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BABACHENKO, O. I. (https://orcid.org/0000-0002-2869-3478),
KONONENKO, G. A. (https://orcid.org/0000-0001-7446-4105),
MERKULOV, O. Ye. (https://orcid.org/0000-0002-7867-0659),
PODOLSKYI, R. V. (https://orcid.org/0000-0002-0288-0641),
and SAFRONOVA, O. A. (https://orcid.org/0000-0002-4032-4275)
Iron and Steel Institute of Z. I. Nekrasov of the National Academy of Sciences of Ukraine,
1, Sq. Ak. Starodubova, Dnipro, 49107, Ukraine,
+ 380 56 790 0514, okc.testcenter@ukr.net

INFLUENCE OF CONDITIONS OF LOW-ALLOY BAINITE GRADE STEEL COOLING ON THE DENDRITIC STRUCTURE PARAMETERS AND SPHERICITY OF GRANULAR BAINITE

Introduction. *Crystallization of metals and alloys typically results in the formation of branched dendritic crystals.*

Problem Statement. *Understanding how crystallization conditions affect the formation of the primary dendritic structure in carbon steels is crucial to comprehending the overall process of structure formation.*

Purpose. *This study aims to investigate the effect of varying cooling rates across the cross section of a bainite steel ingot (composition: 0.378% C, 1.02% Si, 1.38% Mn, 0.77% Cr, 0.192% Mo, 0.095% V) on the primary dendritic structure, dispersion, and sphericity of the structural components.*

Materials and Methods. *Metallographic analysis of the steel samples has been made with the use of Neophot 32 and Axiovert 200 M MAT light microscopes. Microstructure and chemical heterogeneity have been analyzed with a 2—3% alcoholic nitric acid (*HNO_3*) solution and an aqueous solution derived from the reaction between trinitrophenol (picric acid) and sodium hydroxide (NaOH). The dimensions of the primary dendritic structure and final structure have been measured by the imageJ software. Brinell hardness tests have been performed on a TB5004 testing machine. Specialized software such as CalPhad and Qform has been employed for further analysis.*

Results. *Microstructural analysis has shown that as the density of the dendritic structure varies across the cross section of the ingot, there is a corresponding change in sphericity. Sphericity, defined as the ratio of the maximum to minimum diagonals of granular bainite, ranges from 0.1539 to 0.3673. Additionally, the lamellae of granular bainite grow approximately 2.4 times as the cooling rate decreases across the cross section of the billet, from 60 °C/min to 7 °C/min.*

Conclusions. *The study has established an inverse relationship between the density of the dendritic structure and the sphericity of the final granular bainite structure. The dispersion of structural components is promising for enhancing the overall mechanical properties, including both strength and plasticity.*

Keywords: bainite, railway rail, dendrite, sphericity, dependence, cooling rate.

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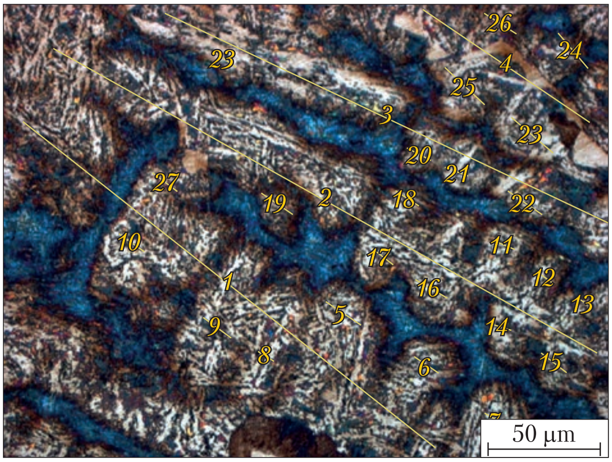


Fig. 1. Measurement of dendritic branches of the first and second order

	Length
1	243.469
2	288.613
3	228.058
4	92.616
5	19.315
6	12.877
7	9.982
8	8.423
9	16.608
10	14.117
11	9.616
12	7.681
13	7.198
14	9.322
15	14.644

The characteristics of the initial cast structure are partially retained during subsequent stages of hot plastic deformation and heat treatment, influencing the development of the final structure and mechanical properties of metal products. Therefore, understanding how crystallization conditions affect the formation of the primary dendritic structure in carbon steels is a critical aspect of studying structure formation processes [1].

During the crystallization of metals and alloys, branched dendritic crystals commonly form. Among the factors influencing dendrite branching and the average distance between branches, the cooling rate of the crystallizing metal is particularly significant. The more rapid is cooling, the shorter is the distance between branches [1, 2].

