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INFLUENCE OF BORON ON FORMING EFFICIENT STRUCTURE OF ROLLED STEEL AND INCREASE ITS TECHNOLOGICAL PLASTICITY AT DRAWING

[1]Eduard Parusov; [2]Alexander Sychkov; [3]SvetlanaGubenko;
[3]Maksim Ambrazhey

[1]Z. I. Nekrasov Iron and Steel Institute of the National Academy of Sciences of Ukraine, Dnipro, Ukraine;
[2]G. I. Nosov Magnitogorsk State Technical University, Magnitogorsk, Russia;
[3]National Metallurgical Academy of Ukraine, Dnipro, Ukraine

Summary. *The features of the influence of alloying of boron on the structure and formation of complex qualitative indicators of rolled steel out high-carbon steels are showed. The mechanism of action microalloying boron additives for steel is to increase the stability of the metastable austenite, and decrease in the ability to release excess phases during continuous cooling rolled stel. The empirical expression that defines the required content of boron in steel for rolled steel is founded.*

Key words: *rolled steel, boron microalloying, structure, continuous casting, technological plasticity*

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Introduction and problem setting. Alloying chemical elements in most cases exert a positive influence on the properties of the metal in proportion to the number of their introduction into steel. It is known that boron significantly alters quality indicators of metal in its introduction to the steel of up to 0,0001...0,001 % [1]. With such quantity the influence of borom calcination meets steel alloying effect of chromium, manganese, nickel or molybdenum content of which 100...300 times exceeds the content of boron. Especially effective is a comprehensive introduction to the boron steel together with other alloying elements. As for deoxidizing property, boron far exceeds such elements as manganese and silicon, and in its affinity to oxide is better than calcium, chromium, vanadium, yielding much with titanium and, to a lesser extent, aluminum [2]. Steel boron microalloying improves impact strength, which is associated with the formation of the dispersed phase – boron nitride [1], which is mainly allocatedafter hot deformation within recrystallizedaustenite grains.

To ensure the desired effect of the introduction of boron into steel, in the absence of additional imposed nitro forming elements (titanium, aluminum), boron is used as an additive for plasticizing instead of strengthening metal. New use of boron in the industry is based on this property. In [3] it is showed that boron is primarily connected with nitrogen to form boron nitride (BN), then reacts with iron and only then with carbon. Also, the formation of complex compound of nitrogen and carbon –boron carbonitride is possible. Connection α-BN is plastic, it is similar in properties to graphite and in some cases is used as a in antifriction material inbearings [4]. Boron nitride with hexagonal lattice (α-modification, microhardness 0,1...0,7 GPa) is formed at atmospheric pressure, in contrast to compounds β-BN with cubic crystal lattice having microhardness 60...98 GPa, which is formed at temperatures above 1350°C, pressure 6200 MPa/m^2 and is diamond analogous [2].

Microspecrtal analysisof grinding square 0,0645 cm^2 of rolled steel of C80D, produced by JSC "Moldovan Metallurgical Plant" (Moldova, m. Rybnytsia) showed that boron nitrides

Corresponding author: Eduard Parusov; e-mail: tometal@ukr.net

are small (up to 1 micron – number of identified inclusions 9 (82%) to 2 microns – the number of inclusions 2 (18%), more than 2 microns – including has not been detected), while the total density of steel in the study was 171 turns on/cm^2, which corresponds to ~ 0,0002% by volume (2 ppm).

Works [5-7] present data on the positive effect of boron on mechanical and technological properties of steel. It was noted that they have high ductility and deformability that can replace boiling with low amount of silicon makes of steel. However, the reasons for such boron properties in carbon steels were not explained.

Boron limitssteel saturation with hydrogen (reducing hydrogen embrittlement) [1]. Boron positive impact on structure and properties of a continuous billet (CB) and rolled steel is as follows:

1. CB identifies the intermediate zone of large globular dendritic crystals, which is absent in boron free steel, and the columnar crystals zone reduces by 1,16 times and the zone of equilibrium crystals is growing, due to the increase in the rate of accumulation of impurities in crystals in columnar boundaries and earlier termination of their growth with the introduction of surfactant additives.
2. The length of the cortical CB area varies slightly, and some increase may be due to reduction of germs in the melt and growth of nucleation crystallization in the presence of boron (formation of even crystallization front).
3. Surface activity leads to a redistribution of boron contaminants, suppressing separation of sulfur phase.
4. Removal of contaminants from the grain boundaries and reduction of energy boundaries can increase the mechanical and technological properties of rolled steel.

