependence of the development processes of strain hardening on the size factor steel structure, in the indicated micro volumes one should expect different values parameters of the strain hardening of the metal. For carbon steel generally, the level density defects of crystalline lattice after annealing and stress of starting and moving of dislocations can determine the nature of the development of the metal strain hardening processes. With an increase in annealing temperature, the accumulated density of the crystal structure defects and, first, dislocations, decreases (Figure 3a). The stress of irreversible moving of dislocations decreases similarly (Figure 3b). From the analysis of the relationship between them (Figure 3c), it follows that the initial stages of propagation of the plastic deformation (the stress range from *B* to *A*, Figure 2c) depend to a greater extent on the density of dislocations preserved after annealing of the metal, with by practically no influence from the remnants subboundaries of the cold-deformed metal. As the degree of plastic deformation increases and increase in density of dislocations, a change in their mobility will determine the nature of the development of the strain hardening processes and the associated level of steel plasticity. Compared to the uneven distribution of cementite particles, where it is rather difficult to separate substructure hardening from the influence of the grain boundaries with large disorientation angles, was used processing to obtain the structure of the ultra-fine ferrite grains (Figure 2a). In this case, the uniform arrangement of cementite particles after tempering the hardened steel excludes the development of cementite spheroidization and its influence on the development of polygonization and recrystallization of ferrite during annealing of deformed steel. Moreover, the practically absent coalescence of cementite particles during annealing of plastically deformed steel excludes the possible location of the carbide phase inside ferrite grains (Figure 2a). Heating of cold-deformed carbon steels with structure (I) (Figure 4) is accompanied by changing of plastic properties, and a similar nature is observed for steel with structure (II) (Figure 3). Analysis of the fine-crystalline structure during annealing of cold-deformed carbon steel with the structure type (Figure 2a), after treatment (I), testifies to an almost monotonic decrease in the density of crystal structure defects introduced by deformation (Figure 4a). In comparison with practically identical character of changes in B_{211} and σ_0 (Figures 3 and 4), some differences are found. One explanation for the non-monotonic decrease in B_{211} and σ_0 with annealing temperature (Figure 3) is the development processes of the spheroidization of cementite plates and coalescence of carbide particles during annealing of deformed steel (treatment II). The observed character relation $\sigma_0 \sim f(B_{211})$ (Figure 3c) is a consequence effect of spheroidization and coalescence of cementite on the development dislocation recombination processes during annealing of plastically deformed metal. Simultaneously, with the presence of a certain amount of structurally free ferrite in the structure of steel with 0.61% C, a change in morphology at the carbide phase and the coalescence of cementite particles during annealing should inevitably lead to significant changes in the average distance between cementite particles. In steel, after treatment (I), during annealing, the development of coalescence has a much smaller effect on the change in the average diameter of cementite particles and the distance between them. Therefore, differences in the development of dislocation annihilation processes during metal annealing after treatments (I) and (II) will have a corresponding effect on the formation of nuclei and subsequent development of ferrite recrystallization. Hence, during treatment (I), the development of ferrite polygonization and recrystallization processes is limited by the space of former subgrains, while the distance between cementite particles remains practically unchanged. Thus, the effect of density defects of the crystal structure from plastic deformation on the value of σ_0 has the form of equidistantly spaced curves (Figure 4c). Even greater differences are found when comparing the nature of the change of the strain hardening index versus the annealing temperature. Comparative analysis dependence of *m* on the annealing temperature indicates qualitative differences for the investigated steel treatments. Indeed, if for treatment (II), an extreme nature of the dependence is observed (Figure 5a), then for treatment (I) when heated from 400 to 550°C, the value of *m* remains practically unchanged (Figure 6a) and only then does it begin to increase from the annealing temperature. The extreme nature of the change in *m* (Figure 5a) indicates a change in the main element of the structure in carbon steel after tempering. So, for temperatures from 400 to 550°C, the strain hardening of steel is determined by the parameters of the substructure, and for temperatures ranging from 550-600°C, the increasing role of ferrite grain boundaries with large angles of disorientation (Figure 2b). Indeed, as follows from [10], in ferrite after plastic deformation and heating to temperatures of 400-450°C, one can observe the first signs of the development of recrystallization processes, and at temperatures of 500-550°C, their already noticeable acceleration. Further, the value of the density of dislocations, according to B_{211}, decreases by 1,5 - 2 times [14]. When the temperature rises to 550-600°C, an acceleration of the development recrystallization processes is observed in ferrite. Although ferrite volumes in which recrystallization is completed are insignificant and the structure as a whole remains dispersed, the regions free of dislocations are already found [10,15]. An increase in the proportion of such metal volumes is accompanied by an increase in the number of grain boundaries with large disorientation angles (Figures 2b). Consequently, decrease volumes of ferrite with subgrain boundaries and *m* starts to grow with a temperature in heating. After the completion of recrystallization and the beginning growth of the ferrite grains, an increase in the strain hardening coefficient of steel is observed (Figure 5a). In this case, there is a transition from the substructure hardening of the metal to the effect of ferrite grain boundaries on the plastic properties (Figure 5b). The practically absent increase relative elongation of annealing temperatures up to 550°C (Figure 5b) is primarily due to the retention of subboundaries in ferrite after plastic deformation. Given that an increase characteristic of strain hardening provides an increase in the stable propagation of the plastic deformation, an increase in *m* should be accompanied by an increase in the plasticity of the metal. Indeed, as follows from the analysis of the ratio $\delta \sim f(m)$, for steel with the structural state (II), an increase in the strain hardening coefficient is accompanied by an increase in the relative elongation (Figure 5c). In this case, the provision of an increase in *m*, regardless of the mechanism, strain hardening (from the presence of subboundaries or boundaries of ferrite grains) is accompanied by an unambiguous increase value of δ. Moreover, a detailed analysis of the δ - *m* ratio reveals division into regions, which correspond to substructure hardening (curves 1 and 3) and hardening from ferrite grain boundaries (curves 2 and 4). Thus, regardless of the strain hardening mechanism, the increase in *m* contributes to an increase in the ductility of the steel. Considering the dependence of the development strain hardening processes on the structural state of steel, a similar relationship should be expected for processing (I). The nature of the influence degree of plastic deformation and the annealing temperature on *m*, δ and the relationship between them for treatment (I) is shown in Figure 6. A comparative analysis of the ratios (Figures 5 and 6) indicates a qualitative similarity only for certain characteristics. If for the strain hardening coefficient as a whole, the extreme character remains, and for the relative elongation it is similar to an exponential dependence on the annealing temperature, then the construction of the relationship between them indicates significant differences in the behavior of the metal with structures after treatments (I) and (II). Therefore, when annealing cold-deformed steel with structure (II), first spheroidization and then coalescence of cementite particles have a known effect on the substructure and development of ferrite recrystallization (Figure 2b). Compared to a deformation of 30%, when δ during annealing to 550°C does not exceed 6% (Figure 5b), an increased dislocation density after deformation of 80% promotes to a greater extent the development of dislocation redistribution processes and increased plasticity of the metal. In steel with structure (I), substructure changes and the development of ferrite recrystallization are mainly limited to the distance between cementite particles, which practically does not change upon annealing.