The temperature gradient, crystallization rate, and concentration of alloying and impurity elements in the melt are the primary factors determining the crystal (dendrite) growth [3]. The temperature gradient at the crystallization front and the crystallization rate are associated with external factors and define the physical kinetics at the growth front. The ratio of the gradient magnitude to the cooling rate determines the type of crystal structure formed, while the product of these factors, represented by the cooling rate, determines the dispersion of the alloy's structural components [4].

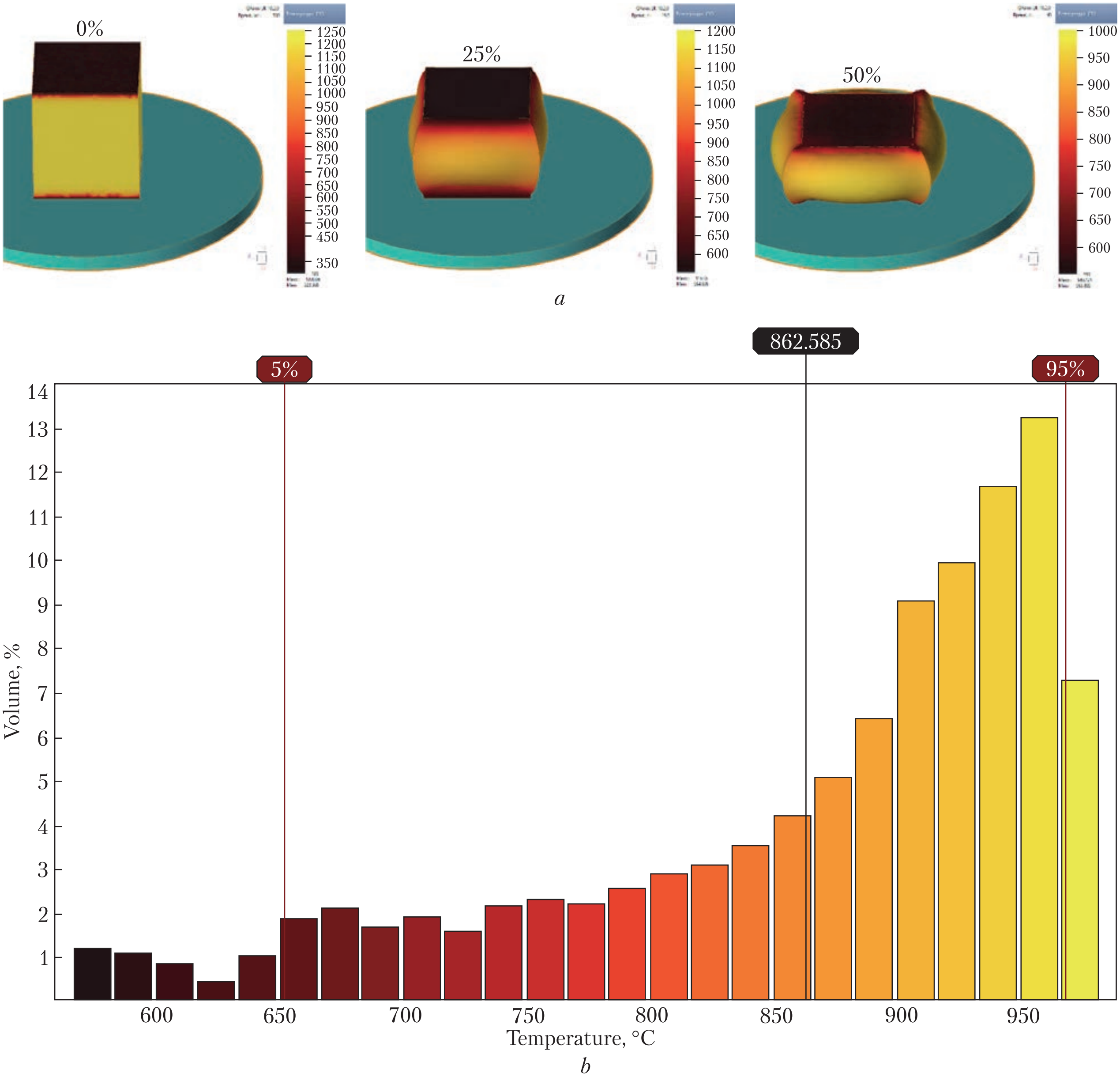
As established in previous studies [1, 5—11], the thermokinetic conditions of solidification result in the billet structure cast in a foundry having a finer dispersion of primary crystals and a more uniform distribution of chemical elements at both macro and micro levels, as compared with a continuously cast billet [12, 13].

