Materials science / Материаловедение

UDC 621.771:620.186.5
DOI 10.17073/0368-0797-2023-6-659-665

Original article
Оригинальная статья

Structure and properties of low-alloy steel 10G2FBYu after rolling in embossed rolls under conditions of electroplasticity

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Abstract. The article describes the features of grain structure formation and mechanical properties of low-alloy steel 10G2FBYu after rolling in flat and embossed rolls under the conditions of ordinary and electroplastic deformation. When rolling in embossed rolls, a significant non-uniformity of deformation is achieved over the rolling cross-section, expressed in localized macroshifts directed at an angle of 45° to the rolling plane. It is shown that local shear deformation during rolling in embossed rolls leads to an increase in the ultimate strength of the steel under study with a decrease in plasticity of the rolled material. Rolling 10G2FBYu steel in embossed rolls under conditions of electroplasticity provides maximum strength characteristics with a high hardening coefficient at the stage of macrodeformation. At the same time, the plasticity is maintained at a level sufficient for technological purposes. Structural metallographic and electron microscopic studies showed that increase in strength of steel when rolling in embossed rolls under conditions of electroplastic effect is caused by the refinement of ferrite grains to sizes less than 0.5 μm. Fractographic studies revealed changes in the nature of fracture in steel during rolling in embossed rolls, which is expressed in appearance of areas of brittle fracture in the rolled samples. Rolling under conditions of electroplasticity increases the proportion of ductile fracture and ductility of 10G2FBYu steel.

Keywords: 10G2FBYu steel, rolling, embossed rolls, electroplastic deformation, fracture, structure

Acknowledgements: The work was performed within the framework of the state task of the Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences, subject no. FWRW-2021-0009.

For citation: Pochivalov Yu.I. Structure and properties of low-alloy steel 10G2FBYu after rolling in embossed rolls under conditions of electroplasticity. *Izvestiya. Ferrous Metallurgy*. 2023;66(6):659–665. https://doi.org/10.17073/0368-0797-2023-6-659-665

Структура и свойства малолегированной стали 10Г2ФБЮ после прокатки в рельефных валках в условиях электропластичности

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Аннотация. Исследованы особенности формирования зеренной структуры и механические свойства малолегированной стали 10Г2ФБЮ после прокатки в плоских и рельефных валках в условиях обычной и электропластической деформации. При прокатке в рельефных валках достигается существенная неравномерность деформации по сечению проката, что выражается в локализованных макросдвигах, направленных под углом 45° к плоскости проката. Локальная сдвиговая деформация при прокатке в рельефных валках приводит к возрастанию предела прочности исследуемой стали при снижении пластичности прокатанного материала. Прокатка стали 10Г2ФБЮ в рельефных валках в условиях электропластичности обеспечивает максимальные прочностные характеристики с высоким коэффициентом упрочнения на стадии макродеформации. Пластичность при этом сохраняется на достаточном для технологических целей уровне. Структурные металлографические и электронно-микроскопические исследования показали, что повышение прочности стали при прокатке в рельефных валках в условиях электропластического эффекта обусловлены измельчением зерен феррита до размеров менее 0,5 мкм. Фрактографические исследования выявили изменения характера разрушения в стали при прокатке в рельефных валках, которое выражается в появлении областей хрупкого разрушения в прокатанных образцах. Переход к прокатке в условиях электропластичности повышает долю вязкого разрушения и пластичность стали 10Г2ФБЮ.

Ключевые слова: сталь 10Г2ФБЮ, прокатка, рельефные валки, электропластическая деформация, разрушение, структура

Благодарности: Работа выполнена в рамках государственного задания Института физики прочности и материаловедения Сибирского отделения РАН, тема номер FWRW-2021-0009.

Для цитирования: Почивалов Ю.И. Структура и свойства малолегированной стали 10Г2ФБЮ после прокатки в рельефных валках в условиях электропластичности. *Известия вузов. Черная металлургия*. 2023;66(6):659–665. https://doi.org/10.17073/0368-0797-2023-6-659-665

Introduction

Improving the quality of rolled sheets stands as the paramount objective in rolling production. Attaining enhanced strength in low-alloy steels, crucial for construction, oil and gas equipment manufacturing, and oil and gas pipeline production, can be achieved through various methods: targeted alloying [1], controlled rolling [1; 2], asymmetric rolling [3], and other techniques [4 – 6]. To produce high-strength fine-grained rolled products, the suggestion is to employ deformation rolling processes featuring local macroshifts. These macroshifts are facilitated by rolling sheet material in rolls with annular grooves [7 – 9]. In [10], it is demonstrated that rolling 09G2BT steel in such rolls results in a 10 % increase in tensile strength and a 17 – 47 MJ/m^2 boost in impact strength, while decreasing anisotropy (r) from 2.8, observed during rolling in smooth rolls, to 1.9 when using rolls with annular grooves.

