RESEARCH AND ENGINEERING
INNOVATION PROJECTS
OF THE NATIONAL ACADEMY
OF SCIENCES OF UKRAINE

https://doi.org/10.15407/scine19.04.047

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SPECIFIC FEATURES OF THE FORMATION OF STRUCTURAL HETEROGENEITY IN CARBON STEEL DEPENDING ON MANUFACTURING TECHNIQUE

Introduction. *Uniform and homogeneous microstructure of dimensional steel products is the most important for ensuring the required set of properties.*

Problem Statement. *Modes of deformation and heat treatment, which are used today, need to be adjusted, depending on the characteristics of steel smelting to ensure high properties of metal products.*

Purpose. *To analyze the effect of the size of original continuous-cast billet, its geometry, the degree of treatment of the finished railway axle and to study the influence of steel purity on the structural properties of railway axles as finished product.*

Material and Methods. *All test samples are taken from half-neck thick rough railway axles. The axles have the same size of Ø 218 mm. All axles undergo two temperature normalizations (820 and 840 °C, respectively). The microstructures are photographed by Axiovert 200 MAT.*

Results. *The experimental findings have shown that the structural formation of the final structure in railway axles manufactured with the use of different production methods has significant differences. Importantly, these differences have also been observed during the experimental heat treatment of non-deformed billets. The process of deformation solely contributes to the softening effect on the original structure casting processes and reduces liquation inhomogeneity, imperfections, and other related structural irregularities.*

Conclusions. *In the context of the optimal chemical composition of steel for the production of crucial railway components, careful consideration shall be given to the steel production method, raw materials, and technological aspects that are specific to the metallurgical facility. This is imperative since steel samples with similar chemical compositions can exhibit distinct patterns of structure formation. In particular, it has been observed that the development of a ferrite boundary adjacent to sulfide inclusions shares similarities with the formation of gas bubbles and exhibits a characteristic structure. The sulfide inclusions are present in the liquation zone together with other liquates and gases in the steel.*

Keywords: microstructure, railway axle, carbon steel, deformation, and liquation heterogeneity.

Citation: Babachenko, O. I., Balakhanova, T. V., Safronova, O. A., and Podolskyi, R. V. (2023). Specific Features of the Formation of Structural Heterogeneity in Carbon Steel Depending on Manufacturing Technique. *Sci. innov.*, 19(4), 47—56. https://doi.org/10.15407/scine19.04.047

In previous works [1—4], for the first time, the difference in the influence of some chemical elements of railway axles steel, in particular, the content of sulfur and manganese, on the impact toughness for several grades of steel for the manufacture of railway axles has been found. In particular, it has been assumed that joint deoxygenation and sulfur content in steel influence the formation of microhardness heterogeneity across the cross-section of cast steel for railway axles and structure microheterogeneity of individual sections. In the study of the effect of micro-liquefaction of steel on the formation of a homogeneous structure and the effect of homogenization on the mechanical properties of carbon steels, the most noticeable effect has been observed in the samples with pulled inclusions [5]. In [5], the effect of sulfides and silicates on changing shape properties has been studied. It has been shown that the mechanical properties after heat treatment (10 min at 1315 °C) improve due to fining or coarsening inclusions rather than because of changing liquation. The importance of controlling the shape of inclusions to optimize the mechanical properties has been emphasized. Back in 1971, Grange [6] showed that elongated non-metallic inclusions had the greatest influence, followed by the effect of phase and structural in homogeneities. Numerous studies have shown that elongated, striped inclusions of manganese sulfide complicate the diffusion of carbon and thus contribute to liquation [7].

The thermodynamic calculations have shown that the area of ferrite formation increases as sulfur content grows, with sulfur stimulating ferrite formation. According to [8], MnS inclusions are the nucleation site of pre-eutectoid ferrite, and the number of isolated MnS inclusions is positively correlated with the fraction of the area of isolated pre-eutectoid ferrite. With the use of the FIB-TEM technique, the relationship between the orientation and crystal structure of the MnS inclusion and pre-eutectoid ferrite has been studied. The results have shown that MnS inclusions are not directly related to the formation of pre-eutectoid ferrite. The Mn depletion zone around the MnS inclusion observed in the EDS and EPMA results is a direct factor inducing the formation of pre-eutectoid ferrite in medium carbon sulfur steel.