Works [1, 8, 9] note that the effect of increasing stability during quenching austenite while coolingis achieved at significantly lower content of boron than carbon, and at lower cooling rates. Alloyage of 1 atom of boron into 25,000 atoms of iron increases the depth of the hardened layer twice. If manganese, chrome and molybdenum increase hardness when in large quantities, the effect of boron is shown at very low concentrations (0,0003...0,0010 %) and depends largely on the chemical composition of steel.

Previous studies have shown that in the presence of steel only "chemically insoluble" boron which is spent entirely on nitrogen fixation significant plasticizing of steel is achieved compared with those without boron steels; low carbon steels undergo decreased tensile strength to 60 MPa (B = 0,003...0,014 %), in welding steel (Sv-08G2S) with the alloyage of boron in 0,0065 % while increasing exposure time on the conveyor line under Stelmor insulating lids weakened strengthis achieved ($\Delta\sigma_B \sim 220…300$ MPa) and increase in plastic ($\Delta\psi \sim 22…28$ %) indices.

This feature is associated with the effect of softening at high temperature deformation and heat treatment, in which an increase ~ 2...3 numbers valid austenite grains (GOST 5639-82).

Increased time of quasi isothermal metal aging onStelmor’s line provides plasticizing effect of boron in rolled steel of low-carbon and low-alloy steels. In contrast, high carbon steel coil requires an intensification of air cooling, resulting in increased degree of dispersion of perlite and durability, while maintaining the necessary level of plasticity [10].

Thus, previous research suggests that boron, by its influence on the formation of complex quality coil indicators, is a unique chemical element.

The purpose of the article. The aim of the research was to study the influence of boron microalloying processes on structure formation and quality indicators of high carbon steel makes.

Material and methods of research. The material used for research was industrial supplyy of rolled steel steel make C70D, manufactured according to the standard EN 16120-1:2011 (Table. 1). Coil in a diameter of 5,5 mm was subjected to cooling at different speeds coil temperatures (850...950) ± 10° C. Metal temperature monitoring in various technological areas was performed using stationary instrumentation and portable pyrometers with laser range measurements up to 1300° C (measurement error ± 0,5%). Research macrostructure CB (125x125 mm) made by comparison of field templetes with standard scales OST 14-1-235-91. Micro hardness measurement was performed by pressing a four-sided pyramid with a square foundation with a load of 200 gs (1,962 H) GOST 9450-76. Metallographic control was performed using an optical light microscope «OLYMPUS IX70» with automatic image analyzer IA-3001, the degree of dispersion of perlite determined on the electronic scanning microscope «VEGA TS5130MM», evaluation of mechanical properties of rolled steel was performed on tensile machine «EU-100» and «EDZ-40».

Table № 1

Chemical composition of rolled steels

№ fusion	Amount of elements, %.									
	C	Mn	Si	S	P	Cr	Ni	Cu	B	N
1	0,70	0,57	0,18	0,005	0,010	0,04	0,05	0,14	-	0,008
2	0,71	0,56	0,17	0,003	0,009	0,05	0,04	0,15	0,0016	0,007

Results of research and their discussion. Studying the efficiency of microalloying of rolled steel of high carbon steel with boron compounds is useful to consider the process of boron and carbon and nitrogen coupling, given that the main phases-strengthener in steel are carbides, nitrides and their complex compounds carbonitrides. The free energy is a thermodynamic function to evaluate the possibility of chemical reactions in specific circumstances, characterized by a decrease in free energy [11]. Priority is determined by reaction with a negative value of the free energy.

Changing standard Gibb's free energy (ΔG^0_T) in the formation of various compounds at a certain temperature is shown in Fig. 1 [11].

