Providing steel with an approximate application of the mechanical properties of wire rod 5.5-6.5 mm from steel grades 70-75 based on a conventional twin of the Stelmor process

A. B. Moller, Dr. Eng., Prof., Head of the Dept. of Materials Processing Technologies[1], e-mail: amoller@mail.ru;
O. N. Tulupov, Dr. Eng., Prof., Dept. of Materials Processing Technologies, Vice-Rector for Research and Innovation[1];
S. A. Levandovskiy, Cand. Eng., Associate Prof., Dept. of Materials Processing Technologies[1],
e-mail: levandovskiy@mail.ru;
D. A. Nazarov, Postgraduate Student, Dept. of Materials Processing Technologies[1]

[1]Nosov Magnitogorsk State Technical University (Magnitogorsk, Russia)

In 2019, the air-cooling line of Mill 170 of PJSC MMK (Magnitogorsk Iron and Steel Works) was upgraded. The main task of modernization was to obtain wire rod sorbitized in the initial state. The use of such products makes it possible to abandon one intermediate heat treatment operation in the wire production process, and should also ensure the stability of the mechanical properties of the finished wire of the entire size range of OJSC MMK-METIZ. On the part of OJSC MMK-METIZ, the following high requirements were imposed on the uniformity of the mechanical properties of the wire rod obtained at the mill - no more than 40 N/mm^2 along the length of the convolution, 50 N/mm^2 along the length of the coil, 60 N/mm^2 within the melt. When analyzing samples of rolled products from steel grades 70-75 with a diameter of 5.5-6.5 mm, it was found that compliance with the requirements in the modes operating at the mill is difficult.
By the order of PJSC MMK, as part of scientific research on the development of wire rod production technology using a digital twin of an air cooling line, a mathematical model was developed, the adequacy of which was proved by developing rolling modes based on it, followed by evaluation of the resulting product. Upon further analysis of the obtained rolled products, it was found that the products manufactured according to the new modes meet the requirements for uneven mechanical properties along the length of the convolution and the coil to a greater extent.
Keywords: long products, wire rod, sorbitization, digital twin, BIM modeling, pearlite, air cooling.
DOI: 10.17580/cisisr.2022.01.06

Introduction

The structure of sorbitized pearlite in the conditions of OJSC MMK-METIZ is achieved by patenting hot-rolled products with a diameter of 5.5-16.0 mm from high-carbon steel grades. This structure is necessary to ensure continuous drawing of a hot-rolled steel with a high degree of deformation, and to obtain a ready-made wire for a responsible purpose (reinforcement, spring, rope, etc.) in accordance with the requirements of normative documents.

The use of sorbitized wire rod in the initial state will allow to abandon one intermediate heat treatment operation in the wire production process, and will also ensure the stability of the mechanical properties of the finished wire.

Sorbitized wire rod is characterized by high strength plastic properties, which is especially important in the production of wire without an intermediate patenting operation [1, 2].

At the moment, the supply of the highest quality metal products to MMK-METIZ OJSC is carried out according to TU 14-101-582-2009, however, the 1-2 points of lamellar perlite laid down in the requirements of this TU is insufficient to ensure stable and reliable performance characteristics of the finished wire and products made from it, and also does not allow to exclude intermediate drawing and patenting operations from the wire manufacturing process. It is required to provide a new level of dispersion of the pearlite microstructure, uniformity of mechanical properties (no more than 40 N/mm^2 along the width of the coil, 50 N/mm^2 along the length of the convolution, 60 N/mm^2 for melt) and microstructure along the length of the coil to reduce the cost of end-to-end technology [3].

Digital models created using BIM technology should be considered in the future as the basis for a virtual interactive copy of a real physical object or process, which helps to effectively manage it, simulate the location of equipment, the movement of employees, work processes and emergency situations. [4-6].

The purpose of the work

To develop the operating modes of the air cooling line, ensuring the uniformity of the mechanical properties of wire rod 5.5-6.5 mm from steel grades 70-75 based on the use of a digital twin of the Stelmor process.