From a review of modern scholarly research literature, it becomes clear that a ferrite border is formed around non-metallic inclusions only under the condition that manganese is displaced during the formation of sulfide. At the same time, the inclusion is a factor affecting the difference in microsegregation rather than a substrate for the formation of ferrite. However, the authors of the available studies have not developed the idea of a relationship between sulfur inclusions and steel gassing. Although it is known that the type of sulfide inclusions and the time of their formation depend on the oxygen content in steel [9]. In [3], when studying a small array of data, the authors have assumed that the formation of pre-eutectoid ferrite depends not only on the content of sulfur and manganese, but also on the deoxidation of steel. Therefore, the problem of the influence of the features of carbon steel manufacture in this research has been studied more thoroughly, by the example of the features of the structure formation of railway axles, as a type of metal product, the quality of which is subject to strict requirements, including for the homogeneity of the microstructure.

The rough railway axles were manufactured by one manufacturer, with close temperature and time regimes of deformation processing. The main difference was technique for producing the original continuous-cast billets (CCB), and the task of the work was to investigate how the morphological features of the steel structure of railway axles were formed with the same normalized chemical composition of steel and the same deformation and heat treatment. The origin, size, and chemical composition of the billets are given in Table 1.

All test samples are taken from the half-neck thick rough railway axles. The axles have the same size of Ø 218 mm. All axes undergo two temperature normalizations (820 and 840 °C, respectively). The railway axles are manufactured by standard technology at PrJSC KAMET-STEEL. All metal, both manufactured by KAMET-STEEL PJSC and by other manufacturers, besides the same deformation and thermal treatment regimes, undergoes mandatory anti-flocculation treatment, despite a relatively low hydrogen content, in addition to the treatment in a vacuum cleaner. Such measures are necessary, first of all, for removing internal stresses that could contribute to the emergence of internal defects and result in rejection of defected pieces during ultrasonic control of finished axles rather than for removing hydrogen from the billets [10]. Such a selection of samples makes it possible not only to analyze the influence of the size of the original CCB, its geometry, the degree of treatment of the finished railway axle, but also to investigate the effect of steel purity on the structural properties of railway axles as finished product.

Electrical steel is now considered purer in terms of non-metallic inclusions. Steel for railway axles produced by DNIPROSTAL is processed in a liquid state in a vacuum cleaner, in a furnace-ladle unit, and while being poured undergoes electromagnetic stirring. Vacuuming of steel not only removes the total gas content, but also significantly reduces the amount of hydrogen. At KAMET-STEEL, the metal undergoes out-of-furnace processing at the universal forge and rolling mill, but is not vacuumed because of the absence of a vacuum cleaner in the process scheme of steel production. It should be noted that railway axle prototypes are subjected to two normalizations, although in recent years the technology for thermal treatment of railway axles includes one-stage normalization with controlled slow cooling (self-tempering) of axles in special wells [8]. Such heat treatment has shown a greater positive effect on the formation of a uniform structure.

The type of used ferroalloys, the content of impurity elements in them, which is not regulated by standards, the sequence of their introduction into the semi-finished metal, and the use of certain solid slag mixtures — all these factors have a certain influence on the formation and removal of non-metallic inclusions. Because of the lack of complete information, this issue has not been considered in this paper. High purity of steel in terms of non-metallic inclusions of certain types, sizes, and quantities can be achieved by creating a scientifically based approach to the selection of technological parameters at each stage of the smelting, refining, and pouring process (crystallization of steel with a regulated residual content of oxygen (sulfur) and active deoxidizing elements, as well as their certain ratios). In [10], it has been found that, other things being equal, the number, type, and size of non-metallic inclusions depends

Table 1. **Chemical Composition and Specific Features of Original Continuous-Cast Billets**

No.	Manufacturer	Manufacturing technique	Cross section of original CCB	C	Mn	Si	S	P	Cr	Ni	Cu	Al
1	KAMET—STAL	Converter, furnace-ladle, without vacuuming	335 × 400	0.47	0.80	0.26	0.006	0.012	0.02	0.01	0.01	0.033
2	Azovelectrostal	Converter, furnace-ladle, vacuuming	Ø 400	0.46	0.72	0.24	0.010	0.009	0.07	0.11	0.16	0.023
3	Alchevsk Metallurgical Works	Vacuuming, converter, furnace-ladle	300 × 1000	0.47	0.81	0.29	0.004	0.012	0.042	0.033	0.024	0.030
4	MZ Dniprostal	Electrosteel, vacuuming	Ø 470	0.49	0.84	0.20	0.003	0.013	0.11	0.13	0.15	0.021