a b c

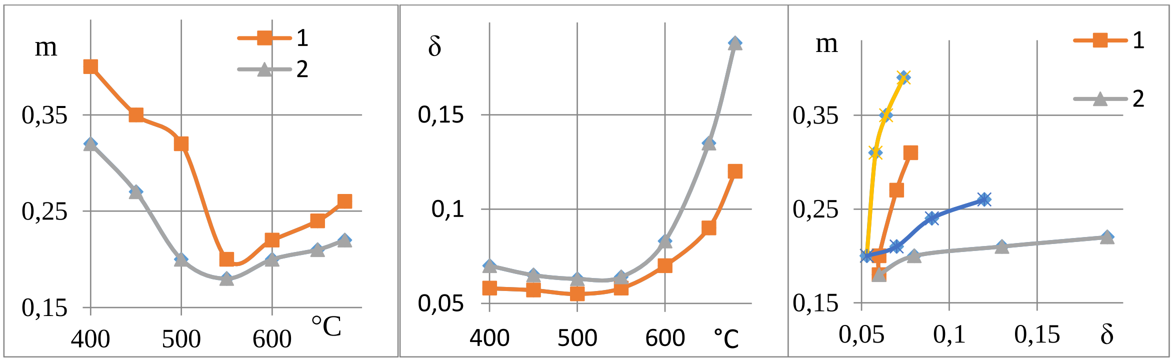
Fig. 3. The change of: (a) - B_{211}; (b) - σ_0; and (c) - the ratio between both of them on the dependence on plastic deformation (1- 30; 2 - 80%) and annealing temperature in the treatment (II) of the carbon steel



