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The Improvement and Development of Hot-Rolled Strip Bar Production Technology at NUST MISiS

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Abstract—This paper presents the results of the work carried out by the Department for Metal Working Processes at NUST for production technology of: high-strength automotive flat stock from bi-phase ferrite martensite steels (BPHFMS) on a broad-strip hot-rolling mill by staged laminar cooling on a runoff table, as well as K52–56 strength grade cold- and corrosion-resistant tubular strip bar. The metal's ferrite grains rolled on the broad-strip mill are ground by combining the controlled rolling (CR) of strips with their rapid cooling (RCL). Thermal kinetic diagrams (TKDs) were created to show modeling sheet cooling, as well as to predict the resulting structure type depending on the metal cooling rate.

Keywords: broad-strip hot-rolling mill, automotive hot-rolled flat stock, bi-phase steels, staged cooling, tubular strip bars, controlled rolling, thermal kinetic diagrams

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Russia's automotive industry is one of the country's main consumers of hot-rolled strip bar. In this case, the most promising kind of such products is high-strength automotive hot-rolled flat bi-phase ferrite martensite steel (BPHFMS) stock. There are two known process flows of producing bi-phase steels for the automotive industry. The first of these includes the production of hot-rolled stock, then cold-rolled, which is followed by its thermal treatment in a continuous annealing unit so that the product acquires automotive flat stock properties; the second process flow includes the production of automotive flat stock in hot-rolled state and its staged laminar cooling on the runoff table of a broad-strip hot-rolling mill (BSHRM) (Fig. 1). The second variant is more promising for improving the economic efficiency of BPHFMS production, because it excludes two stages from the process flow diagram [1]. In other words, the prime cost of hot-rolled BPHFMS products is way lower than the prime cost of cold-rolled products. The necessary properties of hot-rolled products can be achieved using various approaches that consider the objective formative regularities of the properties and structure of bi-phase steels, as well as the capabilities of available metallurgical equipment [2, 3]. In the course of developing this field, NUST MISiS elaborated an efficient technology of producing hot-rolled BPHFMS strip bar with mechanical properties compliant with the current global standards. This technology involves the development of a steel alloying concept and determining balanced process parameters of hot rolling in the broad-strip mill line (final rolling temperature, cooling rate, coiling temperature, etc.).

The hot-rolled BPHFMS production technology was elaborated and tested by creating and utilizing mathematical models that considered the performance of strip cooling systems and the thermal phase transformations in the steel during strip rolling and cooling. The mathematical model was elaborated using obtained statistical and test data while studying the influence of the strain-and-speed, thermal, and temporal parameters of rolling and post-strain cooling on the strip bar's structure and rheological properties.

The specified task was solved using a set of modern test techniques, including plastometry, dilatometry, and optical microscopy. The tests were conducted on unique equipment, designed for physically modeling hot strain and post-strain cooling, as well as using procedures applied in the test study of the plastic characteristics of BPHFMS exposed to hot strain. During the

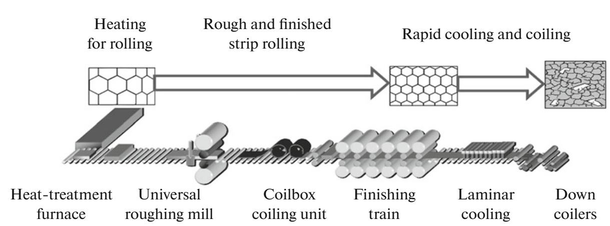

Fig. 1. Process-flow diagram of hot-rolled bi-phase steel production on BSHRM.

