

## МАТЕРІАЛОЗНАВСТВО

UDC 669:[539.43:539.56]

I. O. VAKULENKO<sup>1\*</sup>, D. M. BOLOTOVA<sup>2</sup>, S. V. PROIDAK<sup>3</sup>, H. ASKEROV<sup>4</sup>, H. CUG<sup>5</sup>,  
H. O. TCHAIKOVSKA<sup>6</sup>

<sup>1\*</sup>Dep. «Applied Mechanics and Materials Science», Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 56, e-mail vakulenko\_igor@ukr.net, ORCID 0000-0002-7353-1916

<sup>2</sup>Dnipro Lyceum of Railway Transport, Universalna St., 7, Dnipro, Ukraine, 49024, tel.+38 (098) 351 99 70, e-mail dasha.bolotova@i.ua, ORCID 0000-0001-6947-3963

<sup>3</sup>Dep. «Applied Mechanics and Materials Science», Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 56, e-mail proydak.sv@ukr.net, ORCID 0000-0003-2439-3657

<sup>4</sup>Dep. «Mechanical Engineering», Karabuk University, Karabuk, Turkey, 78050, tel. +90 (538) 455 04 45, e-mail hangardasaskerov@karabuk.edu.tr, ORCID 0000-0003-4771-3406

<sup>5</sup>Dep. «Mechanical Engineering», Karabuk University, Karabuk, Turkey, 78050, tel. +90 (544) 842 62 08, e-mail harun1878@gmail.com, ORCID 0000-0002-6322-4269

<sup>6</sup>Dep. «Materials Science and Materials Processing», Prydniprovsk State Academy of Civil Engineering and Architecture, Chernyshevskoho St., 24a, Dnipro, Ukraine, 49005, tel. +38 (095) 618 14 63, e-mail chaikovska.hanna@pgasa.dp.ua, ORCID 0000-0001-6707-0159

## FORMATION OF CARBON STEEL STRUCTURE DURING HOT PLASTIC DEFORMATION

**Purpose.** The main purpose of the work is to determine the peculiarities of the development of recrystallization processes of carbon steel austenite depending on the degree of hot plastic deformation and to develop proposals for improving the structural state of the metal of the railway solid-rolled wheel. **Methodology.** Two carbon steels of a railway wheel with a minimum and maximum carbon content of 0.55 and 0.65 % and other chemical elements within the grade composition of the steel 60 were used as research material. Samples in the form of cylinders with a diameter of 20 mm and a height of 40 mm were heated in a muffle furnace, exposed for a certain time to equalize the temperature across the cross section of the sample. After that, the samples were subjected to hot compression on Instron type test machine. The temperature interval of hot compression of the samples was 950–1100 °C, with deformation degrees in height in the range of 10–40%. The strain rate was  $10^{-3}$ – $10^{-2}$ sec<sup>-1</sup>. A standard etching was used to detect the boundaries of the austenite grains. Structural studies were performed using Epikvant type light microscope at magnifications sufficient to determine the structure of austenite grains. The grain size of austenite was determined by the methods of quantitative metallography. **Findings.** In the case of hot compression of the railway wheel blank, increasing the concentration of carbon atoms only within the grade composition of the steel is sufficient to increase the average austenite grain size, which confirms the proposals to limit the carbon content in the metal of railway wheels. The formation of a certain degree of austenite structural heterogeneity at the cross section of the rim or hub of the railway wheel is due to a change in the development mechanism of recrystallization processes depending on the deformation value. Under conditions of the same degree of hot plastic deformation, the replacement of one-time compression by fractional one is accompanied by a violation of the conditions of formation of the recrystallization nucleus. As a result of the specified replacement of the scheme of hot plastic deformation we obtain reduction in the austenite grain size. **Originality.** Based on a study of the development of collective recrystallization processes during the hot compression of carbon steel of the railway wheel, it was determined that the increase in carbon content contributes to the austenite grain increase. After hot compression of the wheel blank, the structural inhomogeneity of austenite that occurs is determined by a change in the mechanism of recrystallization

## МАТЕРІАЛОЗНАВСТВО

processes development. During deformations above the critical degree, the recrystallization nuclei are formed and successively grow, which leads to the structure refinement. In the case of deformations below the critical value, the growth of austenite grains occurs according to the coalescence mechanism, according to which fragments of boundaries with large disorientation angles consistently disappear. **Practical value.** For austenite grain refining in massive elements of solid-rolled railway wheel we offer to replace one-time hot compression by fractional one.

*Keywords:* austenite; deformation; temperature; grain size; carbon steel; railway wheel

### Introduction

According to the technology of manufacturing a railway wheel, the blank is subjected to sequential hot compression on a press and rolling on a special state. According to the technology of manufacturing a railway wheel, the blank is subjected to sequential hot compression on a press and rolling on a special mill. The high temperature of hot compression, at the appropriate deformation degrees at each stage of wheel formation, leads to a significant structural inhomogeneity of the metal [4]. This structural inhomogeneity in the railway wheel blank is caused by the formation of a high degree of non-uniformity in the austenite grains size as the main phase of the high-temperature state of carbon steel. This heterogeneous structure is inherited after all subsequent treatments, which significantly reduces the overall set of metal properties of the railway wheel elements [2, 8]. The reasons for the formation of the austenite structure with relatively large and small adjacent grains are the increased diffusion rate and deformation gradient that occurs at the cross section of the wheel elements during hot compression of the blank. As a result, the metal layer located directly with the deforming tool is subjected to maximum compression, and the more distant layer corresponds to a decrease in the degree of hot plastic deformation [4]. Consequently, austenite grains grow to very large sizes in metal volumes that have been compressed at a degree close to critical (according to various estimates, at 8–10 % [1, 7]). At the same time, with slight exaggerations, the deformation of the critical value causes a corresponding dispersion of the austenitic structure, which together with grains of very large sizes will lead to uneven austenite structure as a whole. The formed austenite structure with different grains will inevitably have a negative effect on the structural state of the wheel metal after a separate heating and final heat-strengthening treatment – accelerated cooling [11, 12]. In proportion to the structural state, the set of

the metal properties at the cross section of the rim and the hub, which are the most massive elements of the railway solid-rolled wheel, will also change.