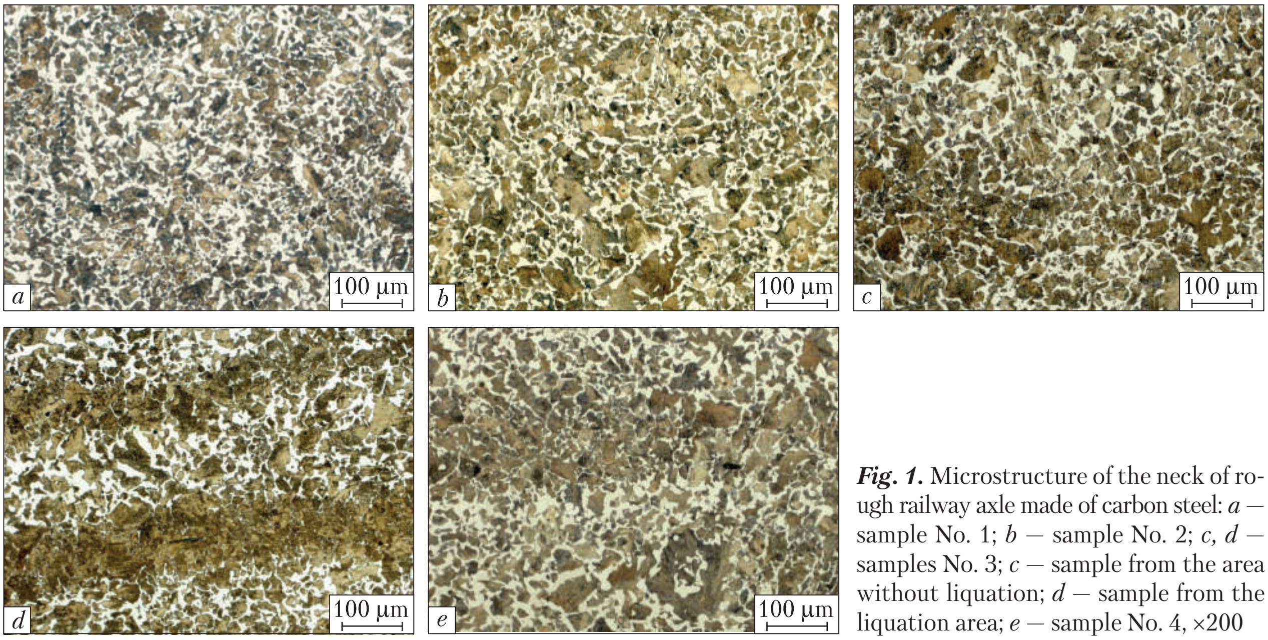

Fig. 1. Microstructure of the neck of rough railway axle made of carbon steel: *a* — sample No. 1; *b* — sample No. 2; *c, d* — samples No. 3; *c* — sample from the area without liquation; *d* — sample from the liquation area; *e* — sample No. 4, ×200