The model for calculating the temperature of a wire rod on an air cooling line

To assess the possibility of obtaining the required sorbitized structure of wire rod on the mill 170 PJSC MMK was existing experience in determining air cooling lines [7, 8]

$$Q_H = C_s \varepsilon (t_k/100)^4 F, \quad (1)$$

где $C_s = 5.77$ W/(m^{2}K^4) – the emission coefficient of a completely black body;

ε – the degree of blackness of the wire rod (it is assumed that $\varepsilon \approx 0{,}8$);

t_k – wire rod temperature, K;

F – the surface area of the wire rod in a given zone of the air cooling line, m^2.

Thus, formula (1) allows us to determine the heat flux transmitted due to emanation from the wire rod into the surrounding space. In this case, the value of the heat flow will depend on which part of the coil of the wire rod is in a given zone of the air cooling line and on the temperature of the wire rod in a given zone. In total, two zones were considered along the width of the air cooling line: a zone with a dense laying of wire rods "pigtails", and a middle zone with a more discharged laying of convolutions (center). If desired, the number of calculated zones can be increased depending on the design of the blast collectors [9].

The equation for calculating heat transfer convection by convection between the wire rod and the injected air has the form:

$$Q_C = \alpha \Delta t F \qquad (2)$$

Where α – coefficient of heat transfer by convection, W/m^{2}K;

Δt – temperature difference of wire rod and air, degrees;

F – the surface area of the wire rod in a given zone of the air cooling line, m^2.

The coefficient of heat transfer by convection will be determined by the formula for the case of air flow around a bundle of rods:

$$\alpha = 0{,}177 K_Z \left(\frac{\lambda}{d}\right) \mathrm{Re}^{0.64}, \qquad (3)$$

где d – wire rod diameter, m;

K_Z – coefficient that takes into account the density of laying coils of wire rod in different zones;

λ – coefficient of thermal conductivity, W/m^{2}K;

Re – Reynolds number.

To determine the thermal conductivity coefficient depending on the temperature of the wire rod, the previously found regression equation for the considered steel grades was used [8]:

$$\lambda = 48.5 - 0.0225 t_k \qquad (4)$$

где t_k – wire rod temperature, °C.

The Reynolds number was determined by the formula:

$$\mathrm{Re} = \frac{\omega d}{\nu}, \qquad (5)$$

где ω – the speed of the injected air, m/s;

ν – kinematic viscosity of air, $15 \cdot 10^{-6}$ m^2/s at 20 °C.

Thus, we can determine the heat flow from the wire rod into the surrounding space due to the main heat losses from radiation and convection [10]. At the same time, we can determine the heat flow from the wire rod when its temperature drops by a given amount over a certain time, depending on the heat capacity of the wire rod:

$$Q_{HC} = C M_k \frac{t_k^i - t_k^{i-1}}{\tau^i}, \qquad (6)$$

где C – specific heat capacity of wire rod depending on its temperature, J/(kg·°C);

M_k – the weight of the wire rod in a given zone air cooling line, kg;

i – air cooling line section number by length;

t_k^i – the temperature of the wire rod at the end of the ith section of the specified zone, °C;

t_k^{i-1} – the temperature of the wire rod at the end of the ith section of the specified zone, °C;

τ^i – the time spent by the wire rod on the ith section, c.

Therefore, the average value of the heat flow within one section, we obtain a recurrent equation with one unknown, namely the current temperature of the wire rod:

$$Q_C = Q_P Q_K. \qquad (7)$$

By sequentially solving this equation for each section and in each zone of the air cooling line, we can find the temperature distribution of the wire rod along the length and width of the conveyor.

In this case, the parameters controlling the value of the wire rod temperature at a given point will be:

– the initial temperature of the wire rod on the coil;

– conveyor speed of the air cooling line section;

– fan speed in the section inconsideration of the fan, as a percentage of the maximum;

– position of the dampers that redistribute the airflow from the fan along the zones of the air cooling line, which affects the air velocity in a given zone [11-13].