### Purpose

The main purpose of the work is to determine the peculiarities of the development of recrystallization processes of carbon steel austenite depending on hot plastic deformation degree and to develop proposals for improving the structural state of the metal of the railway solid-rolled wheel.

### Methodology

Two carbon steels of the railway wheel with a minimum and maximum carbon content of 0.55 and 0.65% and other chemical elements within the grade composition of the steel 60 were used as research material. Samples in the form of cylinders with a diameter of 20 mm and a height of 40 mm were heated in a muffle furnace, exposed for a certain time to equalize the temperature across the cross section of the sample. After that, the samples were subjected to hot compression on Instron type test machine. The temperature interval of hot compression of the samples was 950–1100 °C, with deformation degrees in height in the range of 10–40 %. The strain rate was  $10^{-3}$ – $10^{-2}$  sec<sup>-1</sup>. A standard etching was used to detect the boundaries of the austenite grains. Structural studies were performed using Epiquant type light microscope at magnifications sufficient to determine the structure of austenite grains. The austenite grain size was determined by the methods of quantitative metallography.

### Findings

In the process of manufacturing solid-rolled railway wheels, the sequential compression of the blank in the roll openings of the rolling mill pressure equipment at temperatures of 1200–1250 °C is accompanied by the formation of significant structural inhomogeneity of carbon

## МАТЕРІАЛОЗНАВСТВО

steel. This is due to the high metal compression temperatures, the forms complexity and the different thickness of the individual elements of the railway wheel. Studies of the microstructure [3, 4] found that in the central volumes of the wheel rim, the degree of plastic deformation does not exceed 10 %, and near the rolling surface can reach 50-60 %. The discrepancy in the degree of plastic deformation at these temperatures of hot compression affects the development of austenite recrystallization processes, which in turn determines the final grain size. According to [9, 13], in the case of constant heating temperature, in proportion to the degree of plastic deformation above the critical value, the grain size of austenite will decrease. Based on this, the austenite grain size in the central volumes of the railway wheel rim, after hot pressing and taking into account the separate heating for thermal hardening and tempering, is approximately 0 or 1 point. Near the rolling surface, due to the higher degree of plastic deformation, it will not exceed 2–3 points [4]. In general, the formed metal structure is qualitatively correlated with the plots of the value distribution of the hot plastic deformation along the wheel elements. Thus, maximum compression is achieved in the rim, which leads to the formation of the austenite structure with a grain size of about 2 points. In the areas of the disk near the rim, the picture is much more complicated. The fact is that although the metal near the rim is much less compressed (compared to the rim), the austenite structure actually has a higher dispersion. The grain size for these metal volumes is 3–4 points [4]. This situation is due to the partial preservation of the consequences of hot hardening of austenite after the blank compression on a press of 100 MN (Fig. 1, *b*) before rolling on a rolling mill. The total effect from successive stages of hot deformation leads to the formation of a more dispersed structure of austenite with grain sizes up to 4 points.

Thus, the larger the metal cross section of a certain element of the railway wheel, the greater the unevenness in the austenite grain size should be expected. The austenite structure with different grains has a negative effect on the structural state of the wheel metal after separate heating and accelerated cooling. In proportion to the structural state, the set of the metal properties along the cross

section of the solid-rolled railway element will also change [13].

The railway wheel blank for hot compression is heated to temperatures significantly exceeding the completion of the single-phase austenitic structure formation. During a sufficiently long exposure to equalize the temperature at the cross section of the blank there is a significant increase in the austenite grain size. In addition to the effect of inhibiting the process of moving the austenite grain boundary in the case of the development of the collective recrystallization process, we should also expect the effect from the general carbon content in steel [1, 3]. The degree of exceeding the completion time of the austenitic transformation by the temperature will differently accelerate the process of increasing the austenitic grain size, depending on the concentration of carbon atoms within the grade composition of the railway wheel steel. Qualitative changes in grain sizes can be estimated by comparing real structures according to the accepted point scale. From the structure analysis, it was determined that the austenite structure with expected grain size corresponds to the higher heating temperatures. At the same time, according to the normative documentation, for carbon steel of the railway wheel it is allowed to change the carbon concentration within the grade composition by about 0.1 %. Taking into account this fact during the development of the hardening treatments technology, it is necessary to assess the possible change in the austenite grain size in steel with the maximum carbon content and the minimum value in the process of hot compression.