Based on the discussion, it has been established that variations in thermokinetic solidification conditions, particularly due to changes in the cooling rate across the billet, influence the initial dendritic structure across the cross section. This variation, in turn, affects the dispersion of structural components in Fe—C alloys, thereby impacting the final microstructure.

The objective of this study is to determine the effect of the primary dendritic structure on the dispersion and sphericity of structural components, specifically in relation to changes in the

Table 1. **The Chemical Composition of the Trial Melt, % wt.**

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V
0.378	1.02	1.38	0.027	0.02	0.77	0.192	0.037	0.018	0.028	0.095



a

b

Fig. 2. Modeling of hot plastic deformation of a sample from a laboratory billet made of steel with 0.378% C (*a*), the temperature of the workpiece at the end of the HPD of the trial steel (*b*) in the *QForm* workspace

cooling rate across the cross section of a bainitic steel billet containing 0.37% C and alloyed with Cr—Mo—V.

The material used for this research consists of samples of bainitic-grade carbon test steel produced under laboratory conditions. The chemical composition of the steel is detailed in Table 1. The chemical analysis has been conducted with an arc/spark Optical Emission Spectrometry (OES) metal analyzer, SPECTROMAXx. Additional carbon content analysis has been performed by an AN-7529 analyzer. The trial billet, weighing up to

10 kg, is melted in a laboratory induction melting furnace, comprising a melting module (ITPE-0.01) and a VTG-20-22 generator. The trial steel is cast in a coarse-grained graphite crucible, and the cooling rate is monitored with pyrometric equipment, capturing the temperature-time curve on the billet's surface.

The sampling process involves cutting a transverse template from the bottom part of the billet, followed by a comprehensive microstructural analysis across the entire cross section, from the side surface to the center, to thoroughly investigate the steel crystallization process across varying cooling rates.

Metallographic analysis of the trial steel has been made with *Carl Zeiss* light microscopes, specifically the *Neophot* 32 and *Axiovert* 200 M MAT models. The metallographic sections are prepared mechanically; microstructural detection, along with the assessment of chemical heterogeneity, has been conducted with the use of a 2—3% alcoholic solution of nitric acid (HNO_3) and an aqueous salt solution formed by the reaction of trinitrophenol (picric acid) and caustic soda (NaOH).

The areas corresponding to the former primary dendritic structure and the final microstructure are measured with the *imageJ* software. The density of the dendritic structure is calculated by determining the ratio of the average width of the second-order dendrite branches to the size of the first-order branches (as illustrated in Fig. 1). The sphericity of the granular bainite is assessed by calculating the ratio of the lamellae diameters. Additionally, the structural diagram is based on the actual cooling rate curve, obtained via thermocouple, and the phase fraction is automatically calculated with *Axiovert* 200 M MAT optical microscope that accounts for the color spectra of the photomicrographs.

From the obtained results and data [1], the temperature of the liquidus, solidus, and liquid steel with 0.37%C have been determined based on the known expression (1):

$$d = a(GR)^{-n}, \quad (1)$$

where a is the coefficient proportional to the crystallization period ~ΔT, G is the temperature gradient at the growth front, °C/mm, R is the growth rate of crystallization front, mm/min, n is the power exponent varying from 1/4 to 1/2 for the second-order branch distances and typically very close to 1/2 for the first-order branch distances.

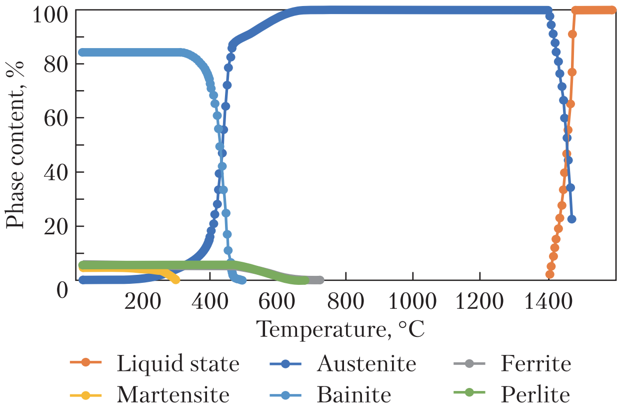


Fig. 3. Phase composition of the studied steel

Brinell hardness is controlled by TB5004 machine with a graduated magnifier MPB 2.

Specialized software, including *CalPhad* and *QForm*, has been employed in the research. The study involves developing a model to calculate the distribution of physical and mechanical properties of trial steel during hot plastic deformation (HPD) by 50% on the cross section of cubic samples, using the *QForm* program, as well as conducting actual deformation tests on a universal testing machine. The initial conditions are set to the *Deformation* operation type, with parameters accounting for thermal processes and elastic-plastic deformation.

