The temperature and degree of hot deformation for steel 10HFTBch have been determined. This made it possible to ensure an increase in the mechanical properties of this steel, namely, the ultimate strength up to 540–560 MPa, as well as the relative elongation up to 25–29 %. As a result, it became possible to increase the service life of wheels with increased carrying capacity. This, in turn, will make it possible to increase the load of the transported cargo by motor vehicles several times.

The mechanism of the influence of the energy-power parameters of rolling on the formation of the macro- and microstructure of a two-phase steel in the process of hot deformation is disclosed. The applied scheme provided an increase in the homogeneity of the structure of the developed steel, which saved the central part of the rolled section from overheating. It has been established that a decrease in the temperature of the end of deformation leads to a decrease in the size of the recrystallized austenite grain, and, consequently, to a refinement of the ferrite grain. Also an important factor in preventing the growth of ferrite grains in the upper part of the ferritic region is the abolition of cooling of the steel in coils.

The recommended mode for multicomponent alloy steel 10HFTBch is as follows: the temperature of the end of rolling is 850 °C, the beginning of accelerated cooling is 750 °C, and the temperature of strip coiling into a coil is 600 °C.

The basis for ensuring the increased strength of two-phase steels is the ratio and distribution of structural fractions – ferrite (initial and precipitated from austenite), as well as martensite. When hardened by such traditional "martensite formations" as manganese, the ability to control properties is limited. This is reflected in a narrow range of variation in the strength and ductility of the developed steel. The optimal combination of strength characteristics of plastic properties reduces the metal consumption of the product by 15–25 %

Keywords: Hensel-Spittel formula, hot deformation, physical modeling, power parameters, ferrite

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ENERGY POWER PARAMETER EFFECT OF HOT ROLLING ON THE FORMATION OF THE STRUCTURE AND PROPERTIES OF LOW-ALLOY STEELS

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1. Introduction

The development of road transport in the world determines the vector of requirements for increasing loads and speed of movement of freight vehicles, creating road trains. This makes it necessary to improve the unsprung part of the car, including the rims and wheel disks, which are critical parts. The main material used all over the world for the production of wheels for trucks, buses, trolley buses is low-carbon steel of the steel 15 type, with a strength of 350–370 MPa. At the same time, ensuring the necessary characteristics of the wheels is directly related to the properties of materials and design features of the wheelsets. On the market for automobile wheels, a stable trend has emerged – the production of wheels with increased carrying capacity, which makes it possible to increase the volume of transported cargo several times under existing operating conditions. Thus, the number of flights is reduced, which leads to significant savings in fuels and lubricants, wheels of carriers [1].

This requires a thorough study of new grades of hardened steels, focused on specific technical requirements, and, accordingly, differing in the method of hardening alloying. For solid solution hardening, manganese, silicon, phosphorus are mainly used. This is done separately or jointly, sometimes in combination with a microaddition of titanium, niobium and vanadium, which makes it possible to have a tensile strength of up to 500 MPa. And all this with the elongation values and normal plastic anisotropy sufficient for stamping. Hot-rolled and cold-rolled two-phase complex alloy steels are distinguished by a wide range of properties. Economical and technological phosphorous steels are of particular interest. At the same time, the determination of the optimal thermomechanical parameters for the processing of such steels, in order to improve the mechanical properties, is an urgent task [1].

2. Literature review and problem statement

In the study [2], it was shown that a promising direction in the development of optimal control of cargo transportation is the development of wheels for road trains with a carrying capacity of up to one railroad car, i.e, 60 tons. For this purpose, dependences of changes in the structure of steel during plastic deformation were obtained. However, the influence of plastic deformation on the technological properties of steel is not fully indicated. At the same time, in European countries and the USA, for the production of wheels, low-pearlitic steels of increased strength are used – more than 500 MPa [3].

Another promising direction for increasing the strength characteristics through the use of nanocomposite materials is considered in [4]. However, the method proposed in this work provides for the use of science-intensive technologies. This leads to the fact that objective difficulties arise in conditions of mass production.

In work [5], the reserves of increasing the mechanical characteristics of low-pearlitic steel 10HFTBch are considered. The effect of thermoplastic treatment in the intercritical temperature ranges proved to be effective. In order to further improve the technological properties of wheels, the formation of polygonized structures and recrystallization during controlled rolling of low-carbon steels are considered in [6]. At the same time, the issues of creating a control system for the structure and properties of low-alloy steels using thermoplastic processing were not considered.