According to the analysis of the steel samples microstructure (Fig. 1, *a*) with a carbon content of 0.55 % after 10 % compression at a temperature of 950 °C, the formation of austenite grains in a shape close to polyhedron, with an average size of about 50–60 μm was detected. For the deformation temperature of 1100 °C, the formation of the austenite structure with significant inhomogeneity is observed simultaneously with the increase in the average grain size (Fig. 1, *b*). The presence of grains with a large difference in size in the steel structure can be considered as evidence of the beginning of the development of recrystallization by the coalescence mechanism [1, 6, 9]. At the same time, the structure of hot-deformed metal shows an increase

## МАТЕРІАЛОЗНАВСТВО

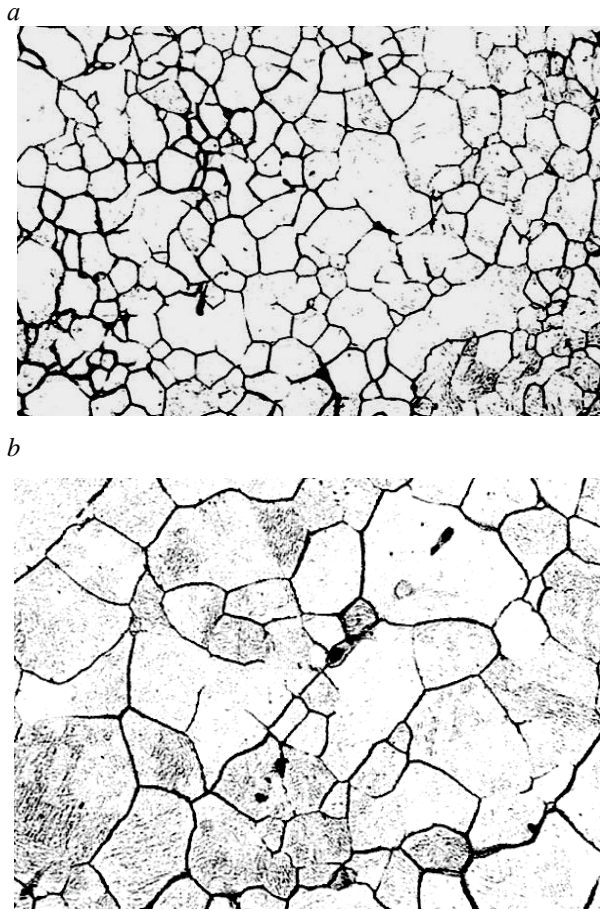


Fig. 1. Austenite steel structure with 0.55 % C after compression by 10 %, at the temperatures: *a* – 950 °C; *b* – 1100 °C. Magnification 100

in the number of grain boundaries with no individual fragments (Fig. 1, *b*). This feature indicates the beginning of abnormal grain growth, which causes a further increase in the austenite structure heterogeneity as a whole [1, 13]. Similar metal volumes (with no boundary sections), although in smaller quantities, were also determined in the structure at lower compression temperatures (Fig. 1, *a*). Increasing the carbon concentration in steel to 0.65 % did not result in qualitative changes in the nature of the formed austenite structure. First of all, it should be noted the invariance of the grains shape. At the same time, the average austenite grain size is more important for steel with high carbon content. Compared with steel with 0.55 % C, for the same temperatures and compression degrees (Fig. 1), the formed austenite structure visually has a larger average grain size (Fig. 2). Indeed, compared to the structures after the same deformation

conditions, for example, after compression by 10 %, for a temperature of 950 °C it can be determined that only increase in carbon concentration in steel by 0.1 % led to an increase in the austenite grain size by 30 μm. The above increase in relative values is approximately 30%. At the same time, the austenite structure heterogeneity as a whole has increased. For the studied steels, the obtained dependences of the austenite grain size on the temperature and the degree of hot compression qualitatively coincide with the known results of experimental studies [3, 4, 12].

Thus, in order to increase the structure uniformity and reduce the austenite grain size after the hot compression of the railway wheel blank, it may be proposed to increase the role of hot metal hardening. Thus, during the rim profile formation, taking into account the limited power of the rolling mill, you can increase the degree of hot hardening by lowering the compression temperature.

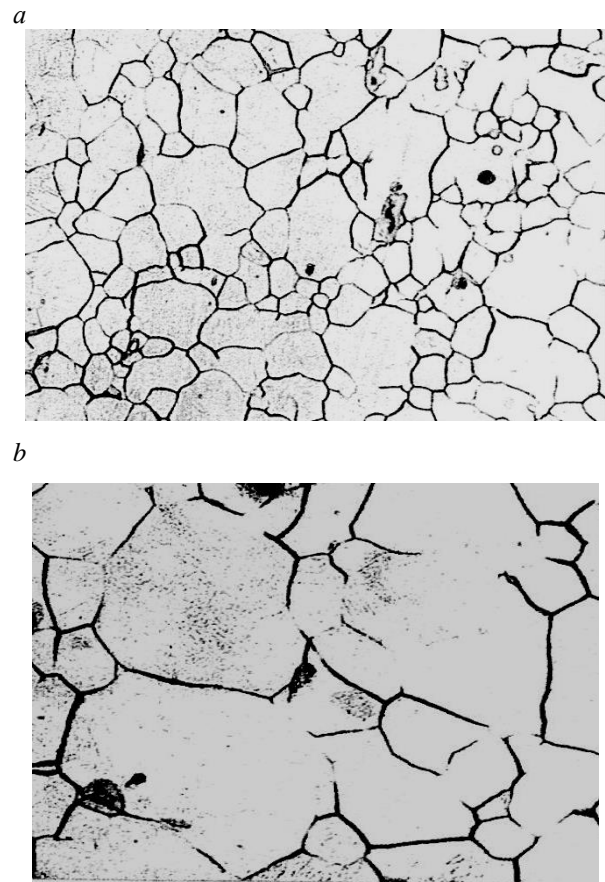


Fig. 2. The austenite structure of the steel from 0.65 % C after compression by 10 % at temperatures: *a* – 950 °C; *b* – 1100 °C. Magnification 100

## МАТЕРІАЛОЗНАВСТВО

Technologically, such an influence on the structure formation can be realized due to the gradual decrease in temperature during hot plastic deformation in case of rim formation. Indeed, after a certain deformation at the final stage of rim formation, even a slight decrease in temperature at the level of 100–150 °C of the surface layers should be sufficient to refine the austenite structure in the areas farther from the surface. This reduction in the compression temperature, providing increase in the resistance of surface layers of the rim metal, will increase the degree of hot plastic deformation of austenite in its central volumes. As a result, the central volumes of the rim will be subjected to more hot-cold work. Thus, increasing the degree of hot-cold work, accelerating the development of recrystallization processes, will lead to the formation of more uniform structure with crushed austenite grain across the rim of the solid-rolled railway wheel.