The sample geometry is constructed by *SolidWorks* and then exported in *.stp format to *QForm*. The deformation temperature is 1250 °C. The process of temperature variation in the material during HPD is illustrated (Fig. 2, *a*), along with a histogram revealing the temperature changes during HPD (Fig. 2, *b*).

The heat treatment of the trial steel is conducted in a SNOL60-1300 laboratory furnace. The samples heat to a temperature of 900 ± 5 °C and subsequently cool at a rate ranging from 0.2 to

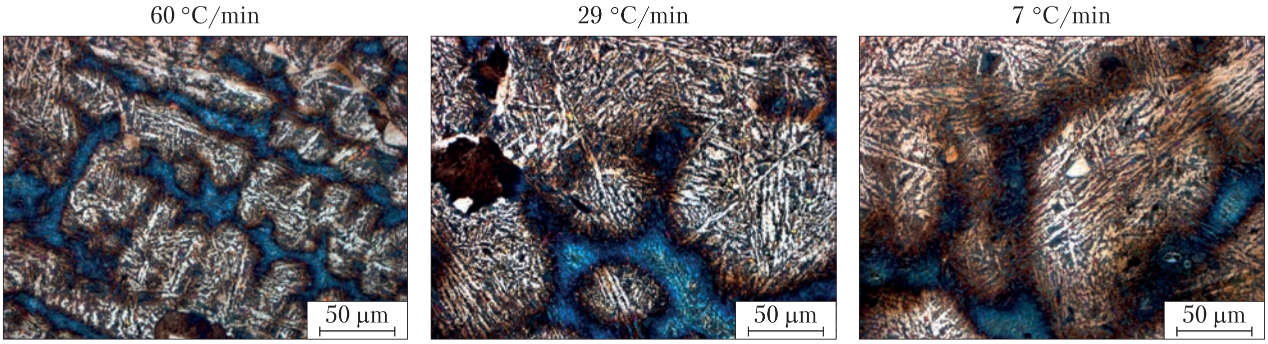


Fig. 4. Dendritic structure of the trial steel, based on the cooling rate across the cross section of the billet, ×500

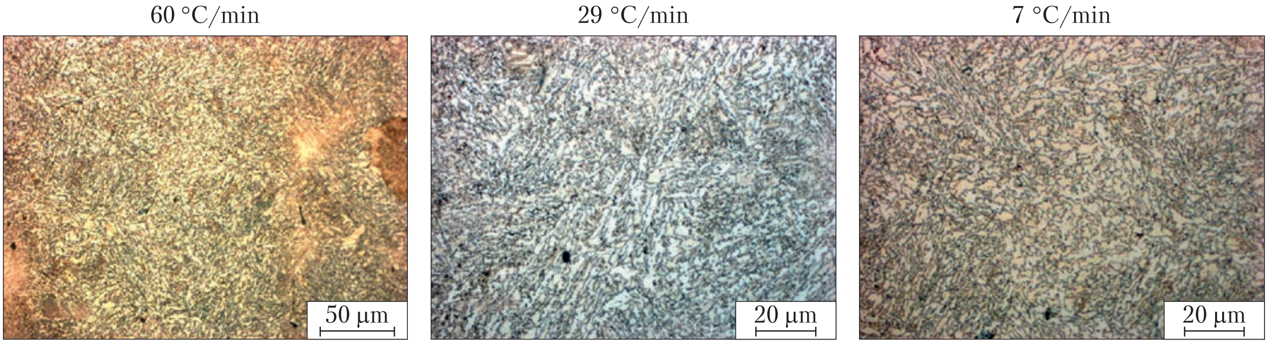


Fig. 5. Microstructure of the trial steel, based on the cooling rate across the cross section of the billet, ×800

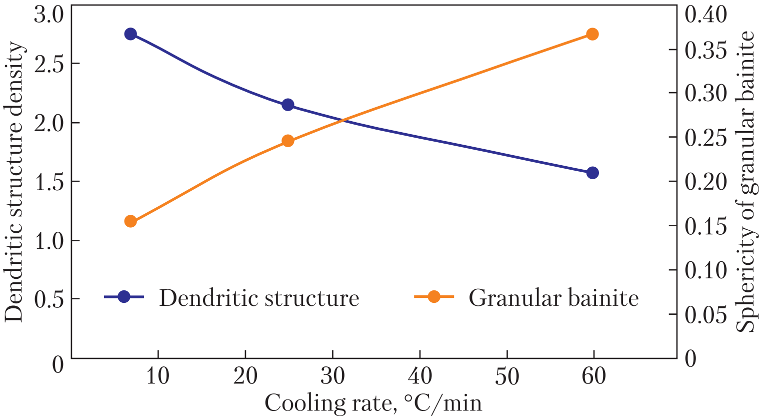


Fig. 6. Dependence of dendritic structure density and granular bainite sphericity on the cooling rate across the billet cross section

5.1 °C/s. The cooling rate is monitored by a chromel-alumel thermocouple fixed within the sample.