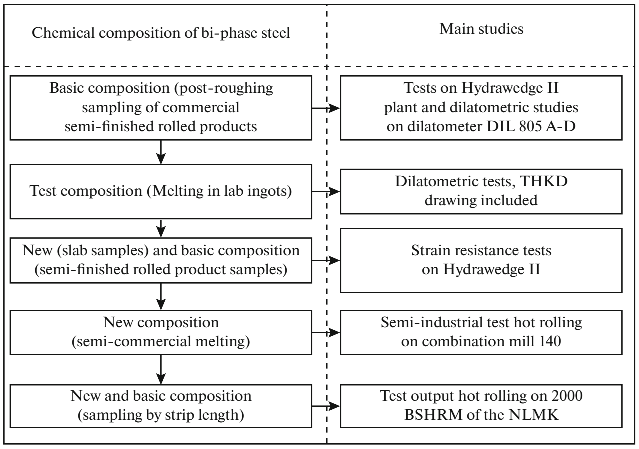

Fig. 2. Flowchart of main kinds of tests conducted to develop the hot-rolling of BPHFMS with a new chemical composition.

staged cooling on the BSHRM runoff table, the conditions for the structure formation compliant with the required physical mechanical properties of the hot-rolled stock of the considered gage were determined using thermal kinetic diagrams (TKDs).

The two areas in which the tests were conducted were: the elaboration of a new efficiently alloyed chemical composition of BPHFMS; and the research, development, and enhancement of the process parameters of the hot rolling and rapid cooling on the runoff table of the 2000 BSHRM of PJSC NLMK (Fig. 2). Special-purpose procedures were used to study the structure formation and mechanical properties; the thermal mechanical processes at hot strain were modeled on the Hydrawedge II plant of a Gleeble 3800 simulator and a DIL 805 A/D quenching dilatometer. The analysis of the dilatometric test results was used to propose an efficiently alloyed chemical composition with an elevated aluminum content. The analytical dependences derived for this composition allow for the calculation of the initial and final temperature of polymorphous transformation.

According to the physically modeling results, the staged cooling on the 2000 BSHRM runoff table using Hydrawedge II, the variation in the final rolling temperature, actually determines the change in the post-strain air rest, and can additionally affect the amount of formed ferrite. Plastometric tests were used to derive regression relationships for calculating the metal's strain resistance according to V. I. Zyuzin's method as applied to the basic (1) and new (2) chemical composition of BPHFMS. The results of physically modeling fractionary strain in the last runs of the BSHRM finishing train were used to correct the dependence considering the accumulation of strain (3) in the derived analytical equations. In addition, a more efficient (by 20 to 25%) ferrite grain crumbling in bi-phase steel with an increased aluminum content was discovered during the metallographic analysis, which is recorded as

$$\sigma_s^{\mathrm{BC}} = 2539.69U^{0.0855}\varepsilon^{0.405}\exp(-0.8664\varepsilon - 0.0023t);$$
$$F_R(4.3595) = 11122.72; \quad R^2 = 0.925, \tag{1}$$

$$\sigma_s^{\mathrm{NC}} = 2926.02U^{0.0864}\varepsilon^{0.438}\exp(-0.9463\varepsilon - 0.0023t);$$
$$F_R(4.1207) = 3610.92; \quad R^2 = 0.923, \tag{2}$$

where U, ε, and t are the strain rate, degree, and temperature, respectively;

$$\varepsilon_i^* = \varepsilon_i + \varepsilon_{i-1}^*(1 - X_{\mathrm{stat}})\varphi, \tag{3}$$

where ε_i^* is the strain accumulated at the entry to stand i; φ is the corrective coefficient equal to 0.55 and 0.65 for the basic and the new BPHFMS, respectively; X_{stat} is the share of recrystallized austenite volume at static recrystallization.

The derived analytical dependences were used in elaborating the thermal state's mathematical model by metal thickness; the model can screen the transfer bar on the intermediate mill table, heat release due to the rolled metal's plastic strain in the finishing train, and polymorphous transformation at post-strain laminar cooling. The model can estimate the temperature of rolled products on the intermediate mill table, in the finishing train, and in the BSHRM runoff table. The mathematical model is adapted to the environment of the 2000 BSHRM of PJSC NLMK. The error in measuring final rolling temperature t_{fn} and coiling temperature t_{clg}, when using the model to describe the thermal state of BPHFMS, is discovered to not exceed 5% at 25°C (Fig. 3), which proves this model coherent.