Compared with the change in the compression temperature, a certain influence on the development of crushing processes of austenite grains can be achieved by changing the scheme of metal deformation. The fact is that during hot compression of carbon steel at temperatures above  $A_{c3}$ , the ratio in the development of polygonization and recrystallization processes will determine the formation of the final austenitic structure [9, 11]. The mechanism of influence on the austenite structural changes in the case of replacement of a one-time deformation by compression in several stages (under conditions of constant total value) is actually determined by the conditions of the recrystallization center formation [1].

The critical degree of plastic deformation is the limit on the recrystallization diagram, which separates the areas with virtually absent signs of recrystallization processes from those in which a few seconds are sufficient to complete it. In this case, the rate of accumulation of defects in the crystalline structure and their location will have a decisive influence on the grain nucleation during recrystallization. Thus, in the initial stages of hot compression, when the accumulation of defects in the crystalline structure corresponds to their uniform distribution in the metal matrix, the conditions for the formation of the recrystallization nucleus will not be met [6]. In case of increasing the

deformation degree of the heterogeneity of the defects distribution and, first of all, dislocations will increase proportionally. The moment of formation of the recrystallization center corresponds to the value of hot compression, when there is a fluctuation in the dislocation distribution of the corresponding level. Thus, by subjecting carbon steel to hot compression by the values that are insufficient for the formation of the recrystallization nucleus, it becomes possible to shift the moment of development of this process towards longer exposures after deformation.

Analysis of the research results [2, 3] confirmed the possibility of improving the structural condition and the associated set of properties after hot compression of rolled carbon steels. At the temperature of hot compression of railway wheel carbon steel 1250 °C, the replacement of the deformation value of 30 % by three stages of 10 % has led to an increase in relative elongation, metal fracture energy, crack resistance by about 10–12 % [1]. The obtained result has its own explanation. Thus, given that the formation of the recrystallization nucleus of carbon steel austenite both in the process of hot compression and during exposure between the deformation stages is largely determined not so much by reducing the defect density in the crystalline structure, as their redistribution, replacement of one-time deformation by the fractional one can significantly change the conditions of this process development.

Based on the analysis of experimental data [12], it can be stated that the development of the recrystallization process «in situ» should lead to the formation of such a substructure, which after hot compression determines the influence on the final structural state of the finished product. The results of the microstructure study are given in Table 1. Analysis of the obtained austenite grain sizes shows that the peripheral metal volumes of the railway wheel rim, which are in direct contact with the deforming tool, have a slightly lower temperature compared to ones that are more distant. As a result, the state of hot-cold work will be maintained in these metal volumes for a longer period of time. In turn, this will increase the defect concentration in the crystalline structure in the austenite grains after the deformation.

Table 1

**Influence of one-time and fractional compression of carbon steel at a temperature of 1250 °C**

General deformation degree 30 %	Austenite grain size (μm) at a distance from the compression surface (mm)	
	10	35
one-time	110	100
fractional	54	100

This increased density of defects in the austenite structure will be an additional stimulus for the development of both dynamic in the compression process and static recrystallization during the exposure after hot compression. On the other hand, the austenitic structure of carbon steel is very sensitive to the density of crystalline defects introduced during hot plastic deformation. For example, increasing the deformation degree by approximately 1.5 times at a temperature of 1000 °C, reduces the completion time of austenite recrystallization to 10 times, from 20–30 to 3 sec [3]. Thus, in case of replacing 30 % of hot deformation with three times 10 %, the conditions for the formation of the austenite structure with smaller grains will be achieved, which will further determine the final metal structure of the railway wheel (Fig. 3). In case of increasing the distance from the compression surface, the change in the deformation scheme (single or fractional) will have a proportionally lower influence on the austenite grain size (Fig. 3, Tab. 1).

Thus, the structural changes in the railway wheel steel are largely due to the austenite structure formation during hot compression. On the other hand, additional dispersion of austenite grains can be achieved by violating the development conditions of collective recrystallization processes, changing the relationship between the degree of hot deformation, the duration of isothermal exposure, etc. [7, 14]. These provisions are explained by the competing influence on the structure formation during heating of the deformed metal material according to qualitatively different mechanisms.

Under conditions when the degree of plastic deformation is not enough to start the development of recrystallization processes, structural transformations occur due to the development of polygonization.