It has been determined that the cooling rate during the solidification of the metal in the billet varies between 60 °C/min and 7 °C/min. The results from the chemical composition analysis and cooling rates have been used as input data for modeling phase transformations (Fig. 3) during the cooling process after crystallization. Additionally, non-metallic inclusions are controlled.

When examining the dendritic structure (Fig. 4) in relation to the cooling rates, it has been obser-

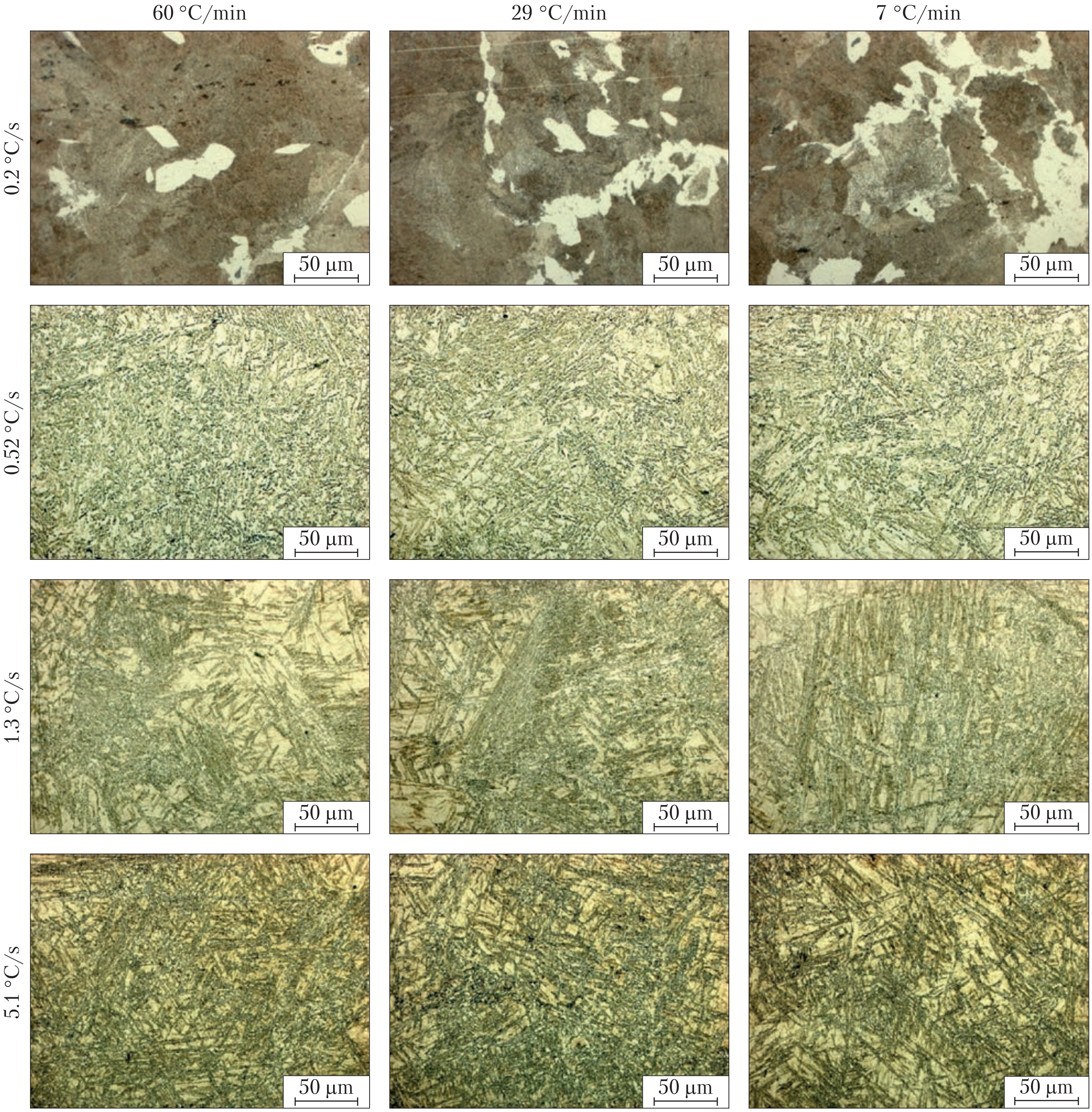


Fig. 7. Microstructure of the trial steel after heat treatment at different cooling rates, based on the cooling rate along the cross section of the billet, ×500