The test-output rolling of the BPHFMS with the new composition was preceded by a test on semi-continuous mill 140 of the Institute of Metal Forming at Bergakademie Freinburg. The test was conducted to particularly define the elaborated staged cooling modes under the 2000 BSHRM conditions close to reality. The furnace space temperature and ingot temperature were measured with the help of pyrometers right at the entry to the rolls, as well as in the subsequent controlled cooling down to the coiling temperature; furthermore, the test involved computer-aided data recording.

The industrial test on the 2000 BSHRM for trying out the technology that produces hot-rolled BPHFMS with the new alloying composition was conducted at the PJSC NLMK. The test output rolling was prepared using the results of the test studies of the structure formation and mechanical properties of TKD and calculations in the thermal state's mathematical model. The results were used to develop the technology of producing BPHFMS with the new alloying composition. The technology includes an algorithm of entering such control parameters of the rapid cooling unit in operation as: the quantity and numbers of its actuated and disabled

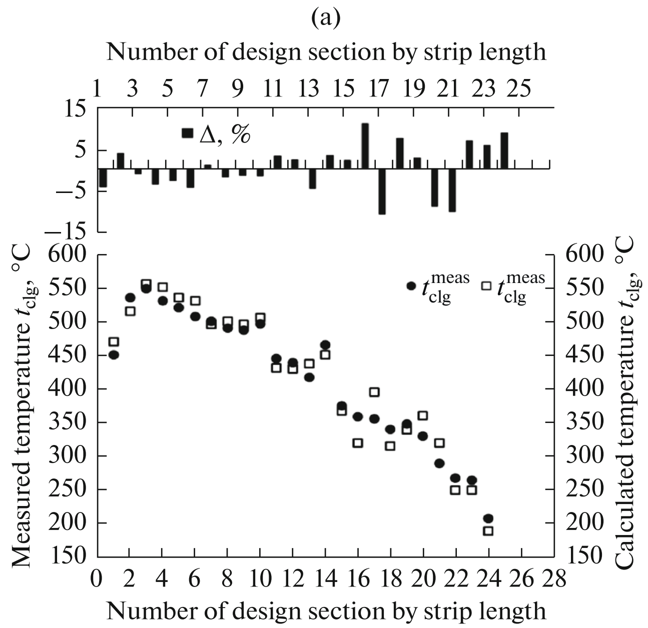

Fig. 3. Results (a and b) of testing the mathematical model of the thermal state of BPHFMS for the 2000 mill at PJSC NLMK.

sections on the runoff table of the 2000 BSHRM. This equipment can create the required set of mechanical properties in the BPHFMS for the DP600 automotive flat stock compliant with EN 10338.

Thus, the enhancements in the hot-rolled strip bar production technology that were elaborated at the NUST MISiS involved the metal physical basics of the technology that produced high-strength automotive flat stock from BPHFMS adapted to the production environment of PJSC NLMK. This also involved the rational thermal and intensity parameters of the stock's staged cooling of the considered gage on the runoff table. On the runoff table of the 2000 BSHRM of PJSC NLMK, the mathematical model of the metal's thermal state was used to determine the strain, the rolling's thermal and speed parameters, as well as the sequence and quantity of inclusions of laminar-cooling half-sections. The hot test and output rolling of automotive steel on the specified mill in the elaborated thermal and strain modes confirms the required structure formation and mechanical properties of the DP600 bi-phase steel.

In addition to automotive flat stock, one popular metal product nowadays is cold- and corrosion-resistant hot-rolled ones for small- and medium-diameter oil pipes. During the transportation of extracted crude hydrocarbons, the pipes used at oil fields are exposed to intensive corrosive attacks, which is determined by the complex corrosion-active composition of the transported oil-water mixture that often contains H_2S and CO_2. The intensive metal corrosion of the metal, i.e., oil-field pipe metal, frequently results in breakdowns and emergencies (Fig. 4). The main characteristics of rolled steel that determine its resistance to corrosion are chemical composition, micro- and macrostructural characteristics, pollution with nonmetallic impurities of different types, as well as surface and inner defects. The expansion of oil mining to the Extreme North makes it necessary to improve the cold endurance of these pipes.