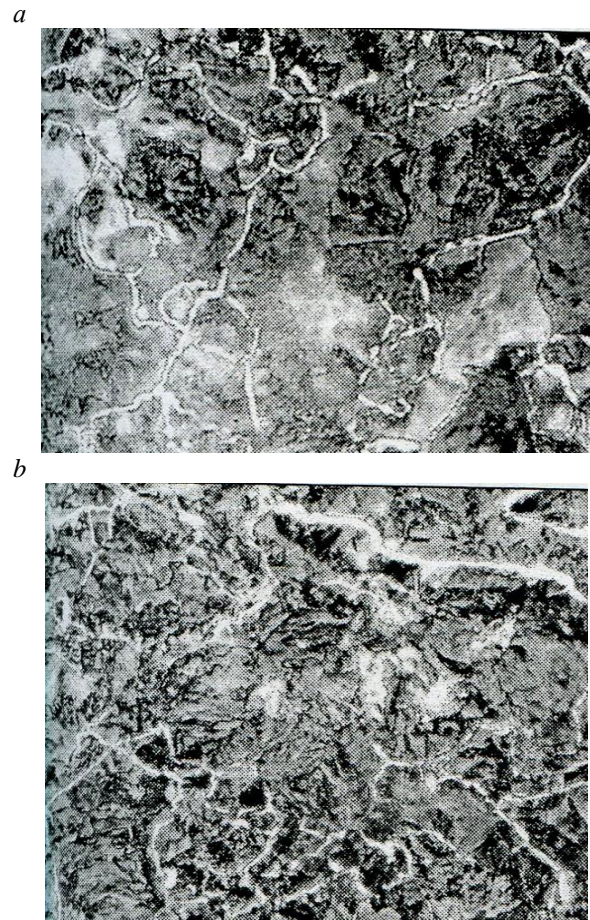


Fig. 3. Structure of railway wheel steel at a distance of 10 mm from the compression surface after one-time deformation of 30 % (a) and fractional one (b). Magnification 300

As a result, the conditions of formation of the recrystallization nucleus in the deformed metal are violated. In order to further promote the recrystallization development, it is necessary to carry out additional plastic deformation or increase the heating temperature of the deformed metal. Thus, the replacement of one-time compression by fractional one will accelerate the development of polygonization processes, which should significantly violate the formation conditions of the nucleus of recrystallized austenitic grain. The austenitic structure formed under these conditions will positively affect the final structural state of the carbon steel of the railway wheel at the final stage of thermal hardening [4, 5, 10].

### Originality and practical value

Based on a study of the development of collective recrystallization processes during the hot compression of carbon steel of railway wheel, it is determined that the increase in carbon content contributes to the increase of austenite grains. After completion of hot compression of the wheel blank, the structural inhomogeneity of austenite that occurs is determined by a change in the development mechanism of recrystallization processes. In case of deformations above the critical degree, the formation and successive growth of recrystallization nuclei takes place, which leads to the structure fragmentation. At deformations below the critical value, the growth of austenite grains occurs according to the coalescence mechanism, according to which fragments of boundaries with large disorientation angles consistently disappear. In order

to refine austenite grains in the massive elements of the wheel, we offer to replace one-time hot compression by fractional one.

### Conclusions

1. In case of hot compression of the railway wheel blank, increasing the carbon atoms concentration within the grade composition of steel contributes to the growth of the average austenite grain size.

2. Formation of a certain degree of structural inhomogeneity of austenite at the cross section of the rim or hub of the railway wheel is due to the dependence of the development mechanism of recrystallization processes on the deformation value.

3. Under conditions of the same degree of hot plastic deformation, the replacement of one-time compression by fractional one helps to reduce the austenite grain size.

### LIST OF REFERENCE LINKS

1. Вакуленко И. А., Большаков В. И. *Морфология структуры и деформационное упрочнение стали*. Днепро : Маковецкий, 2008. 196 с.
2. Вакуленко И., Перков О., Страдомски З. Влияние температуры величины горячей деформации на размер зерна аустенита при изготовлении железнодорожных колес. Copyright by Wydawnictwo Wydziału Inżynierii Produkcji i Technologii Materialow Politechniki Czestochowskiej. *New technologies and achievements in metallurgy, material engineering and production engineering : Collective monograph XVI International Scientific Conference*. Czestochowa, 2015. № 48. С. 365–368.
3. Узлов И. Г., Перков О. Н., Вакуленко И. А. Влияние схемы горячей деформации заготовки на свойства металла обода цельнокатаных железнодорожных колес. *Фундаментальные и прикладные проблемы черной металлургии*. 2002. Вып. 5. С. 196–199.
4. Шифрин М. Ю., Андреев Ю. В., Лихошвай В. А. Влияние деформации заготовки на прессах и в колесопрокатном стане на механические свойства диска и обода цельнокатаных колес. *Кузнечно-штамповочное производство*. 1970. № 8. С. 7–11.
5. Banerjee A., Hossain R., Pahlevani F., Zhu Q., Sahajwalla V. Prusty G. Strain-rate-dependent deformation behaviour of high-carbon steel in compression : mechanical and structural characterization. *Journal of Materials Science*. 2019. Vol. 54. Iss. 8. P. 6594–6607. DOI: <https://doi.org/10.1007/s10853-018-03301-x>
6. Hossain R., Pahlevani F., Quadir M. Z. Sahajwalla V. Stability of retained austenite in high carbon steel under compressive stress : an investigation from macro to nano scale. *Scientific Reports*. 2016. Vol. 6. P. 1–11. DOI: <https://doi.org/10.1038/srep34958>
7. Hubbard D. *Plastic Deformation : Processes, Properties and Applications*. USA : Nova Science Publishers, 2016. 198 p.
8. Ławrynowicz Z. Plastic deformation and softening of the surface layer of railway wheel. *Advances in Materials Science*. 2015. Vol. 15. Iss. 4. P. 6–13. DOI: <https://doi.org/10.1515/adms-2015-0018>
9. Mirzadeh H. Constitutive modeling and prediction of hot deformation flow stress under dynamic recrystallization conditions. *Mechanics of Materials*. 2015. Vol. 85. P. 66–79. DOI: <https://doi.org/10.1016/j.mechmat.2015.02.014>
10. Qiu C., Cookson J., Mutton P. The role of microstructure and its stability in performance of wheels in heavy haul service. *Journal of Modern Transportation*. 2017. Vol. 25. Iss. 4. P. 261–267. DOI: <https://doi.org/10.1007/s40534-017-0143-9>