ved that the density of the dendritic structure in the trial steel varies between 2.7 and 1.5. This indicates that the density of the dendritic structure increases approximately 1.75 times as the cooling rate decreases along the cross section of the billet, from the side surface to the center, within the range of 60 °C/min to 7 °C/min. At lower cooling rates, the secondary dendrite branches are wider, occupy a larger area, and the interdendritic regions between these secondary branches are re-

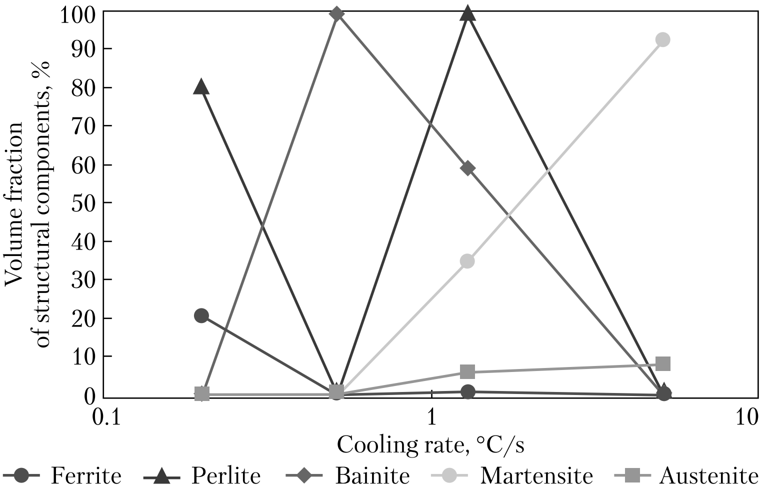


Fig. 8. Diagram of structural components of the trial steel after heat treatment at a cooling rate ranging within 0.2—5.1 °C/s

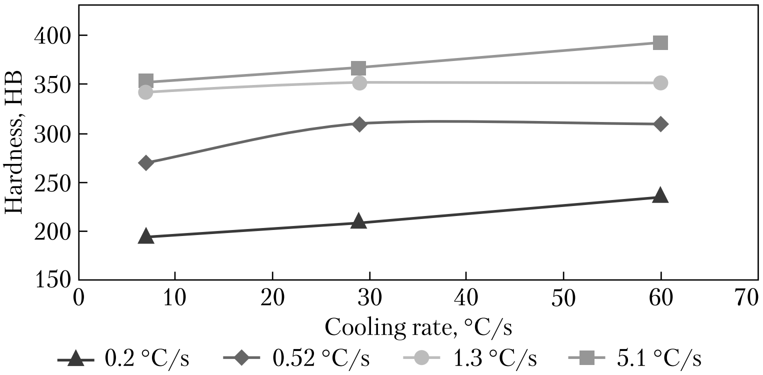


Fig. 9. Dependence of the hardness on the cooling rate after crystallization (60 °C/min, 29 °C/min, and 7 °C/min) and heat treatment in the range of 0.2—5.1 °C/s

duced. When comparing these results with data for carbon steel [1], we see that this relationship is inversed.

After cooling at rate of 60 °C/min, 29 °C/min, and 7 °C/min — corresponding to the cooling rates near the side surface, at half the radius, and at the center of the billet, respectively — the trial steel consists of a microhardness structure ranging from 3687 to 4069 MPa. According to literature [14], this structure is identified as granular bainite. The microstructural studies (Fig. 5) have shown that as the density of the dendritic structure varies across the cross section of the trial billet, the sphericity of granular bainite also changes, ranging from 0.15 to 0.36. Additionally, the lamellae of granular bainite increase approximately 2.4 times as the cooling rate decreases along the cross section of the billet, within the range of 60 °C/min to 7 °C/min.

The changes in the dendritic structure density and in the sphericity of granular bainite, depending on the cooling rate along the trial steel cross section, is shown in Fig. 6.

When investigating the effect of hot plastic deformation, we have determined through both mathematical modeling and the actual HPD process measurements that the temperature reaches 862 °C, on the surface, and 964 °C, at the center of the workpiece. The experimental results have shown that the cooling rate on the surface of the trial steels after HPD is approximately 0.43 °C/s.