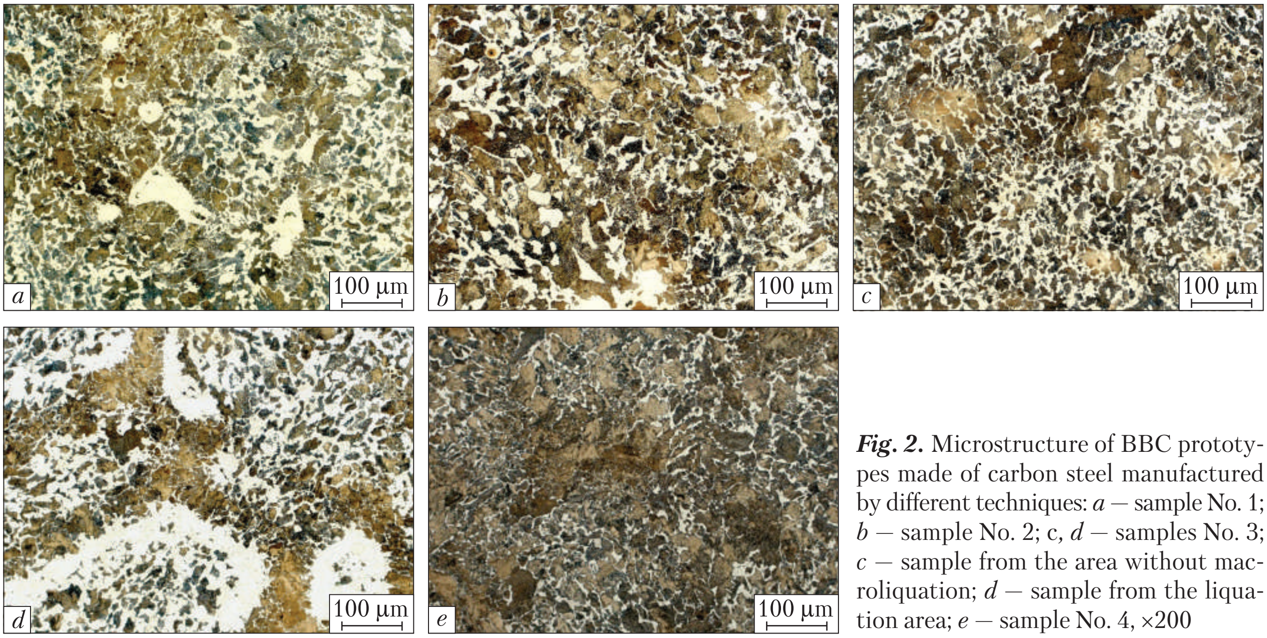

Fig. 2. Microstructure of BBC prototypes made of carbon steel manufactured by different techniques: *a* — sample No. 1; *b* — sample No. 2; c, *d* — samples No. 3; *c* — sample from the area without macroliquation; *d* — sample from the liquation area; *e* — sample No. 4, ×200

primarily on the type and number of used deoxidizers, the degree of assimilation and their residual mass fraction in the finished metal product.

The typical photographs of the microstructures are given in Fig. 1.

The liquation zones are identified by well-known method for detecting sulfide inclusions that are known to be formed in interdendritic liquation areas.

A sample of non-vacuum steel for railway axles of converter production (No. 1) has a more uniform structure without local areas of accumulated pearlite or ferrite. It has been shown that a ferrite border is formed in the areas of microsegregation both near manganese sulfides and smallest oxide inclusions. In electrical steel sample (sample No. 4), despite the lower sulfur content and gassing of the steel, a significant structural heterogeneity is observed, with a dense layer of pearlite formed around the sulfides. The highest content of pearlite has been found in the liquation areas that correspond to the interdendritic space. It can be seen that the structure of samples No. 2 and No. 3 (area without macroliquation) is quite similar. In general, they have a uniform structure, single large pearlite grains located mainly in the interdendritic areas. Thus, the presence of globular sulfides can contribute to the formation of a uniform structure. The authors of [7] have made approximately the same conclusion.

At the same time, it should be noted that there is no relationship between the size of the sulfide inclusion and the thickness of the ferrite border around this inclusion. For example, in the photo of sample No. 1 of KAMET—STEEL, there are both small and large inclusions that can be identified as manganese sulfides and complex manganese and iron sulfides during metallographic analysis. However, the largest amount of ferrite is observed in the areas that contain very small inclusions (< 1 μm). In [11—13], there have been made different conclusions on the possibility of the formation of pre-eutectoid ferrite around sulfide inclusions larger than 10 μm. However, there is a direct relationship between the number of inclusions and the content of ferrite: the greater the number of inclusions, the higher the content of pre-eutectoid ferrite [14]. At the same time, the amount of sulfide inclusions depends primarily on the sulfur content in the steel.

Since in this research, all test samples are selected from rough axles that undergo multi-stage deformation and heat treatment, the influence of the cast structure and the level of liquation on the formation of the final structure cannot be clearly determined. Therefore, an additional experiment has been conducted. During this experiment, samples of carbon steel for railway axles, which are selected from the original CCB made by different manufacturing methods, undergo a normalization heat treatment at 840 °C, in order to reveal differences in the formation of the structure of carbon steel in laboratory conditions and the influence of the primary structure and liquation on these processes. Thus, the effect of external factors is minimized, and only the influence of the primary structure on the formation of fine-grained and coarse-grained structure has been shown. The experiment consists of the following stages: samples are taken from the CCB at a distance of 1/4 thickness from the surface. In the rectangular billet, due to the difference in the length of the faces, samples are taken from each side. The samples taken from 1/4 cross-section of the studied CCB are used because of a distinct difference in the size of the dendrites, their explicit relationship with the grain structure, and the absence of macrodefects in these zones.