a b c

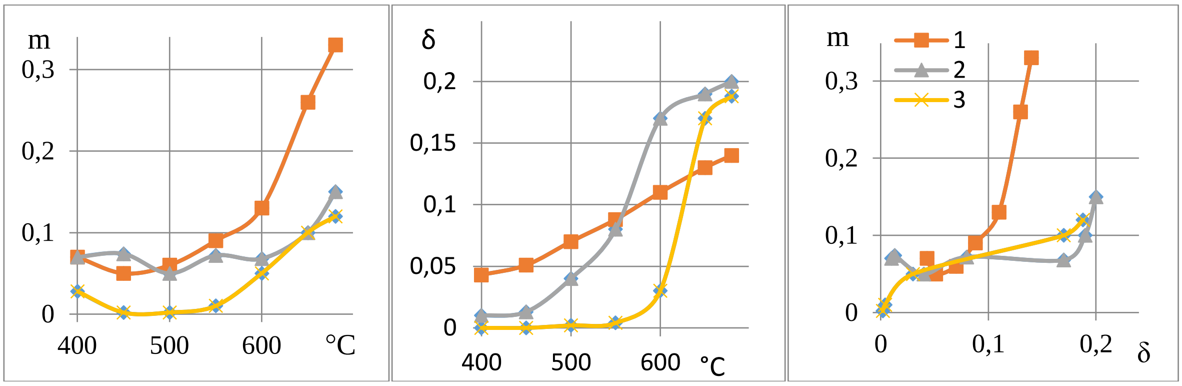
Fig. 4. The change of: (a) - B_{211}; (b) - σ_0 and (c) - the ratio between both of them on the dependence on plastic deformation (1- 30; 2 – 60, 3 - 80%) and annealing temperature in the treatment (I) of the carbon steel

Thus, the sizes of the subgrains during annealing and the ferrite grains during recrystallization should be limited by the distance between cementite particles (Figure 2a). Subsequently, in proportion to the degree of deformation, increase stability of the substructure upon annealing will lead to a shift in the moment of accelerated development of dislocation annihilation towards higher temperatures (Figure 6b). The above position is confirmed by the nature of the influence of the degree of deformation and annealing temperature on the value of δ for structure (I). For steel after deformation of 30%, the observed monotonic increase in δ with an increase in annealing temperature is gradually replaced by the completely brittle state of the metal after deformation of 80% up to 550°C (curve 3, Figure 6b). This is because subboundaries in ferrite formed as plastic deformation cannot perform the functions places of nucleation and annihilation of dislocations. Considering that the main number of dislocations of cold-deformed metal is presented in form of subboundaries, the retention of their presence in the structure up to a temperature of 550°C significantly limits the participation of dislocations in maintaining conditions for the propagation of plastic deformation. On other hand, in proportion degree of plastic deformation, there is a shift onset of intensive development of the steel softening processes towards high temperatures. Indeed, if for a degree deformation of 30% beginning of an increase in steel ductility is observed in the temperature order of 450°C, for 60% - 500°C, then after 80% required heating to temperatures of at least 600°C. Comparative analysis with dependences of *m* and δ on the magnitude of deformation and annealing temperature for the structural state (II) (Figure 5) indicates a less pronounced effect degree of deformation on the temperature onset intense softening of the metal. Moreover, the qualitatively different nature of the mutual change between *m* and δ for structural states (I) and (II), is an additional confirmation of the above explanations. Considering that the structural state rim of the railway wheels is presented in the form of pearlite colonies in different dispersion (Figure 1), the nature of the development\ processes of structural transformations in a thin metal layer near the rolling surface during wheel operation determines the conditions of the surface damage formation. The process formation of surface damage to a railway wheel can be represented as consisting of successively developed processes of structural changes in the metal. Indeed, uneven plastic deformation along the rolling surface and the subsequent heating of the metal during the deceleration of the railway rolling stock leads to the formation of structures with different morphology of cementite particles. In fact, the carbide phase is particles ranging from remnants of cementite plates with incomplete spheroidization process to globular particles, similar to the structural state (II). Subsequent plastic deformation of a metal with such structures and inevitable heating leads to the formation of structures similar to treatment (I). Based on this, the formed structural heterogeneity in adjacent micro volumes of metal is one of the reasons for the occurrence of damage to the rolling surface of railway wheels during operation.