The microstructural analysis (Fig. 7) has demonstrated that the structure of the steel after cooling at a rate of 0.2 °C/s exhibits a ferrite-pearlite structure, with ferrite forming a grid along the grain boundaries. As the cooling rate increases to 0.52 °C/s, the structure transitions to predominantly bainite. At a cooling rate of 1.3 °C/s, a bainitic structure with minor amount of martensite and retained austenite is formed, while at 5.1 °C/s, the structure is mainly martensitic with residual austenite.

Based on these findings, a structural diagram for the trial steel has been developed (Fig. 8). It has been concluded that while cooling in air, the steel has primarily a bainitic structure. This confirms that the trial steel belongs to the bainite class.

It has been found that after heat treatment at a cooling rate of 0.2 °C/s, the microstructure primarily consists of ferrite and pearlite. When the cooling rate of the billet after crystallization reaches 29 °C/min, the ferrite content in the steel increases to 25.0%, with the development of coarse plate pearlite regions. At a cooling rate of 7 °C/min, the ferrite content further increases to 32.5%, with the pearlite regions and the interlamellar spacing of coarse-lamellar pearlite expanding, as compared with those at a cooling rate of 29 °C/min.

At a cooling rate of 0.52 °C/s, the microstructure is predominantly carbide-free bainite. At a cooling rate between 29 °C/min and 7 °C/min, the residual austenite content increases. As the cooling rate goes up to 1.3 °C/s, the structure comprises mainly carbide-free bainite, with a small amount of acicular martensite. At a cooling rate of 60 °C/min, the structure contains a significant amount of acicular martensite (34.9%) and residual austenite (6.1%).

For the billets crystallized at a cooling rate of 29 °C/min, the volume fraction of martensite and austenite decreases to 28.0% and 2.2%, respectively. At a cooling rate of 7 °C/min, these values further decrease to 11.8% for martensite and 0.8% for austenite. When the cooling rate is 5.1 °C/s, the structure predominantly consists of acicular martensite.

The study has shown that different cooling rates after crystallization — 60 °C/min, 29 °C/min, and 7 °C/min — followed by heat treatment at a cooling rate of 5.1 °C/s, result in different volume fractions of residual austenite of 7.8%, 8.9%, and 11.3%, respectively. These findings have highlighted the direct influence of the cooling rate after billet crystallization on the final microstructure of the trial steel both on the surface and in the center of the billet after heat treatment at various cooling rates in the range of 0.2—5.1 °C/s. The hardness of the trial samples has been measured, revealing the effect of the post-treatment cooling rate on both the microstructure and the mechanical properties, specifically hardness (Fig. 9).

The results of the research have shown a pattern of changes in the hardness and microstructure depending on the cooling rate after crystallization at 60 °C/min, 29 °C/min, and 7 °C/min across the cross section of the trial billet and after heat treatment at different cooling rates in the range of 0.2—5.1 °C/s. It has been found that the microstructure of the trial steel after heat treatment at different cooling rates in the range of 0.2—5.1 °C/s retains a hereditary influence depending on the cooling rate after crystallization at 60 °C/min, 29 °C/min, and 7 °C/min along the cross section of the trial billet.

Dispersion of structural components is promising from the point of view of increasing the level of values and homogeneity of a complex of mechanical properties, simultaneously increasing the characteristics of strength and plasticity.

CONCLUSIONS

1. The research has established an inverse relationship between the density of the dendritic structure and the sphericity of the final granular bainite structure. It has been observed that the formation of the dendritic structure in alloyed bainitic steels differs from that in carbon steels. Specifically, the density of the dendritic structure varies between 2.7 and 1.5, while the sphericity of granular bainite ranges from 0.15 to 0.36, depending on the cooling rate, which has been found to be between 60 °C/min and 7 °C/min across the cross section of trial steel containing 0.37% carbon.

2. A direct relationship between the initial cooling rate after crystallization across the cross section and the final volume fraction of structural components in the trial steel has been demonstrated. At a cooling rate of 0.2 °C/s, the resulting structure consists of ferrite and pearlite. At a crystallization cooling rate of 29 °C/min, the ferrite content in the steel increases to 25.0%. In this case, ferrite is accompanied by coarse lamellar pearlite. When the cooling rate drops to 7 °C/min, the ferrite content rises to 32.5%, and there is a corresponding increase in the volume and interlamellar distance of coarse-lamellar pearlite, as compared with those at a cooling rate of 29 °C/min. At a cooling rate of 1.3 °C/s, it has been observed that a high cooling rate of 60 °C/min results in a significant amount of acicular martensite (34.9%) and residual austenite (6.1%). When the cooling rate after crystallization is 29 °C/min, the volume fractions of martensite and austenite decrease to 28.0% and 2.2%, respectively. At a cooling rate of 7 °C/min, these fractions further decrease to 11.89% and 0.89%, respectively. At a heat treatment cooling rate of 5.1 °C/s, at initial crystallization cooling rate of 60 °C/min, 29 °C/min, and 7 °C/min, the volume fraction of the austenitic structural component decreases by 7.8% 8.9%, and 11.3%, respectively.