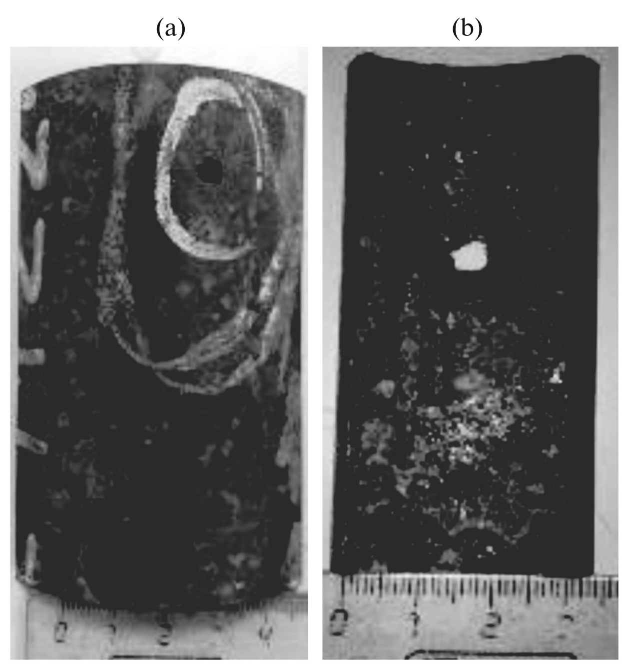

Fig. 4. Corrosive wear of the outer (a) and inner (b) wall of a commercial pipe of 73 mm in diameter, used at oilfield (city of Tomsk).

Thus, one of the topical issues for Russia's fuel-and-energy industry is to extend the life span of oil pipes, as well as to improve their resistance to corrosion in the oil-field production environment. The cold and corrosion endurance of oil-field pipes is determined mainly by the initial quality of the low-alloyed low-carbon strip bar used in manufacturing. As a consequence, one of the major trends followed at NUST MISiS in the field of flat stock production technology research is the elaboration of techniques for manufacturing rolled tubular strip products for the sector's leading enterprises. The integrated project, implemented together with PJSC Severstal as part of developing this trend, is aimed at elaborating the metallurgical technology to manufacture highly cold- and corrosion-resistant K52 to K56 strength grade coiled stock on the 2000 BSHRM.

The measures contemplated by modern metal science for producing longitudinally welded pipes include: minimally alloyed low-carbon rolled stock for attaining good weldability, high strength levels, and enhanced resistance to cold and corrosion. The performance of rolled tubular products largely depend on the alloying composition that determines the kind of structuring in rolled products during strain and cooling. The measure necessary for improving a strip's strength, while keeping the content of carbon at ≤0.08%, is the dispersion hardening at the release of dispersed carbonitride particles (Nb, V) · (C, N) after coiling the strip [4, 5]. It is also possible to form the rolled stock's ferrite bainite microstructure by adding elements that improve austenite's resistance at cooling (Mo, Ni, Cr, Cu, and Nb in case of its presence in solid solution) [4]. A major characteristic of corrosion wear is hydrogen cracking (HGCR). The increased HGCR resistance of tubular steel stems from using low amounts of carbon and manganese to prevent the formation of elongated trap impurities (MnS, Fe_3S, phosphorus emissions), and also from forming an even fine-grained microstructure with weak stresses and subtle texture.