On the basis of these equations and the results of measurements of the injected air velocities in various zones and sections of the air cooling line at the mill 170 of PJSC «MMK», software was developed to simulate the process of air cooling of rolled stock on small-section wire mills [14]. With the help of this software, experimental modes for the production of wire rod with the required sorbitized structure were developed and tested at the mill.

Evaluation of mechanical properties

Samples were cut from the selected wire rod rings according to the approved methodology - 4 samples 500 mm long were cut from the rings taken from the front, back and middle of the coil according to the scheme (**Fig. 1**).

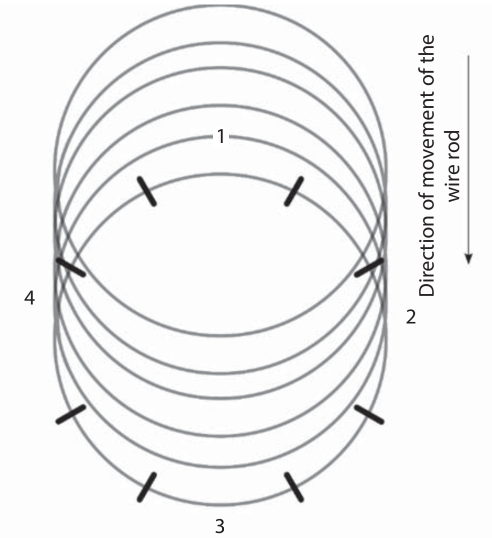

Fig. 1. Scheme of sample cutting

Fig. 2. Shimadzu AG-300KN-1 Universal Tensile Testing Machine

Fig. 3. Sample before testing and after rupture

Samples were made from cut samples for mechanical testing in accordance with the requirements of TU 14-101-582-2020 and microstructure evaluation according to TU 14-101-582-2020 and GOST 8233-56.

Preparation of samples for mechanical testing

During the tests, the following mechanical characteristics of the wire rod were evaluated and compared with the requirements of TU 14-101-582-2020:

- tensile strength;
- relative reduction of the area;
- relative elongation.

In TU 14-101-582-2020, GOST 1497 is specified as the main document for testing mechanical properties (item 3.16 of TU 14-101-582-2020). GOST 1497-84 was used – the last current version of this document [6]. As a characteristic of elongation, δ10 is indicated – tests should be carried out on long samples according to GOST 1497-84 [15].

Working length samples were made from full length samples using bolt cutters.

The marking of the working and initial calculated length of the samples was carried out using a metal ruler (GOST 427-75). Notches were made on the samples with a carbide scribbler and a marker of a contrasting color with the sample.

Table 1. **The results of mechanical tests of wire rod**

Place	Angle	Tensile strength $\sigma_в$, N/mm^2	Relative reduction of the area, ψ, %	Relative elongation, δ10, %
Standart				
Back	0	1069	43	11.9
	90	1063	45	8.7
	180	1111	46	13.5
	270	1007	42	10
Center	0	1033	47	13.5
	90	1022	-	8.5
	180	1059	49	13.1
	270	1085	50	10.4
Front	0	1130	44	11.6
	90	1035	-	8.6
	180	1077	47	8.5
	270	1085	44	12.5
Experiment				
Back	0	1054	44	13.6
	90	1069	44	15.1
	180	1048	42	13.5
	270	1076	50	8.3
Center	0	1073	46	13.1
	90	1122	47	11.9
	180	1110	48	12.2
	270	1126	49	13.5
Front	0	1056	43	17.2
	90	1142	45	12.9
	180	1058	45	12.5
	270	1085	43	10.8

Results and discussion

Research conducted at the Department of Materials Processing Technologies of the Nosov Magnitogorsk State Technical University, aimed at building digital models of rolling mills, and studying various physical processes on their basis, made it possible to reasonably formulate the main directions for improving modern lines for accelerated air cooling of wire rod in order to provide a microstructure containing up to 85 % pearlite of 1-2 points. The similarity of the digital model to the real process was achieved by conducting physical experiments and a number of experimental rolling at the operating rolling mill.