Analysis of the data indicates that according to the distribution of values of Gibbs free energy ($\Delta G^0_{BN} < \Delta G^0_{VC} < \Delta G^0_{Cr_2C_3} < \Delta G^0_{CrN} < \Delta G^0_{VN} < \Delta G^0_{B_4C}$) primarily is a partial nitrogen fixation in boron nitride, then vanadium carbides are formed, chromium carbide, chromium and vanadium nitride, and finally we receive boron carbide. Microalloying was carried out by adding boron powder wire into the steel using tribeaparatus machines after steel achieved special condition in ladle furnace provided by the manufacturer's technical instructions. At wire loss of ~ 40...50 m (weight melting ~ 110,0 t), the degree of assimilation of boron was 78,9 %. Slag samples were characterized by the lack of Fe_2O_3 and FeO that is 0.5%, which is typical of steels with a high degree of deoxidation.

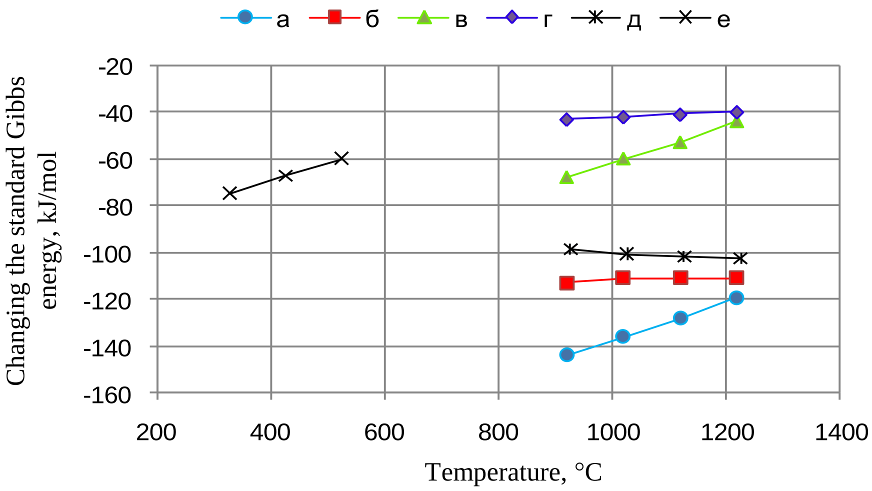

Figure 1. Modifying the standard Gibbs' energy versus temperature for various compounds (according to [11]): а – BN; б – VC; в – VN; г – B_4C; д – Cr_3C_2; е – CrN

Analyzing macrostructure cross templetes of CB it was investigated that boron steel with a length of columnar crystals zone reduced to ~ 1,22 times and equal crystals increase ~ 1,18 times less than steel without boron. The remaining defects of crystallization origin have similar rates (Table 2).

Table № 2

Qualitative indicators of CB section 125×125 mm made of steel make C70D by OST 14-1-235-91*

№ fusion	CP	AS	Quantative performance pieces, marks				
			Cracks			PBP	SB
			crossed	angle	axial		
1	2,2	2,6	1,3	0,0	1,0	0,7	0,5
2	2,5	2,8	1,5	0,0	0,0	1,0	0,5

*Note: CP – central (axial) porosity; AS – axial segregation; PBP– point boundary pollution; SB – subcortical bubble.

Analysis of pollution rolled steel by nonmetallic inclusions showed that the main type of inclusions are silicates. The alloyage of boron steel does not affect the appearance of inclusions, their length distribution. CB heating before rolling was performed in the heating furnace to 518-2012 TE-FS-0009-2011. After a hot plastic deformation at rolling (T_{rol}) rolled steel was subjected to air cooling in coil Stelmor's line temperature($T_{c/f}$). The experimental results are shown in Table. 3, 4 and Fig. 2.

In general, analyzing the data it may be noted that the structure of steel microalloyed with boron (refrigeration regime № 2-2), there is a combination of the highest strength and ductility with a minimum number (~ 2 %) structurally free ferrite (Fig. 2).

Table № 3

Process parameters, cooling modes and the mechanical properties of rolled steel with 5,5 mm in diameter in stainless steel C70D with and without boron

№ regime[1]	Processing regimes[2]				Mechanical properties[3]		
	$T_{\text{пр}}$, ^{0}C	$T_{\text{во}}$, ^{0}C	Position of insulating covers	Fans number	$\sigma_{\text{В}}$, МПа	δ_{10}, %	Ψ, %
1-1	1100±20	850±10	All open	10	1018	11,5	28,9
1-2	1080±20	950±10		10	1052	12,2	34,8
2-1	1090±20	850±10		10	996	12,7	35,8
2-2	1100±20	950±10		10	1080	12,4	39,4

Note: 1 – The first number indicates the number of melting, the next - room cooling mode hire; 2 – rolling speed in the finishing unit 92,5 m/s; moving speed of coils rolled from roller conveyor 0,5 m/s; 3 – shows the average value.