Simulation by the finite element method in metal forming processes (MFP) has become widespread as a mathematical tool for studying the stress-strain state [7]. The finite element method is implemented in various software packages, such as Deform-2D/3D, etc. For the correct formulation of the problem, and therefore the adequacy of the calculated results in these software packages, it is necessary to specify an exact description of the rheological properties of the material under study [8]. In this regard, the presence of a mathematical model describing the rheological properties of a material for various conditions of deformation is an urgent task from a practical and scientific point of view [9].

In works [10, 11], the conditions of deformation are specified, which have a significant effect on the energy-power parameters of the process, the microstructure and mechanical properties of the finished product. In the MFP processes for assessing the stress-strain state, energy-power parameters, an important characteristic is the resistance to deformation [12].

The resistance of a metal to deformation is the flow stress of a metal under static conditions of plastic deformation. The flow stress characterizes the mechanical properties of the material immediately before entering and exiting the deformation zone. In addition, in the intervals between the stands, and in the pauses between passes, during rolling, respectively, on continuous and reversible mills [13]. Therefore, the establishment of the regularities of changes in the metal flow stress is important not only for the theory of rolling, but also for the technology of production of wheel disks for motor vehicles [14].

Investigating works [2–14], one can make sure that there is no control system for the structure and properties of low-alloy steels with the use of thermoplastic treatment. This structure control system will improve the technological characteristics of high-strength wheels of vehicles with reduced metal consumption.

3. The aim and objectives of research

The aim of research is to study the structure and properties of low-alloy steels with the use of thermoplastic processing, to improve the technological and service viscoplastic characteristics, ensuring the production of high-strength wheels of vehicles with reduced metal consumption. This will make it possible to increase the load of the transported cargo several times under existing operating conditions. Thus, the number of flights is reduced, which leads to significant savings in fuel and lubricants, wheels of carriers.

To achieve this aim, it is necessary to solve the following objectives:

– to establish the mechanisms of effective influence of temperature-deformation parameters (thermoplastic deformation) of hot rolling and chemical composition on the formation of the structure and mechanical properties of low-alloy low-pearlitic steel 10HFTBch [15];

– to investigate the effect of the stress-strain state of the metal on the properties of steel 10HFTBch.

4. Materials and methods of research

The research material was a high-strength low-alloy steel grade used for wheel production 10HFTBch (Standard of Ukraine). This steel grade contains, by weight %: C – 0.08–0.12, Si – 0.10–0.50, Mn – 0.15–0.50, Cr – 0.05–0.15, V – 0.10–0.15, Ti – 0.10–0.15, Nb – 0.07–0.15, $S \leq 0.035$, $P \leq 0.035$, Ba – 0.0005–0.0015 [6, 15]. Pilot industrial melting of initial and modified steels was carried out in an IST-0.15 induction furnace with a crucible capacity of 150 (kg). Melting parameters: power W=320 (kW) from a thyristor converter, current I=320000 (A), voltage U=1000 (V), frequency f=2.4 (kHz). The actual grain size and the ratio of the structural components of the ferrite-pearlite samples were determined using a hardware-software complex, which includes an AXIOVERT 200 MAT inverted light microscope with a Video-Test-Metal image analysis system. (Firm "Carl Zeiss Industrielle Messtechnik GmbH", Germany). The structures of the samples were investigated on a SUPRA 40 WDS scanning electron microscope (Carl Zeiss Industrielle Messtechnik GmbH, Germany).

Thermoplastic deformation of steel 10HFTBch was studied using the Gleeble 3800 complex (Dynamic Systems Inc, USA) [3].

The mechanical properties of the steels under study were determined before and after normalization on samples after cutting from templates. Templates were obtained from metal rolled on a continuous wide-strip hot rolling mill 1680 (WSHRM 1680). WSHRM 1680 belongs to the first generation mills and includes a roughing and finishing group of stands: a roughing two-roll scale breaker and four quarto stands are installed in the roughing group. In front of the last three stands, vertical rolls are installed to remove the strip expansion. The peripheral speed of the rolls in the first stand is 1.02...1.09 m/s, and in the fourth – 2.23 m/s. The finishing group has six quarto stands, the distance between which is 5.84 m, and the distance between stands No. 4 (roughing group) and stand No. 5 (clean group) is 64.9 m. The maximum rolling speed in finishing mill No. 10 is 9.2 m/s.