The analysis of the influence of the quantitative characteristics of the pearlite grain structure and the relationship with the dimensional characteristics of the original dendritic structure is beyond the scope of this research, since this problem has been well discussed in [15].

The microstructure of samples of different CCB differs in grain size and morphology of pre-eutectoid ferrite, which is considered typical for medium-carbon steel (Fig. 2). However, the causes of the formation of ferrite with different morphology in medium-carbon steels of the same composition and under the same heat treatment conditions have not been explained in the literature.

After one-time normalization of cast metal, the structure of all samples clearly coincides with the contours of the primary dendritic structure. In the structure of the normalized CCB sample, there is a manifestation of the hereditary influence of the three types of structures: the primary dendritic, the cast grain (boundaries of primary austenite grains), and the final fine ferrite-pearlite.

Samples No. 3—4 correspond to the classic idea of the formation of a heterogeneous ferrite-pearlite structure in medium-carbon steels. At the same time, a large amount of pearlite is formed in the interdendritic areas. Attention should be paid to Fig. 2, *d*, where there is shown the bloom sample that is taken from 1/4 width and falls on the liquation zone. There, the level of liquation is such that without deformation treatment after normalization, the formation of structural inhomogeneity is quite evident, as pearlite is almost completely concentrated in the interdendritic areas, while inside the dendritic branches there is formed almost pure ferrite. The presence of smaller dendrite branches corresponds to a decreased pearlitic component within the steel. The structural heterogeneity of pure steel, influenced by the presence of impurities and gases, aligns with the conventional concept of striped structure formation. In the case of pre-eutectoid steels, the emergence of a striped structure characterized by an uneven distribution of ferrite and pearlite components can be attributed to the impact of manganese on A_{r3}. Manganese acts as a γ-stabilizer and exerts a reducing effect on A_{r3}. Consequently, in steel characterized by a heterogeneous manganese distribution, a distinct pattern emerges during the cooling process. Specifically, ferrite is initially formed in bands with lower manganese concentrations within the austenite matrix. As the cooling proceeds, carbon atoms diffuse from the ferrite nuclei and become concentrated in regions possessing higher manganese content. Subsequently, pearlite forms in these carbon-enriched areas. When the size of the austenite grains is smaller than the microsegregation wavelength, ferrite nuclei are generated at both the grain boundaries of austenite and locations with elevated A_{r3} temperatures. These grains exhibit growth both in the rolling direction and, subsequently, transversely to the rolling direction, forming common boundaries and extending towards Mn-rich regions. Continuous cooling experiments [16] have demonstrated that the development of ferrite/pearlite bands in a hot-rolled alloy characterized by microsegregation of manganese (Mn) and silicon (Si) is directly influenced by the cooling rate during the transition from the austenitic state. It is crucial to use a cooling rate equal to or greater than 2 K/s to effectively suppress the formation of striped microstructures. This observation aligns with previous research indicating that, even in the presence of Mn/Si microsegregation, it is primarily the kinetics of the phase transformation, particularly of ferrite, that governs the actual manifestation of microstructural bands. Notably, pearlite exhibits significantly faster growth as compared with ferrite due to the higher driving force at lower transformation temperatures and the shorter diffusion length resulting from its layered structure. The carbon enrichment of austenite, which depends on the available time for ferrite growth, plays a crucial role in the nucleation of ferrite or pearlite in regions with contrasting manganese (Mn) content under non-isothermal conditions. At low cooling rates, ferrite nucleation is predominantly initiated in areas with lower Mn concentrations, resulting in an extended duration for ferrite formation and carbon diffusion over relatively longer distances. Consequently, the occurrence of new ferrite nucleation in Mn-rich regions becomes limited, leading to the continuous formation of pearlite in these areas. Generally, when the difference in the ferrite nucleation rates remains below 6–8%, a striped microstructure does not manifest itself. The formation of microstructural bands has been primarily attributed to the segregation of substitutional alloying elements, such as nickel (Ni) and chromium (Cr) [17]. These bands result in anisotropic flow behavior during significant deformations, where deformation is restricted to the stripes composed of solid granular ferrite. Notably, the formation of pre-eutectoid ferrite surrounding sulfide inclusions has not been observed in samples of higher quality steel; however, pearlite colonies are formed in close proximity to these inclusions.