Table № 4

Parameters of steel structure C70D with and without boron of rolled steel 5,5 mm in diameter

№ regime	Perlite mark[1]	Amount of sobing perlite, %	The maximum depth of the carbon free layer[2], %	Valid grain number[3]	Number of structurally free ferrite, %
1-1	1…3	60	2,0	8, 9, 10	5,0
1-2	1…2	78	1,5	8, 9	4,0
2-1	1…3	65	2,0	7, 8	3,5
2-2	1…2	90	1,2	6, 7, 8	1,5

Note: 1 – GOCT 8233-56 trial; 2 – GOCT 1763-68 (method M) trial; 3 – GOCT 5639-82 trial.

This metallographic analysis indicates that the optimum forming quality indicators of rolled steel is achieved when it is cooled by regimes № 1-2 (steel without boron) and № 2-2 (steel with boron). In the latter case, the quality of rolled steel is undeniably superior to metal without boron in all the studied criteria: minimum depth of carbon free layer,maximum values of strength and plastic characteristics.

Effect of boron as an element that combines with nitrogen reduces strain aging (deformation tensile residual elongation of 6 %, followed by tempering at 200° C for one hour) is demonstrated in the table. 5, according to which the growth indicators for the strength of steel rolled, microalloyed boron lower than steel without boron. A more significant difference to increase the strength of steel with and without boron is observed with temporary resistance ($\Delta\sigma_{\text{В}}$ = 56 MPa, $\Delta\sigma_{\text{т}}$ = 19 MPa). Similarly, in deformation aging in microhardness of pearlite steels with boron without boron changes (tab. 6). Increasedstrength indicators of hot metal microalloyedwith boron and high plasticity resource, along with structural parameters (see. Table. 4), are determined by the characteristics of the fine structure perlite: cooling mode at a constant temperature of 950°C of rolled steel the average value of interlayer distance of pearlite steel microalloyed with boron is 0,123 mm, which ~ 15 % less than steel without boron (0,142 microns).