The concept approved for producing the coiled stock of the considered gage consists in alloying low-carbon, low-alloyed steels based on the Cu–Cr–Ni composition, as well as facilitates high corrosion resistance while maintaining the required level of strength characteristics and low-temperature impact strength (cold endurance). The pipe surface's chromium protective layer prevents the corrosion propagation. A reduced carbon content decreases the axial segregation of a continuous cast ingot and allows chromium to remain in the solid solution. The microscale alloying by Nb and V reduces the grain size and improves cold endurance, as well as enhances strength properties. The action of these elements (Ti, Nb, V) consists in the formation of excess phase precipitations, such as carbides, nitrides, and carbide nitrides that hold the grain boundary migration and can also lead to strengthening by dispersion hardening. The existence of some alloying elements in the solid solution of low-carbon steels provides durability by solid-solution strengthening. In this case, the alloying composition ensures a comparatively low-carbon equivalent of $C_{eq} \leq 0.36$ that favors the obtainment of HQ pipe welds [6].

The metal corrosion resistance is negatively affected by harmful contaminant pollution (S, P, etc.) and nonmetallic impurities. Certain nonmetallic impurity types form when liquid steel is processed in the bucket. Thus, highly corrosive nonmetallic impurities (HCNMIs) often lead to emergency breakdowns of oil-field pipelines. The corrosion pattern in the HCNMI zone can be related to the different coefficients of thermal expansion in the impurity and the metal matrix or to the growing impurity volume (hydration) in contact with a water electrolyte and with the impurity dissolution itself, pitting formation included [7]. The corrosion damage intensity to modern tubular steels affected most heavily by HCNMIs based on magnesium aluminates (aluminum-magnesium spinel) with a sulphide component (from magnanous and calcic sulphide) [6] is known. They also have the oxide component that generates high stresses around the impurity, as well as the sulphide component that makes the impurity chemically active. Their nascence is determined by the bucket's ladle lining, where the steel is exposed to ladle treatment in the steel-melting production area. Therefore, one of the conditions for producing the Severkor highly corrosion-resistant coiled stock is to minimize the content of aluminum-magnesium spinel HCNMIs. Within this framework, a ladle treatment technology has been elaborated that minimizes the content of these HCNMIs.

The necessary structure and the required level of mechanical performance and cold endurance for the chosen alloying compositions of tubular steels are attained using rational thermal speed and straining modes for rolling and cooling coiled stock. The ferrite grain refinement on broad-strip mills is carried out by exposing the strip to the combination of CR and RCL. In most cases, the grain refinement to the minimal possible size in the course of producing the rolled ferrite-perlite and ferrite-bainite products of the indicated strength grades is attained during hot rolling, followed by cooling and coiling.

To determine the rational modes of rolling and cooling continuously cast ingots with the chosen alloying composition on the 2000 BSHRM of PJSC Severstal, a TKD was drawn that modeled the strip bar cooling and predicted the produced structure type, depending on the cooling rate. The TKD analysis in based on the metal physical ideas about structural formation and phase transitions during the poststrain cooling of a rolled coil strip [9].

The TKD for the Severkor K52 mill bar was drawn according to the data from the dilatometric tests of its specimens on the DIL 805 A/D TA Instruments quenching-and-straining dilatometer. This was designed for registering phase and structural transitions of the high-precision assessment of changes in the specimen size when controlling its temperature for different cooling rates. The phase transitions that emerge with continuous cooling or in the isothermal waiting phase (that can also be multistaged) are determined from the specimen's linear strain at its certain temperatures. The instrumental indications and analysis of the produced structure results are used to determine the austenite transition's evolution type and behavior. The beginning and end of structural transitions are separated by fields of, i.e., ferrite, carbide, perlite, bainite, martensite, or other eutectoid phase mixtures [10].

As shown by analyzing the resulting TKD, a low cooling rate of about 1 to 2°C/s can form a ferrite perlite structure with ferrite as the main component. However, at a cooling rate over 5°C/s, ferrite bainite transition begins in which the resulting specimens have a ferrite bainite structure with polygonal, nonpolygonal, and acicular ferrite. Nonpolygonal ferrite can be found at or around the boundaries of former austenite grains. Also, it is important to note that all of the indicated structures contain sorbitic perlite in the interfaces of structural phase fragments. With the further increase in cooling rate, the share of ferrite and bainite goes down and rises, respectively [10]. At a cooling rate of 3 to 4°C/s, unstable structuring is possible [9]. It is expedient to achieve cooling rates above 5 or below 2°C/s to produce ferrite bainite and ferrite perlite structure, respectively. Thus, it is confirmed that the suggested alloying composition can be used to produce the ferrite bainite structure that ensures the compliance with K52 strength grade and with the production requirements on corrosion resistance and cold endurance [10].