3. The study has identified patterns in the changes in the hardness and microstructure as a function of the cooling rate after crystallization (60 °C/min, 29 °C/min, and 7 °C/min) across the cross section of the trial sample, as well as after heat treatment at different cooling rates in the range of 0.2—5.1 °C/s. These patterns have shown the hereditary influence of a crystallization cooling rate of 60 °C/min on the final mechanical properties, depending on the cooling rate during heat treatment, as compared with a crystallization rate of 7 °C/min. This influence is particularly evident, with variations in mechanical properties ranging between 10—17%, for steel containing 0.378% C, 1.02% Si, 1.38% Mn, 0.77% Cr, 0.19% Mo, and 0.09% V.

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О.І. Бабаченко (https://orcid.org/0000-0002-2869-3478),
Г.А. Кононенко (https://orcid.org/0000-0001-7446-4105),
О.Є. Меркулов (https://orcid.org/0000-0002-7867-0659),
Р.В. Подольський (https://orcid.org/0000-0002-0288-0641),
О.А. Сафронова (https://orcid.org/0000-0002-4032-4275)

Інститут чорної металургії ім. З. І. Некрасова Національної академії наук України,
пл. акад. Стародубова, 1, Дніпро, 49107, Україна,
+380 56 790 0514, okc.testcenter@ukr.net

ВПЛИВ УМОВ ОХОЛОДЖЕННЯ ЕКОНОМНОЛЕГОВАНОЇ СТАЛІ БЕЙНІТНОГО КЛАСУ НА ПАРАМЕТРИ ДЕНДРИТНОЇ СТРУКТУРИ ТА СФЕРИЧНІСТЬ ГРАНУЛЯРНОГО БЕЙНІТУ

Вступ. Найчастіше кристалізація металів і сплавів призводить до утворення розгалужених дендритних кристалів.

Проблематика. Встановлення закономірностей впливу умов кристалізації на формування первинної дендритної структури вуглецевих сталей є одним з основних завдань дослідження процесу структуроутворення.

Мета. Встановити вплив зміни швидкості охолодження по перерізу зливка сталі бейнітного класу з 0,378 % C, 1,02 % Si, 1,38 % Mn, 0,77 % Cr, 0,192 % Mo, 0,095 % V на первинну дендритну структуру, дисперсність та сферичність структурної складової.

Матеріали й методи. Металографічний аналіз дослідних сталей виконано на світловому мікроскопі моделей *«Neophot 32»* і *«Axiovert 200 M MAT»*. Визначення мікроструктури та характеру хімічної неоднорідності здійснено із застосуванням 2—3 % спиртового розчину азотної кислоти (HNO_3) та водного розчину солі, що утворюється при реакції тринітрофенолу (пікринової кислоти) і їдкого натру (NaOH). Підрахунок розмірів ділянок колишньої первинної дендритної структури та кінцевої структури зроблено методом вимірювання довжин в програмі *«imageJ»*. Контроль твердості за Бринеллем проведено на випробувальній машині «ТБ5004». У дослідженнях застосовано спеціалізоване програмне забезпечення: *CalPhad* та *Qform*.

Результати. Мікроструктурні дослідження показали, що при зміні щільності дендритної структури по перерізу дослідного зливку відбувається зміна сферичності, яка визначається як співвідношення максимальної та мінімальної діагоналей, гранулярного бейніту в діапазоні 0,1539—0,3673, ламелі гранулярного бейніту збільшуються у ~2,4 рази при зменшенні швидкості охолодження по перерізу зливку в діапазоні 60—7 °C/хв.

Висновки. Встановлено зворотній зв’язок щільності дендритної структури та сферичності кінцевої структури гранулярного бейніту. Диспергування структурних складових є перспективним з точки зору підвищення рівня значень й однорідності комплексу механічних властивостей, одночасного підвищення характеристик міцності та пластичності.

Ключові слова: бейніт, залізнична рейка, дендрит, сферичність, залежність, швидкість охолодження.