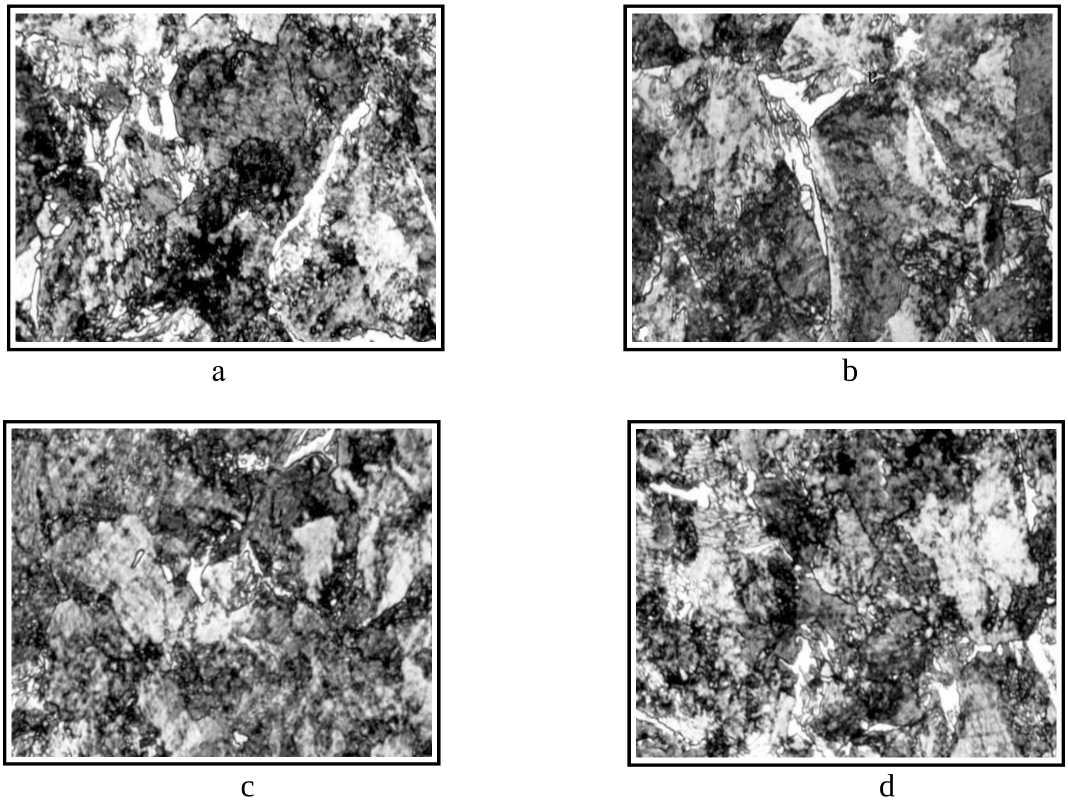

Figure 2. The microstructure of steel C70D (×1000) of rolled steel 5,5 mm in diameter: a, b – steel without boron modes№ 1-1 and 1-2 , respectively; c, d – steel with boron mode № 2-1 and № 2-2 respectively (B = 0,0016 %)

This effect ofboron microadditives on reductionof the propensity of pearlitic class to strain aging is an important link in question to increase the drawing manufacturability of rolled steel in cord redistribution. Microalloying of high carbon steel with boron can increase strength of rolled steel not only after appropriate deformation-heat treatment, but after cold deformation of metal on the cord redistribution.

Table № 5

Changes in strength characteristics of rolled steel 5,5 mm in diameter of steel C70D under strain aging

№ fusion	Strength Indicators					
	Hot rolling condition, MPa		After strain aging, MPa		Increase after strain aging, MPa	
	σ_B	σ_T	σ_B	σ_T	$\Delta\sigma_B$	$\Delta\sigma_T$
1	1038	612	1178	993	140	381
2	1067	629	1151	991	84	362

Table № 6

Changes in microhardness of pearlite in steel C70D of rolled steel diameter of 5,5 mm at a strain aging

№ fusion	Microhardness (H_μ 200), MPa		
	The initial state	After deformation and tempering	The growth of micro hardness as a result of aging
1	3370	3820	450
2	3430	3740	310

If necessary, increase of strength indicators of rolled steel high carbon steel necessary should be carried out by alloying steel with chemical elements such as vanadium, chromium, aluminum, and manganese. Alloying elements perform various functions: improve quality and macrostructure of a workpiece; increase strength and ductility properties of metal; improve impact strength; eliminatingaging effects and others. However, it should be understood that all of the alloying elements strengthen steelby different mechanisms. If vanadium is more susceptible to the formation of dispersed particles of carbides and nitrides (dispersion strengthening), the manganese and chrome strengthen steel by hardsoluble mechanism. Aluminum forms refractory compounds with nitrogen, reduces its negative impact and, like vanadium strengthens steel by dispersion mechanism. However, aluminum cannot always be used due to the fact that during the pouring of liquid steel there is a risk of closing holes of steel teeming glasses by the formation of decking. For eutectoid (alloyed) steel composition by manganese, overheating is undesirable because of a tendency to increase austenitic grain, whereas for steels alloyed with vanadium, aluminum or chrome, overheating is not dangerous [12]. Alloying elements form dispersed carbides and determine the stability of steel when heated, reducing sensitivity to changes of austenitic grain that actually starts to grow after the soluble carbides pass into solid solution. Carbides of some chemical elements, including titanium, niobium, vanadium completely pass into solid solution even by heating steel to temperatures much higher than the equilibrium critical point of steel [12]. This creates additional conditions that provide resistance to grain growth of austenitic steel when heated.

In addition to the features listed, alloying elements increase austenite cooled stability and reduce the critical speed of hardening. Therefore, the air cooling of high rolled steel on Stelmor line equipped with powerful ventilation systemsthe possibility of disintegration of metastable austenite structure to form intermediate or shear mechanism should be taken into account. In this regard, rolled steel cooling should be based on previous detailed study of the kinetics of decomposition of austenite appropriate steel make [13-15].