In [11 – 13], the study explores rolling in rolls with a corrugated or wavy surface as a form of intense plastic deformation. This induces local macroshifts, influencing the rolled metal through localized deformation effects. Such macroshifts play a crucial role in processing the entire thickness of the sheet, refining the grain structure, and forming a fine-crystalline grain structure. This overall enhancement leads to improved strength characteristics in the rolled metal, including an increase in impact strength.

The quality of rolled metal can undergo substantial improvement through the application of specialized rolling methods combined with additional impact on the metal via low-duty impulses of high-density electric current (up to 1000 A/mm^2) [14 – 16]. This approach is grounded in the electroplastic effect, which entails an augmentation in the plasticity of materials under the influence of an electric current. Notably, higher deformations have been achieved through rolling in the electroplastic deformation mode, eliminating the need for intermediate high-temperature annealing [17 – 19]. In a related study [20], it was demonstrated that rolling with current could lead to the formation of a nanocrystalline structure in titanium-based alloys and titanium nitride, significantly enhancing their strength characteristics.

The current investigation encompasses an examination of the combined method involving rolling in embossed rolls with the additional impact of electric current pulses on the structure and mechanical properties of low-alloy steel 10G2FBYu. This is compared to rolling in flat rolls, encompassing the electroplastic deformation (EPD) mode.

Materials and methods

This study focused on low-alloy low-carbon steel 10G2FBYu. The steel composition includes, wt. %: C 0.10; Mn 1.58; Si 0.38; S 0.005; P 0.015; Ti 0.019; Al 0.034; V 0.076; Nb 0.048; N_2 0.008.

The investigation involved steel in its as-delivered state, specifically a 56 mm thick sheet after hot rolling. Billets for rolling, in the form of rectangular section rods measuring 15×10 mm with a length of 200 mm, were cut from the original sheet along the rolling direction. Four rolling modes were employed. Mode *1*: rolling billets in flat rolls, reducing thickness from 10 mm to 1 mm without intermediate annealing in multiple passes with a reduction per pass of 0.2 mm (referred to as rolling in flat rolls). Mode *2*: rolling samples from 10 mm to 3 mm in flat rolls, from 3 mm to 1.6 mm in embossed rolls, and from 1.6 mm to 1 mm in flat rolls without intermediate annealing in multiple passes with a reduction per pass of 0.2 mm (referred to as rolling in embossed rolls). Modes *3* and *4* differed from modes *1* and *2* by applying electrical current pulses, with a frequency of 4 kHz and a duration of 100 μs, from a specialized pulse generator with a power of 600 W (referred to as rolling with EPD).

The rolling of steel samples took place on a VEM 3 laboratory mill.

Mechanical tests for uniaxial tension were conducted using an Instron-5582 universal testing machine at a speed of 10^{-4} s^{-1} at room temperature. Samples of 10G2FBYu steel for mechanical testing were cut into double-sided blades with a working length of 25 mm and a cross-section of 1×5 mm.

Metallographic studies utilized a Zeiss Axiovert 25 CA optical microscope.

Fractographic studies of the destroyed samples were carried out using the raster electron microscopy with a Tesla BS-300 scanning microscope.