The tests were carried out on the Shimadzu AG-300KN-1 machine (accuracy class 1 %) at Nanosteels Research Institute of the Nosov Magnitogorsk State Technical University.

The characteristics of: tensile strength, relative reduction of the area and relative elongation were determined. The relative elongation of the calculated length of the sample was measured using a video extensometer of the Shimadzu AG-300KN-1 machine (**Fig. 2**) and using manual measurement (caliper). The relative reduction of the area was measured using a caliper by folding the sample after destruction with measurement of the bottleneck. The tensile strength value was measured using the software of the Shimadzu AG-300KN-1 universal testing machine [9].

Tests were carried out on a comparative assessment of the mechanical properties of a 5.5 mm steel rod of grade 70 (**Fig. 3**).

In the case of destruction of the sample outside the area of the calculated length, the indicators of tensile strength and relative reduction of the area are taken into account if they can be reliably determined, and the relative elongation is not accepted for analysis. By agreement with the representatives of the customer, for such samples for analysis, the indicators of tensile strength and relative reduction of the area are taken into account, if it is possible to reliably determine them. Results not accepted for analysis in the table and figures are highlighted in color.

The measurement results are presented in the **tables 1-3**.

Table 2. **Evaluation of the tensile strength of wire rod samples along the length of the coil**

Parameters		Location 0	90	180	270
Standard (current mode)	Back	1069	1063	1111	1007
	Center	1033	1022	1059	1085
	Front	1130	1035	1077	1085
Estimation of uniformity along the length of the coil at 1 point	Min	1033	1022	1059	1007
	Max	1130	1063	1111	1085
	Mean	1077	1040	1082	1059
	Range	97	41	52	78
Experiment	Back	1047	1047	1069	1050
	Center	1036	1097	1035	1038
	Front	1021	1107	1059	1067
Estimation of uniformity along the length of the coil at 1 point	Min	1021	1047	1035	1038
	Max	1047	1107	1069	1067
	Mean	1035	1084	1054	1052
	Range	26	60	34	29

Table 3. **Evaluation of the tensile strength of wire rod samples along the length of the convolution and within the batch**

Parameters		Evaluation of uniformity along the length of the convolution / throughout the billet: Min	Max	Mean	Range
Standard (current mode)	Back	1007	1111	1063	104
	Center	1022	1085	1050	63
	Front	1035	1130	1082	95
Estimation of uniformity along the length of the convolution at 1 point	Min	1007			
	Max		1130		
	Mean			1065	
	Range				123
Experiment	Back	1047	1069	1053	23
	Center	1035	1097	1052	62
	Front	1021	1107	1063	87
Estimation of uniformity along the length of the convolution at 1 point	Min	1021			
	Max		1107		
	Mean			1056	
	Range				87

Conclusions

Based on the data obtained, it can be concluded that:

• mechanical properties are within the requirements of TU 14-101-582-2020;

• uniformity of the value of tensile strength is not observed either for the standard or for the experimental conditions.

For standard mode:

• along the length of the convolution ≤ 104 N/mm^2 (norm ≤ 40 N/mm^2)

• along the length of the coil ≤ 97 N/mm^2 (norm ≤ 50 N/mm^2),

• within the melt ≤ 104 N/mm^2 (norm ≤ 60 N/mm^2).

For experimental mode :

• along the length of the convolution ≤ 60 N/mm^2 (norm ≤ 40 `N/mm^2)

• along the length of the coil ≤ 87 N/mm^2 (norm ≤ 50 N/mm^2),

• within the melt ≤ 87 N/mm^2 (norm ≤ 60 N/mm^2).

When analyzing the data, it is clear that for the experimental mode, it was possible to achieve uniformity of the tensile strength value along the length of convolutions for the following cases:

- 0° – a spread of 26 N/mm^2 (the norm of TK ≤ 50 N/mm^2);
- 180° – a spread of 34 N/mm^2 (the norm of TK ≤ 50 N/mm^2);
- 270° – a spread of 29 N/mm^2 (the norm of TK ≤ 50 N/mm^2).