Ultimate strength and relative elongation were determined according to ISO 6892-84 on a tensile testing machine MUP-20 at a load of 5 tons and an active grip speed of 2.5 mm/min. During the test of the sample, a tensile diagram was recorded, which fixed the relationship between the force P acting on the sample and the deformation Δl caused by it [16].

Impact strength was tested on an MK-30 pendulum impact machine on Charpy samples according to DSTU EN 10045-1: 2006. Impact strength was determined on a sample with a U-type concentrator at room temperature. The maximum impact energy of the pendulum was 300 J, the depth of the concentrator was 2 mm, and the width of the sample was 10 mm [17].

The effect of the stress-strain state of the metal on the properties of steel 10HFTBch was investigated by the method of determining the relationship between the stress-strain state of the metal with the grain size d and the yield stress σ_t.

Numerical simulation of the rolling process is implemented by the finite element method.

5. Results of the study of the power performance of hot rolling and the properties of low-alloy steels

5. 1. Study of temperature-deformation parameters of hot rolling

Fig. 1 shows comparative curves (experimental, approximated) at different temperatures and strain rates [18]. Analysis of the graphs shows the comparability of experimental and theoretical data.

As a result of mathematical processing of experimental data, equation (1) was obtained, showing the dependence of the resistance of the metal to deformation on the conditions of thermoplastic processing:

$$\sigma_p = 0.000082\varepsilon^{0.524152}\exp\left(\frac{-0.000163}{\varepsilon}\right)\times$$

$$\times\exp(1.11363\varepsilon)(1+\varepsilon)^{-0.0033637}\cdot$$

$$u^{-0.216846}u^{0.000336T}T^{2.97098}\exp(-0.004952T). \qquad (1)$$

The austenite grain size d_γ of low-alloy steel, depending on the initial grain size d_0, holding time t and temperature T, is described by the equation (1), (2) [19]:

$$d_\gamma = \left[d_0^3 + 5.47\cdot 10^{20}t\exp\left(-\frac{460{,}000}{RT}\right)\right]^{\frac{1}{3}}. \qquad (2)$$

Hot rolling is characterized by the passage of metadynamic or static recrystallization (3). One of the methods for modeling recrystallization is the "Kolmogorov – Johnson – Mehl – Avrami" expressions [20–23]. For static recrystallization of low-alloy steel, the recrystallized volume is determined by expressions (1), (2):

$$X_{srex} = 1-\exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.5}\right]. \qquad (3)$$

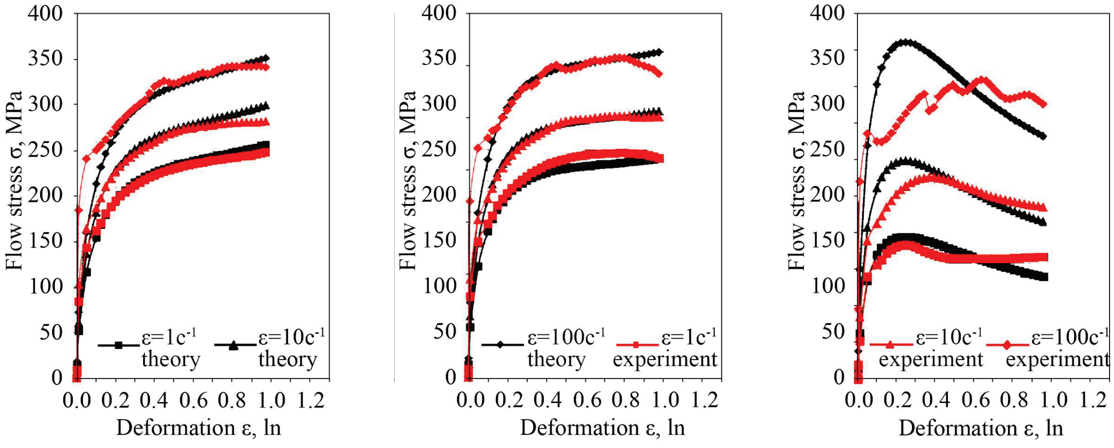
Time required for 50 % static recrystallization of low alloy steel (1), (2):

$$t_{0.5} = 4.92\cdot 10^{-17}d^1\varepsilon^{-2}\dot{\varepsilon}\exp\left(\frac{338{,}000}{RT}\right). \qquad (4)$$