In sample No. 1, there is observed a relatively uniform structure within the dendritic branches, whereas the interdendritic regions exhibit a notable presence of ferrite. This occurrence of ferrite is directly associated with sulfide inclusions. Additionally, in Sample No. 1, ferrite is formed in close proximity to a cluster of small non-metallic inclusions, followed by the development of a dense pearlite rim surrounding it. This particular structure bears resemblance to a defect commonly referred to as a "gas bubble" in the metal structure. The pearlite areas appear elongated. A distinct white ferrite band is observed at the boundary inherited from the primary grain during casting. Large ferrite regions emerge at the junction areas of secondary and tertiary dendritic branches, with the size of these regions showing minimal dependence on the presence, size, and number of sulfide inclusions. Remarkably, a ferrite border can be formed even in the absence of visible large inclusions. Near one large inclusion, there may be present a relatively thin layer of ferrite, contrasting with a rougher layer near other inclusions. Quantitative analysis, examining the size of sulfide inclusions and the thickness of the surrounding ferrite layer, has not established any correlation. The formation of a ferrite border exclusively around sulfide inclusions (attributable to local decreases in manganese concentration) has not been generally acknowledged. At the same time, between the branches of dendrites of the same order, the ferrite-pearlite structure is formed around sulfide inclusions, while oxide inclusions are found independently of the structural components [5].

The composition of sulfide inclusions is not constant. For example, complex sulfides of iron and manganese increase the content of manganese in their composition during hot deformation (forging) and cooling. As already mentioned, the formation of a structure in the places of growth of dendritic branches is similar to the formation of gas bubbles. In the steel, there are various gases, such as carbon monoxide, nitrogen, hydrogen, silicon monoxide, as well as fusible metal vapors. Carbon monoxide usually makes up 70–80% of the gases released during solidification of boiling steel. During the crystallization of carbon steel, the places where dendritic branches grow are enriched not only with alloying elements and gases, but oxygen is found in the steel only in compounds (CO, MnO, SiO_2, and FeO).

The author [18] has suggested that stress relaxation in steel with a lower carbon content occurs earlier and is carried out along the austenite grain boundaries, causing grain boundary sliding, a change in their structure, and the formation of pre-eutectoid ferrite. Impurities have different effects on the surface energy of grain boundaries that determine the ability of grains to recrystallize. In [18], it has been established that in the area of shrinkage pores, the metal integrity is preserved until the shrinkage reaches 20—25%, and the grain size, according to visual assessment, is approximately 2 times smaller than in the bulk of solid metal of the casting. Since the shrinkage is proportional to the metal deformation, in the area of the shrinkage pore the deformation is bigger by $\geq 15\%$ than in the rest of the casting. The author mentions that the cause of the formation of a smaller grain is the presence of a bigger shrinkage and, consequently, deformation. At the same time, the presence of non-metallic inclusions of particularly small size is not taken into account, and the formation of large pearlite grains occurs in interdendritic areas in relatively pure steels.

As a rule, no structural heterogeneity is observed in austenitic and ferritic steels. In steels, usually there is a decarburized zone near the bubble cavity. Often near the bubbles, there are sulfides of manganese and iron, as well as a little amount of small globular oxides of manganese and iron such as FeO and MnO. It can be assumed that the number of oxides is much greater than observed. However, their sizes are much smaller than the minimum detectable by light microscopy. The formation of the steel structure near gas bubbles has been understudied. In the places of accumulation of oxides around the cavities, there is observed a decarburized zone, with a border of pearlite grains. This border is often bag-shaped, which is very similar to the pattern of structure formation observed by us in the places of growth of dendritic branches, especially in sample No. 3

taken from the area of macroliquation. However, this description is typical for gas bubbles with a size of 10—70 mm, which is hundreds of thousands times larger than the observed zones of irregular structure. It is also known from the literature that the size of the decarburized zone is much larger than the defect itself (more precisely, the cavity). The peculiarities of the structure are preserved from the ingot to the finished roll. In steel with a high oxygen concentration, a carbon oxidation reaction takes place, resulting in the release of carbon oxide or carbon dioxide.

It is important that as a result of the experiments, it has been shown that the main differences in the formation of the final structure, which are found in ready railway axles made of billets produced by different manufacturing methods, are also observed during the experimental heat treatment of the undeformed billet. Deformation leads only to softening the effects of the cast original structure, liquidation inhomogeneity, imperfection of the structure, etc.