Electron microscopic analysis was conducted utilizing a JEM–100 CXII transmission electron microscope operating at an accelerating voltage of 100 kV. To prepare samples for this analysis, sections were precisely cut using an electrical discharge machine, ground to a thickness of 100 μm, and discs with a diameter of 3 mm were

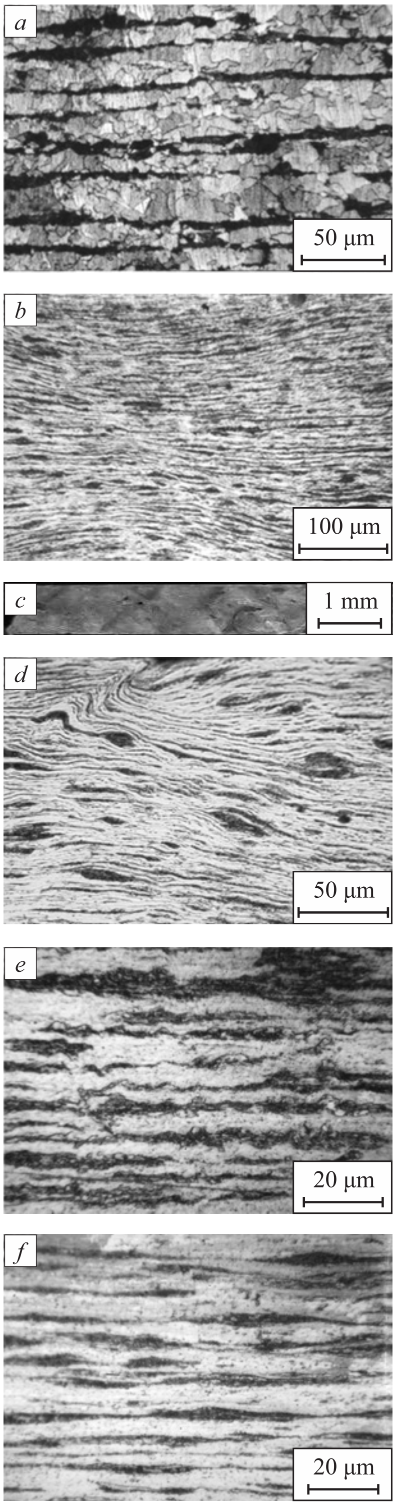

Fig. 1. Structure of 10G2FBYu steel in the state of delivery and after rolling under different conditions:
a – in the state of delivery; *b* – after rolling in flat rolls;
c, *d* – after rolling in embossed rolls;
e – after rolling in flat rolls with electroplastic deformation (EPD);
f – after rolling in embossed rolls with EPD

Рис. 1. Структура стали 10Г2ФБЮ в состоянии поставки и после прокатки в разных условиях:
а – в состоянии поставки; *b* – после прокатки в плоских валках;
c, *d* – после прокатки в рельефных валках;
e – после прокатки в плоских валках с ЭПД;
f – после прокатки в рельефных валках с ЭПД

subsequently cut. The samples were further polished until a hole emerged through jet electropolishing in an electrolyte composed of 125 ml CH_3COOH, 25 g GrO_3, and 5 ml H_2O.

Results and discussion

In Fig. 1, *a*, the structure of 10G2FBYu steel is depicted in its as-delivered state after pickling in a 4 % nitric acid solution.

The steel exhibits a typical two-phase grain structure characterized by grains elongated along the rolling direction, displaying ferrite-pearlite banding (Fig. 1, *a*). Ferrite grain sizes range from 5 to 15 µm, and the width of pearlite strips is 3 – 7 µm. The tensile diagram of the steel in its as-delivered state is illustrated in Fig. 2, curve *1*, with a tensile strength of 563 ± 12 MPa and a ductility of approximately 15 % (refer to the Table).

Following rolling in flat rolls, 10G2FBYu steel develops a structure with grains elongated along the rolling direction (Fig. 1, *b*). During the rolling process, pearlite colonies undergo substantial crushing and transformation into small particles, measuring 3 – 5 µm in size and exhibiting irregular shapes. The ultimate strength of the steel experiences a notable increase (Fig. 2, Table). However, concurrently, the ductility undergoes a significant reduction, almost halving in comparison.