After static recrystallization of low alloy steel, the grain size can be determined using expressions (1), (2):

$$d_{rex} = 1{,}200d_0^{0.33}H^{-0.79}\exp\left(-\frac{88{,}000}{RT}\right). \qquad (5)$$

The Hensel-Spittel expression (5) describes the curve of stress versus thermomechanical parameters with different changes in values. The experimental data presented in [24, 25] confirm this.



a *b* *c*

Fig. 1. Comparison of dependences of yield stress on deformation at different temperatures: *a* – T=850 °C; *b* – T=900 °C; *c* – T=1200 °C

5. 2. Influence of temperature-deformation parameters of rolling and chemical composition on the formation of macro- and microstructure

Fig. 2 shows the distribution pattern of stress intensity (σ_i) during rolling of steel 10HFTBch in the finishing group of stands of the WSHRM 1680mill.

The results obtained by numerical modeling made it possible to establish the following regularities:

1) when rolling in the first stand above the specified mill, the stress intensity (σ_i) at the initial moment of rolling is concentrated in the zones of metal capture by the rolls of the mill. With an increase in compression, the accents σ_i are transferred from the surface to the center and edges of the deformable workpiece;

2) deformation in the next stands of the finishing group of the mill, it is possible to gradually transfer the area of concentration of the deformation intensity from the center to the middle part of the strip, and then to the contact zone of the roll with the rolled billet. This distribution of stress and strain intensity over the stands leads to a more uniform distribution of the total G and σ_i over the deformation zone;

3) the most uniform distribution of the total σ_i along the height and length of the rolled strip was obtained when rolling with a single reduction along the stands:

- the first – 38–45 %;
- the second – 35–40 %;
- the third – 33–38 %;
- the fourth – 28–30 %;
- the fifth – 22–25 %;
- the sixth – 11–14 %;

4) in the process of rolling in the first stand, the temperature in the contact zones “hot metal - rolls” decreases. Rolling in subsequent stands allows, due to the release of the heat of deformation and friction, to equalize the temperature along the deformation zone.

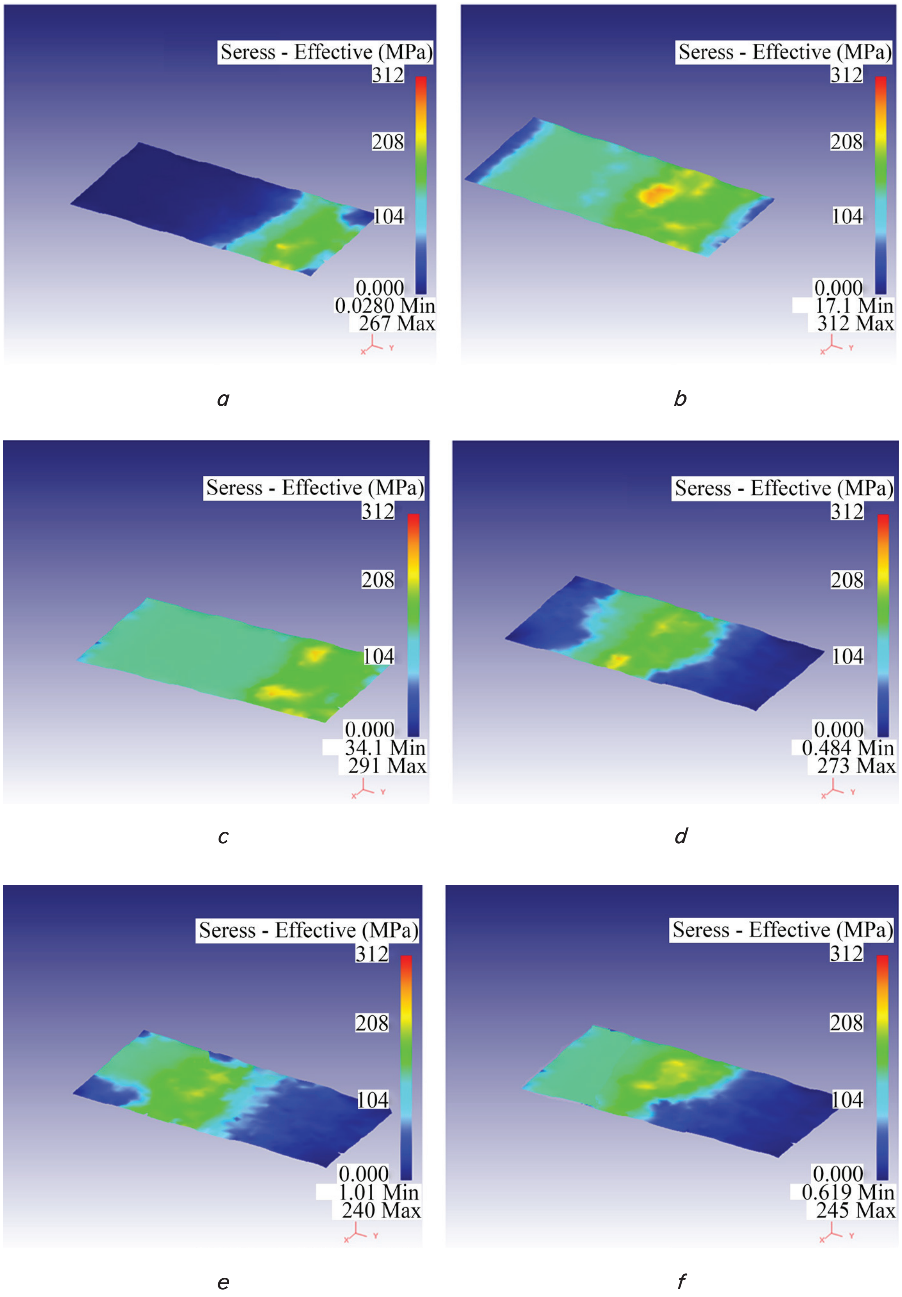
Using the obtained picture of the distribution of the intensity of deformation and stress, the dependence of the change in the grain size d on the parameters of deformation was obtained (Fig. 3).