a b c

Fig. 5. The change of: (a) - *m* ; (b) - δ , on the dependence on plastic deformation (1 - 30; 2 - 80%) and annealing temperature in treatment (II) of the carbon steel.
The ratio between both of them: (c) - (3,4 - 30; 1,2 - 80%)



a b c

Fig. 6. The change of: (a) - *m* ; (b) - δ –; (c) - the ratio between both of them on the dependence on plastic deformation (1- 30, 2 – 60, 3 - 80%) and annealing temperature in treatment (I) of the carbon steel

4. CONCLUSIONS

1. The ratio of gradient of plastic deformation along the rolling surface and heating up of temperatures onset of the phase transformations determine the structural state of the steel in the rim of the railway wheel, the ability to strain hardening, and achieve a level of plasticity.
2. When plastically deformed steel is heated to temperatures of 500-550ºC, the development of substructure hardening processes is accompanied by a decrease in the ability of the steel to strain hardening and the level of plasticity.
3. In proportion to the heating temperature of deformed steel from 500-550ºC, a gradual transition from substructure hardening to hardening in the boundaries of ferrite grains is observed, contributing to an increase in strain hardening and plasticity.
4. Regardless of the nature of the main element of the structure, the ability to strain hardening explains the change in the level of plasticity of carbon steel on the rolling surface of railway wheels during operation.

References

1. Hollomon J.H. 1945. "Tensile deformation". *J. Member AIME* 162: 268-290.
2. Morrison W.B. 1966. "The effect of grain size on the stress–strain relationship in low-carbon steel". *Trans. Am. Soc. Metals*. 59: 824-846.
3. Morrison W.B. 1971. "Effect of changes in temperature and strain rate on the double in behavior of alpha-iron". *Met. Trans*. 2: 331-332.
4. Imamura J., H. Hayakawa, T. Taoka. 1971. "Contribution of local strain rate at Luders band front to grain size dependence of lower yield stress in iron". *Trans. Iron. Steel. Inst. of Japan*. 11: 191-200.
5. Ren C., W. Dan, Y. Xu, et.al. 2018. "Effect of heterogeneous microstructures on the strain hardening behaviors of ferrite – martensite dual phase steel". *Metals.* 8: 824-841. DOI: https//doi.org/103390/met 8100824.

6. Calado W.R., R. Barlosa. 2013. "Influence of carbon content and deformation temperature on ultra-grain refinement of plain carbon steels by means of torsion test". *ISIJ International* 53 : 1-13. DOI. : https//doi.org/102355/isijinternational.53.909.
7. Cottrell A.H. 1963. "The relation between the structure and mechanical properties of metals". *Symposium NPL*. Teddington. P. 455-473.
8. Guinier A. 1956. *Theorie et Technique de la ragiocristallographie*. Dunod, Paris.
9. Ludwik P. 1909. *Elemente der technologischen mechanik*. Verlag von Julius Springer. Berlin.
10. Babich V.K., Yu.P. Gulj, I.E. Dolzhenkov. 1972. *Deformation aging of steel*. Moskow: Metallurgiya.
11. Crist B.W., C.V. Smith. 1967. "Comparison of the Hall–Petch parameters of zone-refined iron determined by the grain size and extrapolation methods". *Acta met.* 15: 809-816.
12. Ohmori Y., A.T. Davenport, R.W.K. Honeycombe. 1972. "Crystallography of pearlite". *Trans. I.S.I.J.* 13: 128-137.
13. Staker M.R., D.L. Holt. 1972. "The dislocation cell size and dislocation density in cooper deformed at temperatures between 25 and 700^{O}C". *Acta met.*: 569-579.
14. Prnka T. 1971. "Beitrag zur theorie der streckgrenze ousscheilungs verfestigter niedriglegierter stahle". *Arch. Eisenhiittenw* 42: 919-925.

Received 29.01.2022; accepted in revised form 28.03.2022