The structure of 10G2FBYu steel after rolling in embossed rolls is presented in Fig. 1, *c*, *d*. Notably, rolling in embossed rolls achieves significant, uneven deformation across the cross-section of the rolled product, evident in localized macroshifts directed at a 45° angle to the plane of the rolled product (Fig. 1, *c*). These shifts result

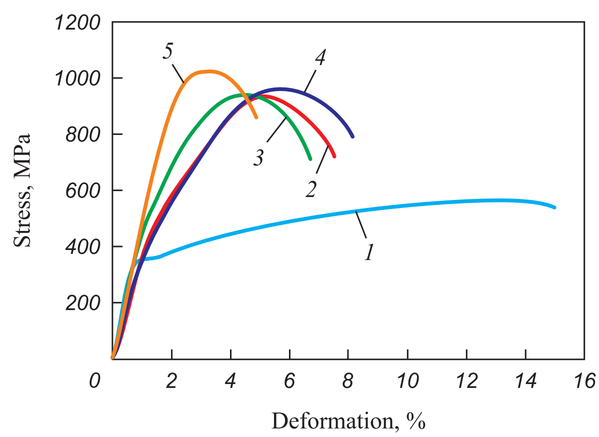

Fig. 2. Stretching diagrams of 10G2FBYu steel:
1 – in the state of delivery; *2* – after rolling;
3 – after rolling in embossed rolls; *4* – after rolling with EPD;
5 – after rolling in embossed rolls with EPD

Рис. 2. Диаграммы растяжения стали 10Г2ФБЮ:
1 – в состоянии поставки; *2* – после прокатки;
3 – после прокатки в рельефных валках; *4* – после прокатки с ЭПД;
5 – после прокатки в рельефных валках с ЭПД

Mechanical properties of 10G2FBYu steel samples in the state of delivery and after rolling without and with EPD

Механические свойства образцов стали 10Г2ФБЮ в состоянии поставки и после прокатки без ЭПД и с ЭПД

State (type of treatment)	Elastic strength σ_0, MPa	Yield strength $\sigma_{0.2}$, MPa	Ultimate strength σ_u, MPa	Relative elongation, %
As delivered	265 ± 22	353 ± 2	563 ± 12	15.0 ± 2
After rolling	307 ± 27	502 ± 47	934 ± 14	7.5 ± 0.1
After rolling in embossed rolls	321 ± 15	540 ± 29	938 ± 4	6.8 ± 0.1
After rolling with EPD	278 ± 9	423 ± 24	958 ± 2	8.3 ± 0.1
After rolling in embossed rolls with EPD	511 ± 16	905 ± 17	1024 ± 12	5.0 ± 0.1

from local shear deformation during the rolling process in embossed rolls. Post-rolling, the grain structure undergoes significant refinement, and a less pronounced banded ferrite–pearlite structure is formed (Fig. 1, *d*) compared to the original steel sample (Fig. 1, *a*). Strength characteristics after rolling in embossed rolls are nearly identical to those of 10G2FBYu steel rolled in flat rolls (Fig. 2, Table). Notably, there is a noticeable increase in the elastic limit, the hardening coefficient at the macrodeformation stage, and, consequently, an elevation in the conditional yield strength $\sigma_{0.2}$.

Rolling in flat rolls in the electroplasticity mode marginally enhances the tensile strength and ductility of the steel compared to conventional rolling (Fig. 2, Table). The structure of the steel rolled in the electroplasticity mode remains consistent with that observed during conventional rolling in flat rolls.

The structures of 10G2FBYu steel after rolling in flat and embossed rolls in the electroplastic deformation mode are depicted in Fig. 1, *d*, *f*. Notably, the size and morphology of cementite particles exhibit marked variations depending on the rolling method applied. Cementite particles in 10G2FBYu steel after rolling in flat rolls with EPD (Fig. 1, *e*) are larger in size, with an average width of 3.5 μm, compared to rolling in embossed rolls with EPD (Fig. 1, *f*) where the average width of cementite plates is 2.2 μm. In both rolling scenarios, highly dispersed carbide particles are observed inside the ferrite grains (Fig. 1, *e*, *f*).

The aforementioned mechanical test results for 10G2FBYu steel, following various rolling schemes, underscore the significant influence of the rolling scheme and additional impact on the strength properties of the rolled material. During rolling in embossed rolls, where plastic flow occurs in both longitudinal and transverse directions with significant local macroshifts, the strength of 10G2FBYu steel surpasses that achieved through conventional rolling in flat rolls. Rolling the steel samples with the application of powerful electric current pulses in the electroplastic deformation mode also leads to an increase in its strength characteristics. The peak strength for 10G2FBYu steel is achieved after rolling in embossed rolls while simultaneously subjecting it to shear deformation and electric current pulses. In this scenario, the tensile strength reaches 1000 MPa, accompanied by a substantial increase in the hardening coefficient at the macrodeformation stage, rising from 200 MPa during conventional rolling to 500 MPa when rolling in embossed rolls in the EPD mode.