As a result of calculating the grain size d, the following facts were established:

1) after rolling in the first stand, the structure in the center of the strip is fine-grained and the austenite grain size is 70–85 µm, while in the surface zones of the strip the austenite grain size is coarser (130–145 µm);

2) rolling in subsequent stands of the finishing group of the mill, allows to gradually align the size of the austenite grains, which over the entire section of the rolled strip are equal to 55–65 microns;

3) a decrease in the rolling temperature to 850 °C promotes some refinement of ferrite grains and a decrease in the size of pearlite colonies. Thus, the average grain size of ferrite samples rolled at 900 °C was about 45–50 µm, and after rolling at 850 °C it was about 30–36 µm. The ratio of the structural components under the selected deformation conditions is: ferrite about 60 %, pearlite – about 40 %.



a *b* *c* *d* *e* *f*

Fig. 2. Pattern of stress intensity distribution in the strip during rolling in the finishing group of the mill (the second stage of rolling in each stand): *a* — stand No. 1; *b* — No. 2; *c* — No. 3; *d* — No. 4; e — No. 5; *f* — No. 6

Experimental verification of the simulation results and study of the effect of the hot deformation scheme of steel

10HFTBch was carried out by rolling samples (models) and studying their structure (Fig. 4–7).

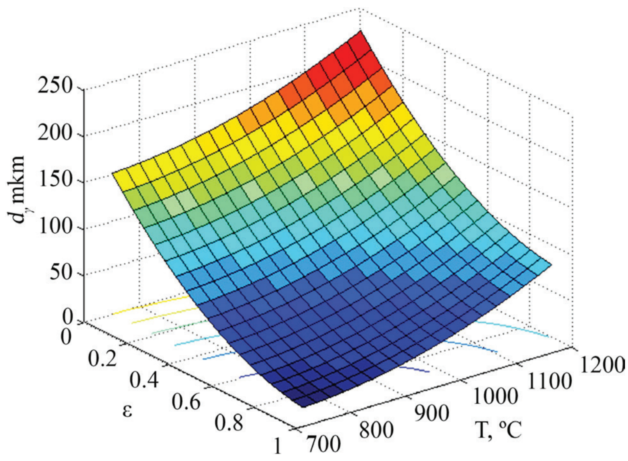


Fig. 3. Change in the grain size *d* of steel 10HFTBch, when rolling in the finishing group of stands

In the general case, three zones can be distinguished, with different degrees of deformability in accordance with [26, 27]. In the first zone, the difference between the stresses is insignificant and may not meet the plasticity condition, although the stresses (levels) themselves are large. In the third zone, the restraining effect of friction forces is the same as in the second, but the stress state pattern is different (tensile stress dominates), which increases the deformation intensity. All rolled samples with different deformation temperatures had different grain sizes over the strip section.