When performing experiments experimental batches of rolled steel of 5,5 mm in diameter of steel grade C70D with high boron content of 0,0037...0,0053 % [16] were produced, which are characterized by a decreased plastic metal performance. This feature is related to the effect of "overdose" - the formation of a segregation at grain boundaries, film and bulk discharge of incoherent phases (boron nitrides, carboboronitrides Me_{23} (B, N, C)$_6$ Me_3 (B, N, C) etc.) and dispersed precipitates and particles that hinder the movement of dislocations appear in the volume of grains as well.

The formation of precipitates and particles at the borders and within the scope of austenite grains reduces the degree of supercooling of austenite eutectoid before the collapse.Increased levels of boron reducessorbitol like perlite in rolled steel and reduces its mechanical properties.

Statistical analysis of the data obtained in the course of years of observation (2005...2011) of technological processing in rolled steel at hardware companies in Ukraine and the EU allowed to establish the following empirical relationship:

$$B = ((0{,}82-0{,}74\cdot C)\pm 0{,}1)\cdot N,\ \%$$

where B – boron quantity, %; C, N – carbon and nitrogen quantity in steel determined by bucket analysis, %.

Reproduced empirical expression was obtained for rolled steel of wide brand assortmentincluding: low-carbon steel makes of general purpose and in the cold landing, low makes of steel welding supplies, where boron content is significantly higher than compared to products with brands of high carbon steel.

Controlled introduction of boron solved the problem associated with degassing steel by its nitrogen content, and with the developed modes of high deformation-thermal processing helped to ensure the efficient formation of structural state of rolled steel [16]. The efficiency of boron steel microalloying is to improve the complex mechanical and technological properties of metal without a significant rise in production technology.

The developed method of steel microalloying with boron has been recognized as intellectual property, a patent of Ukraine for invention under number №103113 "Steel for deep drawing" has been received [17].

The research and practical results depicted in the work in [16] indicate that the use of boron in the industry offers great opportunities for sparingly steel production of new generation whose performance is superior to the level of rolled steel properties, is manufactured with traditional alloying.

Conclusions

1. The features (patterns) of impact by boron alloying on structure and formation of complex quality indicators of rolled high carbon steel are depicted.

2. It has been established that enhancing durability performance of rolled steel, microalloyed with boron and high ductility metal resources, along with structural parameters are determined by the characteristics of fine pearlite structure: with identical interlayer cooling average of the distance in pearlite steel microalloyed with boron ~ 15 % less than steel without boron is 0,123 mkm.

3. The efficiency of boron microalloying steel has been grounded; its effect on increasing complex mechanical and technological properties of the metal, without significantly higher costs of rolled steel has been established.

4. The mechanism of influence of boron microalloying additives on steel which is to improve the stability of metastable austenite and the ability to reduce the allocation of surplus phase in the continuous cooling of rolled steel has been investigated.

5. The developed method of steel microalloying with boron has been recognized as intellectual property, a patent of Ukraine for invention under number №103113 "Steel for deep drawing" has been received.

6. Empirical expression that allows todetermine the required content of boron in rolled steel has been established.

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ВПЛИВ БОРУ НА ФОРМУВАННЯ ЕФЕКТИВНОЇ СТРУКТУРИ БУНТОВОГО ПРОКАТУ І ПІДВИЩЕННЯ ЙОГО ТЕХНОЛОГІЧНОЇ ПЛАСТИЧНОСТІ ПРИ ВОЛОЧІННІ

[1]Едуард Парусов; [2]Олександр Сичков; [3]Світлана Губенко; [3]Максим Амбражей

[1]Інститут чорної металургії ім. З.І. Некрасова НАНУ, Дніпро, Україна;
[2]Магнітогорський державний технічний університет
ім. Г.І. Носова, Магнітогорськ, Росія;
[3]ДВНЗ «Національна металургійна академія України»,
Дніпро, Україна

Резюме. *Показано особливості впливу легування бором на структуроутворення і формування комплексу якісних показників бунтового прокату з високовуглецевих сталей. Механізм впливу мікролегуючих добавок бору на сталь полягає в підвищенні стійкості метастабільного аустеніту і в здатності зниження виділення надлишкових фаз у процесі безперервного охолодження бунтового прокату. Встановлено емпіричне вираження, що дозволяє визначати необхідний вміст бору в сталі для бунтового прокату.*

Ключові слова: *бунтовий прокат, мікролегування бором, структуроутворення, безперервнолита заготовка, технологічна пластичність.*

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