## МАТЕРІАЛОЗНАВСТВО

11. Ren X., Qi J., Gao J., Wen L., Jiang B., Chen G., Zhao H. Effects of Heating Rate on Microstructure and Fracture Toughness of Railway Wheel Steel. *Metallurgical and Materials Transactions A*. 2016. Vol. 47. Iss. 2. P. 739–747. DOI: <https://doi.org/10.1007/s11661-015-3264-y>
12. Shen X., Yan J., Zhang L., Gao L., Zhang J. Austenite grain size evolution in railway wheel during multi-stage forging processes. *Journal of Iron and Steel Research Internation*. 2013. Vol. 20. Iss. 3. P. 57–65. DOI: [https://doi.org/10.1016/s1006-706x\(13\)60070-9](https://doi.org/10.1016/s1006-706x(13)60070-9)
13. Zhao H., Qi J., Su R., Zhang H., Chen H., Bai L., & Wang C. Hot deformation behaviour of 40CrNi steel and evaluation of different processing map construction methods. *Journal Materials Research and Technology*. 2020. Vol. 9. Iss. 3. P. 2856–2869. DOI: <https://doi.org/10.1016/j.jmrt.2020.01.020>
14. Wang J., Xiao H., Xie H. B., Xu X. M. Simulation of Recrystallization Behavior and Austenite Grain Size Evolution during Hot Deformation of Low Carbon Steel Using the Flow Stress. *Advanced Materials Research*. 2011. Vol. 337. P. 178–183. DOI: <https://doi.org/10.4028/www.scientific.net/AMR.337.178>

I. O. ВАКУЛЕНКО<sup>1\*</sup>, Д. М. БОЛОТОВА<sup>2</sup>, С. В. ПРОЙДАК<sup>3</sup>, Х. АСКЕРОВ<sup>4</sup>, Х. КУГ<sup>5</sup>,  
А. О. ЧАЙКОВСЬКА<sup>6</sup>

<sup>1\*</sup>Каф. «Прикладна механіка та матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 56, ел. пошта [vakulenko\\_igor@ukr.net](mailto:vakulenko_igor@ukr.net), ORCID 0000-0002-7353-1916

<sup>2</sup>Дніпровський ліцей залізничного транспорту, вул. Універсальна, 7, Дніпро, Україна, 49024, тел.+38 (098) 351 99 70, ел. пошта [dasha.bolotova@i.ua](mailto:dasha.bolotova@i.ua), ORCID 0000-0001-6947-3963

<sup>3</sup>Каф. «Прикладна механіка та матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 56, ел. пошта [proydaak.sv@ukr.net](mailto:proydaak.sv@ukr.net), ORCID 0000-0003-2439-3657

<sup>4</sup>Каф. «Інженерна механіка», Карабукський університет, Карабук, Турція, 78050, тел. +90 (538) 455 04 45, ел. пошта [hangardasaskerov@karabuk.edu.tr](mailto:hangardasaskerov@karabuk.edu.tr), ORCID 0000-0003-4771-3406

<sup>5</sup>Каф. «Інженерна механіка», Карабукський університет, Карабук, Турція, 78050, тел. +90 (544) 842 62 08, ел. пошта [harun1878@gmail.com](mailto:harun1878@gmail.com), ORCID 0000-0002-6322-4269

<sup>6</sup>Каф. «Матеріалознавства та обробки матеріалів», Придніпровська державна академія будівництва та архітектури, вул. Чернишевського, 24а, Дніпро, Україна, 49005, тел. +38 (095) 618 14 63, ел. пошта [chaikovska.hanna@pgasa.dp.ua](mailto:chaikovska.hanna@pgasa.dp.ua), ORCID 0000-0001-6707-0159

## ФОРМУВАННЯ СТРУКТУРИ ВУГЛЕЦЕВОЇ СТАЛІ ПІД ЧАС ГАРЯЧОЇ ПЛАСТИЧНОЇ ДЕФОРМАЦІЇ

**Мета.** Основною метою роботи є визначення особливостей розвитку процесів рекристалізації аустеніту вуглецевої сталі залежно від ступеня гарячої пластичної деформації та розробка пропозицій щодо поліпшення структурного стану металу залізничного сучільнокатаного колеса. **Методика.** Як матеріал для досліджень використані дві вуглецеві сталі залізничного колеса з мінімальним і максимальним вмістом вуглецю 0,55 і 0,65 % та іншими хімічними елементами в межах марочного складу сталі 60. Зразки у вигляді циліндрів діаметром 20 мм і висотою 40 мм нагрівали в муфельній печі, витримували певний час для вирівнювання температури по перетину зразка. Після цього зразки піддавали гарячому обтискуванню на випробувальній машині типу «Інстрон». Температурний інтервал гарячого обтискування зразків складав 950–1 100 °С, за ступенів деформації по висоті в інтервалі 10–40 %. Швидкість деформації дорівнювала  $10^{-3}$ – $10^{-2}$  с<sup>-1</sup>. Для виявлення меж зерен аустеніту використовували стандартний травник. Структурні дослідження проводили з використанням світлового мікроскопа типу «Епіквант» за збільшень, достатніх для визначення особливостей будови зерен аустеніту. Величину розміру зерна аустеніту визначали за методиками кількісної металографії. **Результати.** У разі гарячого обтискування заготовки залізничного колеса збільшення концентрації атомів вуглецю лише в межах марочного складу сталі достатньо для зростання середнього розміру зерна аустеніту, що підтверджує пропозиції щодо обмеження вмісту вуглецю в металі залізничних коліс. Формування визначеного ступеня структурної неоднорідності аустеніту по перетину обода або маточини залізничного колеса обумовлене зміною механізму розвитку процесів рекристалізації залежно від величини деформації. За умов однакового ступеня гарячої пластичної деформації заміна одноразового обтискування на подрібнене супроводжується порушенням умов формування зародка рекристалізації. У результаті вказаної