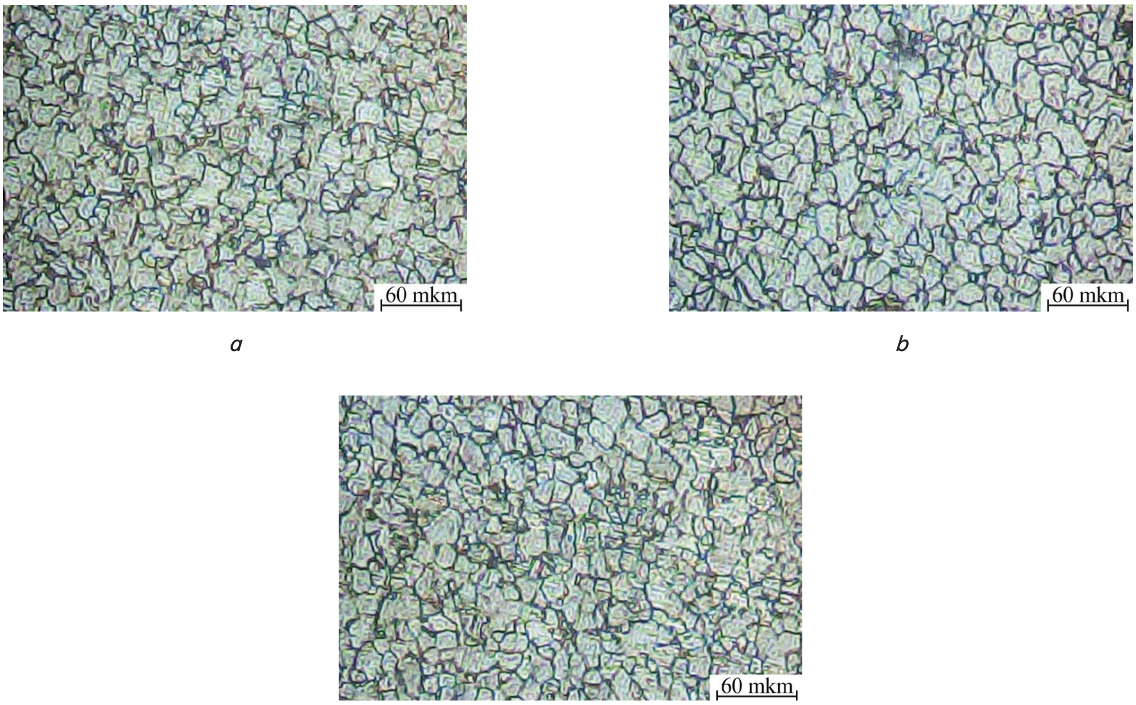
Comparative studies of changes in mechanical properties were carried out on well-known and developed steels 10HFTBch [15], 10XM, steel 15 (Table 1). The following mechanical properties were obtained, determined by tensile testing: ultimate strength (US) 540–560 MPa, impact strength (IS) 0.80–0.85 MJ/m^2, elongation 25–29 %. In the case of a decrease in the deformation temperature, an increase in strength characteristics is provided with a noticeable decrease in plasticity and impact toughness [28, 29].

Table 1

Chemical composition and mechanical properties of steels 10HFTBch, 10XM, Steel 15

Steel grade, Patent	The content of the main alloying elements, in % mass, not less					Mechanical properties, not less		
	C	Cr	Si	Mn	Other elements	*US*, MPa	*IS*, MJ/m^2	δ_5, %
10XM No. 81167	0.11	0.12	0.05	0.35	Mo – 0.20	390	0.9	22
10HFTBch No. 105341	0.10	0.10	0.30	0.32	Nb – 0.11; Ti – 0.12; V-0.12 B – 0.001; REM – 0.005	550	0.8	28
Steel 15	0.15	0.2	0.06	0.4	Cu – 0.25 Ni – 0.25	360	0.8	30

Fig. 4. Macrostructure of a deformed sample



a

b

c

Fig. 5. Microstructure of deformed steel samples at a deformation temperature of 850 °C (×360): *a* – contact zone with the tool, I; *b* – periphery zone, II; *c* – central zone of severe deformation, III