An examination of the microstructure of 10G2FBYu steel through transmission electron microscopy reveals that in the as-delivered state, the predominant component is ferrite (Fig. 3, *a*), with an average grain size of 5 – 10 μm. Deposits of iron carbide Fe_3C of lamellar or spherical type are observed inside and along the grain boundaries. After rolling, a fine-grained structure with an average grain size of 5 – 7 μm forms in the steel, featuring a cellular dislocation structure with misorientation between cells ranging from 2 to 10°. It's worth noting that the post-rolling structure is highly heterogeneous.

Following rolling in embossed rolls, the average grain size further decreases to 2 – 3 μm, and the grains become fragmented into cells with sizes less than 0.5 μm. This reduction in grain size during embossed roll rolling is attributed to shear stresses, contributing to grain refinement. Rolling under conditions of electroplastic deformation, influenced by electric current pulses, leads to an even more significant reduction in the average grain size (less than 1 μm) and the formation of a cellular structure with dimensions less than 0.3 μm. This rolling mode corresponds to the highest strength achieved for the studied steel.

Similar findings were reported in [21], where it was observed that rolling L80 brass in rolls with grooves led to a reduction in the average size of the initial grain from 22 to 3 μm. In contrast, traditional rolling only resulted in a decrease in grain size to 9 μm. The formation of a fine-crystalline structure, as demonstrated in both studies, contributes to an enhancement in the strength properties of the rolled material.

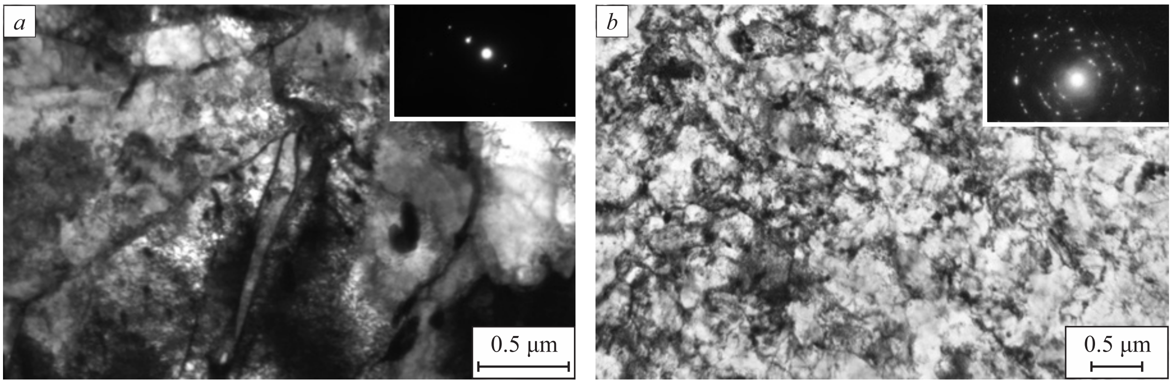

Fig. 3. Electron microscopic images of structure of 10G2FBY steel:
a − in the state of delivery; *b* – after rolling in embossed rolls

Рис. 3. Электронно-микроскопические изображения структуры стали 10Г2ФБЮ:
a − в состоянии поставки; *b* – после прокатки в рельефных валках

The analysis of fracture patterns in 10G2FBYu steel samples subjected to active tension reveals distinctive characteristics. In the as-delivered state, fractures result in knife-like patterns, with the fracture surface characterized by plastic materials featuring a cup-shaped appearance (Fig. 4, *a*, *c*). The size of pits on the fracture surface ranges from 0.5 to 15 μm. Some pits contain small (≈2 μm) non-metallic inclusions. Tensile testing in this state demonstrates the maximum ductility of 10G2FBYu steel. The elongation of fracture pits indicates the presence of a shear stress component during fracture.