The drawn TKD was used to determine thermal and speed modes of rolling and cooling for the production of the 8 mm Severkor K52 coiled stock on the 2000 BSHRM of PJSC Severstal. The mechanical characteristics of the pilot rolled stock batch comply with K52 strength grade, having enhanced corrosion resistance and cold endurance: σ_u = 600 to 610 N/mm^2; $\sigma_{0.2}$ = 530 to 540 N/mm^2; σ_t/σ_u = 0.88–0.89; δ = 25 to 26%, KCV_{-50} = 175 to 245 J/cm^2; grain score is 10; the ductile component content (DCCN) is 80 to 100%. According to NACE TM 0284, the HGCR level of the produced mill product in the type A test medium does not exceed SCR = 0.1. The overall corrosion rate in the H_2S-containing medium measured by the technique of ZAO NIPTS NefteGasService is 0.2 mm/g. The resulting HGCR and overall rate of corrosion in the H_2S-containing medium are pretty low, which confirms the importance of utilizing the mill products of this gage in manufacturing oil-field pipes for Russia's FEI [10].

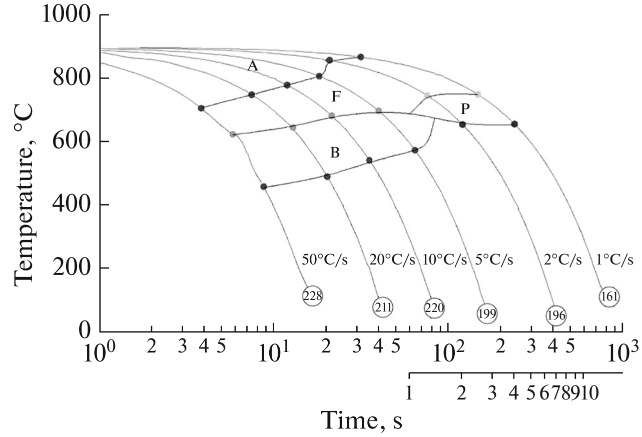

Fig. 5. TKD of K52 Severkor coiled stock.

Thus, NUST MISiS and PJSC Severstal have jointly elaborated the technological basics of producing cold- and corrosion-resistant mill products for longitudinally welded oil-field pipes. The theory regarding alloying composition for producing the mill products of the gage in question has been suggested and implemented. The TKD drawn for this composition has been used to determine the structuring type during the straining and cooling of the mill products. Also, the modes of rolling and cooling on the 2000 BSHRM have been suggested. The integrated study of the main performance parameters of the produced specimens of the Severkor K52 strip bar, including corrosion resistance, cold endurance, strength and structural phase properties, has been conducted. The study results confirm the possibility of producing K52–K56 mill products for highly corrosion- and cold-resistant oil-field pipelines.

The NUST MISiS detailed the modifications of the hot-rolled stock production technology: In order to create high-strength automotive flat stock from BPHFMS adapting to the production environment of the 2000 BSHRM of PJSC NLMK, the metal physical basics of the technology was produced. As a result, the rational modes of rolling and cooling automotive plate steel strips ensure the required structure formation and mechanical properties of DP600 strength grade biphase steel.

A theory of the alloying composition and the technology of manufacturing cold- and corrosion-resistant tubular mill products for oil-field pipelines has been suggested and implemented on the 2000 BSHRM of PJSC NLMK. The integrated study of the main performance parameters of the industrial specimens confirms their compliance with the product requirements of the gage in question and products with K52 strength grade.

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