## МАТЕРІАЛОЗНАВСТВО

заміни схеми гарячої пластичної деформації досягається зменшення розміру зерна аустеніту. **Наукова новизна.** На основі дослідження розвитку процесів збиральної рекристалізації під час гарячого обтискування вуглецевої сталі залізничного колеса визначено, що збільшення вмісту вуглецю сприяє збільшенню зерна аустеніту. Після завершення гарячого обтискування заготовки колеса структурна неоднорідність аустеніту, що виникає, визначається зміною механізму розвитку процесів рекристалізації. Під час деформацій вище критичного ступеня відбувається формування й послідовне зростання зародків рекристалізації, що призводить до подрібнення структури. У разі деформацій нижче критичного значення зростання зерен аустеніту відбувається за механізмом коалесценції, за яким послідовно зникають фрагменти меж із великими кутами дезорієнтації. **Практична значимість.** Для подрібнення зерен аустеніту в масивних елементах залізничного суцільнокатаного колеса пропонуємо заміну одноразового гарячого обтискування на подрібнене.

*Ключові слова:* аустеніт; деформація; температура; розмір зерна; вуглецева сталь; залізничне колесо

И. А. ВАКУЛЕНКО<sup>1\*</sup>, Д. М. БОЛОТОВА<sup>2</sup>, С. В. ПРОЙДАК<sup>3</sup>, Х. АСКЕРОВ<sup>4</sup>, Х. КУГ<sup>5</sup>, А. О. ЧАЙКОВСКАЯ<sup>6</sup>

<sup>1\*</sup>Каф. «Прикладная механика и материаловедение», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепро, Украина, 49010, тел. +38 (056) 373 15 56, эл. почта vakulenko\_ihor@ukr.net, ORCID 0000-0002-7353-1916

<sup>2</sup>Днепропетровский лицей железнодорожного транспорта, ул. Универсальная, 7, Днепро, Украина, 49024, тел. +38 (098) 351 99 70, эл. почта dasha.bolotova@i.ua, ORCID 0000-0001-6947-3963

<sup>3</sup>Каф. «Прикладная механика и материаловедение», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепро, Украина, 49010, тел. +38 (056) 373 15 56, эл. почта proydak.sv@ukr.net, ORCID 0000-0003-2439-3657

<sup>4</sup>Каф. «Инженерная механика», Карабукский университет, Катабук, Турция, 78050, тел. +90 (538) 455 04 45, эл. почта hangardasaskerov@karabuk.edu.tr, ORCID 0000-0003-4771-3406

<sup>5</sup>Каф. «Инженерная механика», Карабукский университет, Катабук, Турция, 78050, тел. +90 (544) 842 62 08, эл. почта hagnun1878@gmail.com, ORCID 0000-0002-6322-4269

<sup>6</sup>Каф. «Материаловедения и обработки материалов», Приднепровская государственная академия строительства и архитектуры, ул. Чернышевского, 24а, Днепро, Украина, 49005, тел. +38 (095) 618 14 63, эл. почта chaikovska.hanna@pgasa.dp.ua, ORCID 0000-0001-6707-0159

## ФОРМИРОВАНИЕ СТРУКТУРЫ УГЛЕРОДИСТОЙ СТАЛИ ПРИ ГОРЯЧЕЙ ПЛАСТИЧЕСКОЙ ДЕФОРМАЦИИ

**Цель.** Основной целью работы является определение особенностей развития процессов рекристаллизации аустенита углеродистой стали в зависимости от степени горячей пластической деформации и разработка предложений по улучшению структурного состояния металла железнодорожных цельнокатаных колес. **Методика.** В качестве материала для исследований использованы две углеродистые стали железнодорожных колес с минимальным и максимальным содержанием углерода 0,55 и 0,65 %, и другими химическими элементами в пределах марочного состава стали 60. Образцы в виде цилиндров диаметром 20 мм и высотой 40 мм нагревали в муфельной печи, выдерживали требуемое время для выравнивания температуры по сечению образца. После этого образцы подвергались горячему обжатию на испытательной машине типа «Инстрон». Температурный интервал горячего обжатия образцов составлял 950–1100 °С, при степенях деформации по высоте в интервале 10–40 %. Скорость деформации составляла 10<sup>-3</sup>–10<sup>-2</sup> с<sup>-1</sup>. Для выявления границ зерен аустенита использован стандартный травитель. Исследования структуры осуществляли с использованием светового микроскопа типа «Епиквант» при увеличениях, достаточных для определения особенностей строения зерен аустенита. Величину размера зерна аустенита определяли с использованием методик количественной металлографии. **Результаты.** При горячем обжатии заготовки железнодорожного колеса увеличения концентрации атомов углерода только в пределах марочного состава стали достаточно для роста среднего размера зерна аустенита, что подтверждает предложения по ограничению содержания углерода в металле железнодорожных колес. Формирование определенной степени структурной неоднородности аустенита по сечению обода или ступицы железнодорожного колеса обусловлено изменением механизма развития процессов рекристаллизации в зависимости от величины деформации. В условиях одинаковой степени горячей пластической деформации замена одноразового обжатия на дробное сопровождается