Following rolling in flat rolls, fractures in 10G2FBYu steel exhibit delaminations along the rolled planes, significantly elongated fracture pits, and the emergence of quasi-cleavage areas (Fig. 4, *b*, *d*). The ductility of the steel sharply decreases after rolling. These fracture features persist during rolling in relief rolls and in the electroplastic deformation mode. After rolling in embossed

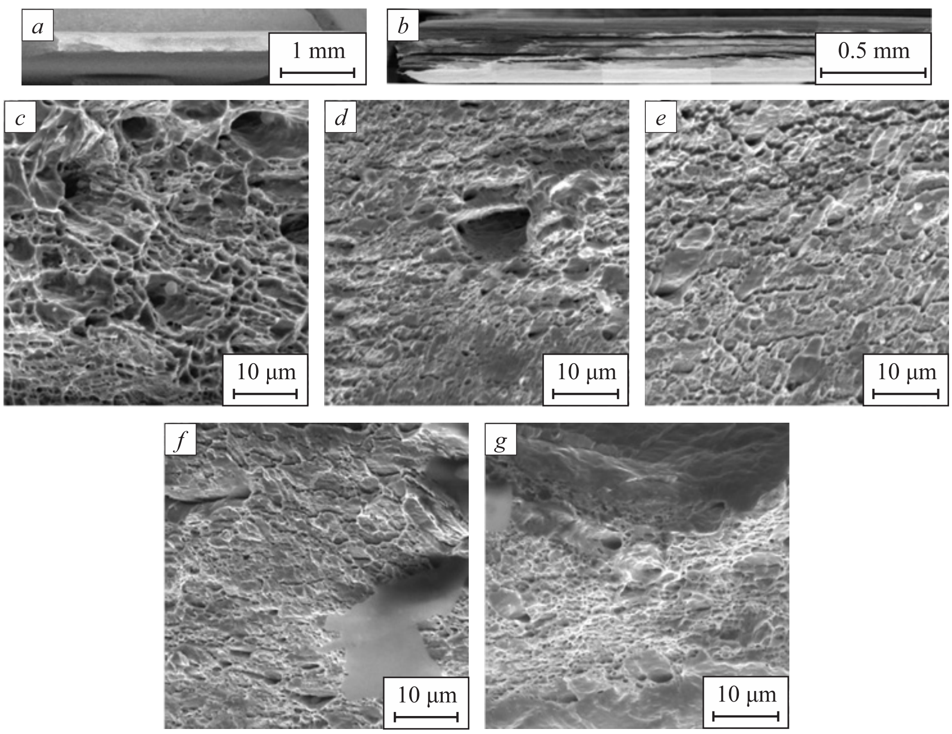

Fig. 4. Fracture factors of 10G2FBYu steel samples:
a, *c* – in the state of delivery; *b*, *d* – after rolling in flat rolls; *e* – after rolling in embossed rolls;
f – after rolling in flat rolls with EPD; *g* – after rolling in embossed rolls with EPD

Рис. 4. Фрактуры разрушения образцов стали 10Г2ФБЮ:
a, *c* – в состоянии поставки; *b*, *d* – после прокатки в плоских валках; *e* – после прокатки в рельефных валках;
f – после прокатки в плоских валках с ЭПД; *g* – после прокатки в рельефных валках с ЭПД

rolls, the proportion of quasi-cleavage increases, and the fractograms of the fracture surface show large areas with a quasi-brittle type of fracture (Fig. 4, *e*). Samples rolled in the electroplastic deformation mode exhibit a decrease in the proportion of brittle fracture. Fig. 4, *f*, *g* display fractograms of the destruction of samples rolled in flat and embossed rolls in the electroplastic deformation mode.

Conclusions

The local shear plastic deformation occurring during rolling in embossed rolls induces the formation of localized deformation bands. These bands play a crucial role in effectively refining the grain structure and pearlite plates. Structural investigations have demonstrated that, particularly during such rolling under conditions of electroplastic deformation, a submicrocrystalline structure with a grain size of less than 0.5 μm is established.

The development of a submicrocrystalline structure results in a significant enhancement of the strength characteristics of the studied steel, including an increase in the hardening coefficient at the stage of macrodeformation. In this scenario, ductility experiences a reduction but remains at a sufficient level for practical applications. Fractographic studies have revealed alterations in the nature of fracture in the steel during rolling, manifested in the emergence of areas featuring brittle fracture in the rolled samples. The shift to rolling under electroplastic deformation conditions increases the proportion of ductile fracture and enhances the ductility of 10G2FBYu steel.

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Received 01.11.2022
Revised 07.09.2023
Accepted 11.09.2023

Поступила в редакцию 01.11.2022
После доработки 07.09.2023
Принята к публикации 11.09.2023