The measures to be taken to obtain the final uniform structure of carbon steels used for the manufacture of railway axles, of almost identical chemical composition, but produced by different manufacturing methods, differ significantly. For the railway axles completely manufactured at KAMET—STEEL (starting from the original billet), it has been found that the reduction of the number of normalization treatments to one is effective, with the prolongation of exposure at these temperatures, due to the reconfiguration of non-metallic inclusions, improving the structure and properties [8]. It can be assumed that such heat treatment for steels that are purer in terms of non-metallic inclusions and gas content can only increase the manifestations of liquation heterogeneity. To eliminate the effect of liquation, it is necessary to strengthen the deformation effect and to add heat normalizing treatments with a shorter exposure time. Thus, the purer is the steel, the more deformation is required to obtain a higher level of properties. It can be assumed that there is an optimal content of non-metallic inclusions (the degree of steel deoxygenation), which allows obtaining a uniform homogeneous structure of railway axles made of carbon steel.

CONCLUSIONS

1. The authors have shown that deoxygenation and sulfur content in steel have a significant influence on the formation of inhomogeneity of microhardness across the cross-section of cast steel for railway axles and that individual sections have a microheterogeneous structure. With an extremely low or increased content of harmful impurities, the maximum liquation is formed both along the cross-section of the ingot or CCB, and in micro-areas.

2. In the context of the optimal chemical composition of steel for the production of crucial railway components, careful consideration shall be given to the steel production method, raw materials, and technological aspects that are specific to the metallurgical facility. This is imperative since steel samples with similar chemical compositions can exhibit distinct patterns of structure formation. To ensure high properties of metal products, the modes of deformation and heat treatment used today need to be adjusted depending on the characteristics of steel smelting.

3. It has been observed that the formation of a ferrite boundary adjacent to sulfide inclusions shares similarities with the formation of gas bubbles and exhibits a characteristic structure. The sulfide inclusions are present in the liquation zone together with other liquates and gases in the steel.

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Received 26.10.2022
Revised 23.01.2023
Accepted 25.01.2023

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ОСОБЛИВОСТІ ФОРМУВАННЯ СТРУКТУРНОЇ НЕОДНОРІДНОСТІ У ВУГЛЕЦЕВІЙ СТАЛІ ЗАЛЕЖНО ВІД СПОСОБУ ВИГОТОВЛЕННЯ

Вступ. Гомогенна, однорідна мікроструктура габаритних металевих виробів є найбільш переважною при забезпеченні необхідного комплексу властивостей.

Проблематика. Режими деформаційної та термічної обробки, які застосовують сьогодні, потребують коригування залежно від особливостей виплавки сталі для забезпечення високого комплексу властивостей металопродукції.

Мета. Проаналізувати вплив розміру вихідної безперервнолитої заготовки (БЛЗ), її геометрії, ступеню проброблення готової залізничної осі й дослідити вплив ступеня чистоти сталі на особливості структуроутворення вже готового продукту — залізничних осей.

Матеріали й методи. Всі дослідні зразки відібрані з 1/2 товщини шийки чорнових залізничних осей. Розмір осей був однаковий і становив ∅ 218 мм. Всі осі пройшли дві нормалізації за температур 820 та 840 °C відповідно. Фото мікроструктур зроблено на Axiovert 200 MAT.

Результати. В результаті проведених експериментів показано, що основні відмінності структуроутворення кінцевої структури, що виявлялися у готових залізничних осей, виготовлених з заготовок різного способу виготовлення, спостерігаються і при проведенні експериментальної термічної обробки недеформованої заготовки. Деформація призводить лише до пом'якшувальної дії процесів впливу литої вихідної структури, ліквацiйної неоднорідності, недосконалості будови тощо.

Висновки. Визначено, що при виборі оптимального хімічного складу сталі для виготовлення відповідальних деталей залізничного призначення, необхідно брати до уваги спосіб виробництва сталі, вихідні матеріали та технологічні особливості металургійного підприємства, оскільки сталь навіть близького хімічного складу може мати різну природу структуроутворення. З'ясовано, що формування феритного облямування біля сульфідних включень має природу формування, схожу з утворенням газових бульбашок, і демонструє характерну структуру. Наявність сульфідних включень обумовлена насамперед одночасним перебуванням їх в ліквацiйній зоні поруч з іншими ліквантами й газами в сталі.

Ключові слова: мікроструктура, залізнична ось, вуглецева сталь, деформація, ліквацiйна неоднорідність.