## МАТЕРІАЛОЗНАВСТВО

нарушением условий формирования зародыша рекристаллизации. В результате указанной замены схемы горячей пластической деформации достигается уменьшение размера зерна аустенита. **Научная новизна.** На основе исследования развития процессов собирательной рекристаллизации во время горячего обжата углеродистой стали железнодорожного колеса определено, что увеличение содержания углерода способствует приросту размера зерна аустенита. После завершения горячего обжата заготовки колеса возникающая структурная неоднородность аустенита объясняется изменением механизма развития процессов рекристаллизации. При деформациях выше критической степени происходит формирование и последовательный рост зародышей рекристаллизации, приводя к измельчению структуры. При деформациях ниже критического значения рост зерен аустенита происходит по механизму коалесценции, по которому последовательно исчезают фрагменты границ с большими углами разориентации. **Практическая значимость.** Для измельчения зерен аустенита в массивных элементах железнодорожного цельнокатаного колеса предлагаем замену одно-разового горячего обжата на дробное.

*Ключевые слова:* аустенит; деформация; температура; размер зерна; углеродистая сталь; железнодорожное колесо

## REFERENCES

1. Vakulenko, I. A., & Bolshakov, V. I. (2008). *Morfologiya struktury i deformatsionnoe uprochnenie stali*. Dnepropetrovsk: Makovetskiy Y. V. (in Russian)
2. Vakulenko, I., Perkov, O., & Stradomski, Z. (2015). Influence of Temperature and Value of Hot Deformation on Size of Grain in Austenite at Making of Railway Wheels. Copyright by Wydawnictwo Wydziału Inżynierii Produkcji i Technologii Materialow Politechniki Czestochowskiej. *New technologies and achievements in metallurgy, material engineering and production engineering: Collective monograph XVI International Scientific Conference. Czestochowa*, 48, 365-368. (in Russian)
3. Uzlov, I. G., Perkov, O. N., & Vakulenko, I. A. (2002). Vliyanie skhemy goryachey deformatsii zagotovki na svoystva metalla oboda tselnokatanykh zheleznodorozhnykh koles. *Fundamentalnye i prikladnye problemy chernoy metallurgii*, 5, 196-199. (in Russian)
4. Shifrin, M. Yu., Andreev, Yu. V., & Likhoshvayj, V. A. (1970). Vliyanie deformatsii zagotovki na pressakh i v kolesoprokatnom stane na mekhanicheskie svoystva diska i oboda tselnokatanykh koles. *Kuznechno-shtampovoechnoe proizvodstvo*, 8, 7-11. (in Russian)
5. Banerjee, A., Hossain, R., Pahlevani, F., Zhu Q., Sahajwalla V., & Prusty G. (2019). Strain-rate-dependent deformation behaviour of high-carbon steel in compression: mechanical and structural characterization. *Journal of Materials Science*, 54(8), 6594-6607. DOI: <https://doi.org/10.1007/s10853-018-03301-x> (in English)
6. Hossain, R., Pahlevani, F., Quadir, M. Z., & Sahajwalla, V. (2016). Stability of retained austenite in high carbon steel under compressive stress: an investigation from macro to nano scale. *Scientific Reports*, 6, 1-11. DOI: <https://doi.org/10.1038/srep34958> (in English)
7. Hubbard, D. (2016). *Plastic Deformation: Processes, Properties and Applications*. USA: Nova Science Publishers. (in English)
8. Ławrynowicz, Z. (2015). Plastic deformation and softening of the surface layer of railway wheel. *Advances in Materials Science*, 15(4), 6-13. DOI: <https://doi.org/10.1515/adms-2015-0018> (in English)
9. Mirzadeh, H. (2015). Constitutive modeling and prediction of hot deformation flow stress under dynamic recrystallization conditions. *Mechanics of Materials*, 85, 66-79. DOI: <https://doi.org/10.1016/j.mechmat.2015.02.014> (in English)
10. Qiu, C., Cookson, J., & Mutton, P. (2017). The role of microstructure and its stability in performance of wheels in heavy haul service. *Journal of Modern Transportation*, 25(4), 261-267. DOI: <https://doi.org/10.1007/s40534-017-0143-9> (in English)
11. Ren, X., Qi, J., Gao, J., Wen, L., Jiang, B., Chen, G., & Zhao, H. (2016). Effects of Heating Rate on Microstructure and Fracture Toughness of Railway Wheel Steel. *Metallurgical and Materials Transactions A*, 47(2), 739-747. DOI: <https://doi.org/10.1007/s11661-015-3264-y> (in English)
12. Shen, X., Yan, J., Zhang, L., Gao, L., & Zhang, J. (2013). Austenite grain size evolution in railway wheel during multi-stage forging processes. *Journal of Iron and Steel Research International*, 20(3), 57-65. DOI: [https://doi.org/10.1016/s1006-706x\(13\)60070-9](https://doi.org/10.1016/s1006-706x(13)60070-9) (in English)

МАТЕРІАЛОЗНАВСТВО

---

13. Zhao, H., Qi, J., Su, R., Zhang, H., Chen, H., Bai, L., & Wang, C. (2020). Hot deformation behaviour of 40CrNi steel and evaluation of different processing map construction methods. *Journal Materials Research and Technology*, 9(3), 2856-2869. DOI: <https://doi.org/10.1016/j.jmrt.2020.01.020> (in English)
14. Wang, J., Xiao, H., Xie, H. B., & Xu, X. M. (2011). Simulation of Recrystallization Behavior and Austenite Grain Size Evolution during Hot Deformation of Low Carbon Steel Using the Flow Stress. *Advanced Materials Research*, 337, 178-183. DOI: <https://doi.org/10.4028/www.scientific.net/AMR.337.178> (in English)

Received: January 21, 2020

Accepted: May 25, 2020