It was also possible to achieve the required uniformity of the tensile strength value along the length of convolutions selected from the rear end of the experimental sample – the value 23 N/mm^2 at a norm of ≤ 40 N/mm^2.

Based on the fact that the indicators for the minimum run-up (standard deviation) of the tensile strength of the wire are priority on a rope wire made from sorbitized wire rod, then, according to the totality of the data obtained, an experimental batch of wire rod, which was fabricated using the technology proposed by the Nosov Magnitogorsk State Technical University, has the most favorable indicators for manufacturing rope wire without applying the patenting operation.

The work aimed on improving the modes to obtain the required uniformity in melting is continued.

REFERENCES

1. Sychkov A. B., Parusov E. V., Zavalishin A. N., Kozlov A.V. Inherent effect of the crystal structure of continuous cast steel billets on the formation of structure of high carbon wire rod in coils. *Journal of Chemical Technology and Metallurgy*. 2018. Vol. 53. No. 5. pp. 977-985.
2. Wollschlaeger M, Sauter T., Jasperneite J. The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0. *Institute of Electrical and Electronics Engineers Industrial Electronics Magazine*. 2017. No. 11. pp. 17–27.
3. Lu Y., Xu X. Resource virtualization: A core technology for developing cyber-physical production systems. *Journal of Manufacturing Systems*. 2018. Vol. 47. pp. 128–140.
4. Levchenko G. V., Borisenko A. Yu., Mospan V. V. et al. Production of wire rod for various purposes from sectional and bloom continuously cast billets. *Stal*. 2018. No. 8. pp. 48-53.
5. Nefedov D. V., Telegin V. E., Miyanov A. G. et al. Aspects of quality and technology for the production of patented high-strength packaging tape. *Stal*, 2019. No. 6. pp. 30-33.
6. Gorbanev A. A., Filippov V. V., Zhuchkov S. M. et al. Increasing the uniformity of cooling of coils of wire rod on a roller conveyor of a modern wire mill. *Metallurgicheskaya i gornorudnaya promyshlennost*. 2002. No. 3. pp. 44-47.
7. Evteev E. A., Klekovkin A. A., Podol'skii B. G. Reconstruction of section for air cooling of wire rod in the 150 mill. *Steel in Translation*. 2010. Vol. 3 (40). pp. 273-276.
8. Sarancha S. Yu., Levandovsky S. A., Moller A. B., Kinzin D. I., Podolsky B. G. Improving the efficiency of section rolling production: modeling the process of cooling wire rod. *Modelirovanie i razvitie protsessov OMD*. 2016. No. 22. pp. 50-56.
9. Talapov V. V. BIM technology. The essence and features of the implementation of building information modeling. DMK Press. 2015. 410 p.
10. Dantzig J. A., Pappaz M. Solidification. Lausanne : Efpl. Press, 2009. 621 p.
11. Moller A. B., Shcherbak A. V., Levandovsky S. A., Sarancha S. Yu. Modeling of the process of air cooling of rolled stock on small-section wire mills. Certificate of registration of the computer program 2021681688, 12/24/2021. Application No. 2021680953 dated 12/20/2021.
12. Tulupov O. N., Moller A. B., Kinzin D. I., Levandovskiy S. A., Ruchinskaya N. A., Nalivaiko A. V., Rychkov S. S., Ishmetyev E. N.. Structural-matrix models for long product rolling processes: modeling production traceability and forming consumer properties of products. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta*. 2013. Vol. 5 (45). pp. 46-50.
13. Parusov E. V., Parusov V. V., Sychkov A. B. Theoretical and technological foundations for the production of highly efficient types of wire rod. Dnepropetrovsk : Art-Press. 2012. 376 p.
14. Rumyantsev M. I., Tulupov O. N. Further developments in simulation of metal forming processes. *CIS Iron and Steel Review*. 2018. Vol. 16. pp. 21-24.
15. GOST 1497-84. Metals tensile test methods. Date of introduction: 01.01.1986.