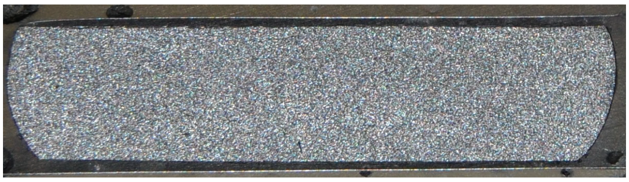
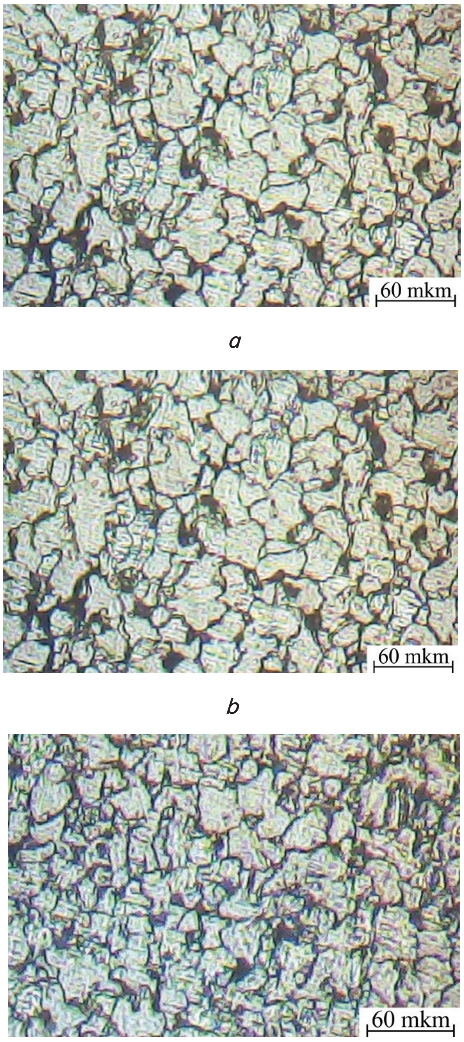


Fig. 6. Macrostructure of a deformed sample



a

b

c

Fig. 7. Microstructure of deformed steel samples at a deformation temperature of 950 °C (×360): *a* — contact zone with the tool, I; *b* — periphery zone, II; *c* — central zone of severe deformation, III

Mechanical properties were determined on samples after recrystallization treatment at 850 °C.

6. Discussion of the results of the study of power parameters of hot rolling and properties of low-alloy steels

The influence of the energy-power parameters of hot rolling on the formation of the structure and properties of low-alloy steels is explained by the fact that a decrease in the temperature of the end of deformation leads to a decrease in the size of the recrystallized austenite grains. This, therefore, leads to the refinement of the ferrite grain (Fig. 4–7). Also an important factor in preventing the growth of ferrite grains in the upper part of the ferritic region is the abolition of cooling of the steel in coils. The existing methods of physical modeling do not fully reflect the effect of thermoplastic deformation parameters to increase the homogeneity of the steel structure.

The recommended mode for multicomponent alloy steel 10HFTBch is as follows: the temperature of the end of rolling is 850 °C, the beginning of accelerated cooling is 750 °C, and the temperature of strip coiling into a coil is 600 °C. Comparative studies of the mechanical properties of known and developed steels are presented (Table 1). One of the disadvantages of rolling metal is the uneven temperature distribution over the strip section. In the case of a decrease in the deformation temperature, an increase in strength characteristics occurs with a noticeable decrease in plasticity and impact toughness.

Thus, at 850 °C, the following mechanical properties were obtained, determined by tensile testing: ultimate strength 540–560 MPa, impact strength 0.80–0.85 MJ/m^2, elongation 25–29 % (Table 1).

The subsequent direction of development of this research is to improve the mechanical and technological properties of the wheels of motor vehicles. The results of such studies can make it possible to increase the mass of the transported cargo in order to save fuel and lubricants and reduce the number of flights.

7. Conclusions

1. Using the method of physical modeling, rational temperature-deformation parameters of rolling and chemical composition, influencing the formation of macro- and microstructure of low-pearlitic steel 10HFTBch, in the process of its hot deformation, have been determined. As a result of using work rolls of variable cross-section, the influence of the stress-strain state of the metal in the finishing group of WSHRM 1680 stands on the properties of steel 10HFTBch was established. This contributed to an additional increase in the homogeneity of the structure of the developed steel and relieved the central part of the rolled section from overheating.
2. As a result of the analysis of the Hensel-Spittel expression, the temperature and the degree of hot deformation were determined, which ensure the increased mechanical properties of the developed steel 10HFTBch.

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