Open Joint Stock Company
Scientific-Research Institute of Metallurgical Heat Engineering
OJSC VNIIMT

16 Studencheskaya St., Yekaterinburg, Russia, 620137 Tel: +7 (343) 374-03-80, fax: +7 (343) 374-29-23
E-mail: aup@vniimt.ru, website: www.vniimt.ru

A/c 40702810902400230701 in Yekaterinburg affiliate of NOMOS-BANK (JSC) Yekaterinburg
Correspondent account No.30101810800000000918, BIK 046577918, INN 6660011779, KPP 667001001, OKVED 73.10 OKPO 00190259

OJSC Scientific-Research Institute of Metallurgical Heat Engineering (VNIIMT) established in 1930 as Ural Division of All-Union Heat Engineering Institute is widely known in Russia and the CIS. The Institute focuses on development of high-technology heat engineering units, energy efficient and ecologically friendly technologies in ferrous and non-ferrous metallurgy, machine-building and other fuel-consuming branches of industry.

Highly-qualified academic researchers, unique experimental and production facilities and own research and design centre enable efficient scientific-and-research, design-and-experimental, engineering and project works, delivery of equipment, designer's supervision and commissioning works including execution of turnkey contracts in the following areas:

Sintering:

- development of techniques and modes of metal raw material heat treatment;
- design of energy-efficient agglomeration hearths and agglomeration gas heat recovery circuits allowing to reduce energy consumption and dust and gas emissions.

Pellet production:

- optimal traveling grate pelletizing furnaces for heat treatment of iron-ore pellets from various concentrates (hematite, magnetite, etc.) with optimal automatic process control system.

Preparation of metallic and nonmetallic raw materials:

- technique of iron-ore raw material dephosphorization by roasting and leaching;
- installations for drying high-moisture dispersive materials of various designs;
- efficient techniques of magnetizing roasting and subsequent dressing;
- technique of rare-earth element extraction (for example, germanium from germanium iron ores).

Blast-furnace ironmaking:

- explosion-proof near-furnace systems of blast furnace slag granulation giving a high-quality product for cement production;
- optimal control system for hot blast stoves;
- an innovative bench for drying hot metal and steel-smelting ladles;
- copper coolers and tuyeres of blast furnaces.

DRI (direct reduction of iron)

- improvement of the reduction technique in shaft furnaces for radical improvement of technical and economic indicators of their operation (productivity is increased twice);
- technique of raw material reduction in rotary furnaces using coal as the reductant.

Lime production: development of the technique and increase of lime production process efficiency:

- in shaft furnaces;
- in double-shaft furnaces;
- in rotary furnaces;
- in “stacked-tower preheater - rotary furnace” installations;
- in “shaft calciner - rotary furnace” installations (VNIIMT innovative technology).

Granulation of metal melts:

- development of technologies and designs of explosion-proof plants for near-furnace granulation of metallurgical slag, molten metal, etc., including heat recovery;

Reheating furnaces:

- development of new and update of the existing designs of furnaces for stock heating;
- high-performance systems of reheating furnace firing with recovery and regeneration firing systems based on the innovative burner units designed by VNIIMT;
- switching the furnace firing systems to cheaper fuel types;
- development and implementation of optimal furnace operating parameters.

Heat-treatment furnaces development of techniques and equipment for heat treatment of roll stock and metal products including those with protective atmospheres:

- thermochemical treatment conditions ensuring retention or directional change in chemical composition of metal surface;
- gas dampers for heat-treatment furnaces;
- spray quenching units and other elements of convective cooling systems;

Furnaces with protective atmosphere and gas treatment units:

- development of the furnace structure, design, manufacture, delivery and commissioning works;
- development of a technology for treatment of articles and devices for protective gas generation;
- calculation, development and manufacture of endogas and exogas atmosphere generators for metal product thermochemical treatment units;
- gas analysis systems for monitoring and control of physico-chemical properties of protective process atmospheres.

Reheating, heat-treatment and drying furnaces with convection heat transfer:

- development, design and manufacture using industrial heat-resistant (up to 900 ^{o}C) furnace fans designed by VNIIMT.

Rolled products:

- techniques and units for controlled high-speed air-to-water cooling (quenching) of rolled ferrous and non-ferrous metal products including thick plate on mill 5000;
- replacement of oil quenching technology with VNIIMT's eco-friendly air-to-water technique;
- innovative technique of oily mill scale processing;
- line of wire rod accelerated air cooling with process improvement.

Manufacturing manufacture and delivery of:

- high-performance burner units;
- heat-resistant (furnace) fans (up to 900 ^{o}C);
- copper coolers for blast furnaces and nonferrous furnaces based on VNIIMT technology;
- Pitot tubes for measuring flow rates and pressures.

OJSC VNIIMT developments are widely used in metallurgical enterprises of Russia, Ukraine, Kazakhstan, China, India and others.

For detailed information on institute developments, please visit OJSC VNIIMT site at www.vniimt.ru

Contact details:
CEO: Lik Zajnullin
Scientific Research Institute of Metallurgical Heat Engineering OJSC VNIIMT
Tel: +7 (343) 374-03-80, fax: +7 (343) 374-29-23
16 Studencheskaya St., Yekaterinburg, Russia, 620137,
e-mail: aup@vniimt.ru,
website: www.vniimt.ru

ISSN 0967-0912, Steel in Translation, 2015, Vol. 45, No. 3, pp. 226–230. © Allerton Press, Inc., 2015.
Original Russian Text © Yu.I. Lipunov, K.Yu. Eismondt, E.V. Nekrasova, M.V. Zakharchenko, Yu.G. Yaroshenko, E.V. Abramov, 2015, published in "Stal'," 2015, No. 3, pp. 83–87.

Water-Jet Cooling in the Thermal Strengthening of Asymmetric Profiles

Yu. I. Lipunov[a], K. Yu. Eismondt[b], E. V. Nekrasova[a], M. V. Zakharchenko[b], Yu. G. Yaroshenko[b], and E. V. Abramov[c]

[a]*OAO VNIIMT, Yekaterinburg, Russia*
e-mail: aup@vniimt.ru
[b]*OOO Nizhnesaldinskii Metallurgicheskii Zavod (NSMZ), Nizhnyaya Salda, Russia*
[c]*Yeltsin Ural Federal University, Yekaterinburg, Russia*

Abstract—Thermal strengthening of complex profiles by cooling in water jets is replacing the traditional technology: quenching in oil. This technology has been tested in laboratory conditions and introduced experimentally. It permits the attainment of optimal self-tempering temperature by regulating the cooling time. That permits the creation of metal structures with good mechanical properties and excellent performance.

Keywords: thermal strengthening, accelerated-cooling system, quenching, fishtails, mechanical properties

DOI: 10.3103/S0967091215030122

Differential cooling by water jets is the most recent approach to the thermal strengthening of steel products. Benefits of this technology in comparison with traditional bulk cooling include the following:

—controlled heat liberation from the part and flexible regulation of the thermal strengthening;

—fire safety and low environmental impact because the coolant employed is water;

—no need for periodic replacement and disposal of the spent quench fluid.

The development of water-jet systems for the thermal strengthening of asymmetric profiles with components of different mass is of particular importance. Such systems are of interest, in particular, for specific railroad-track components—fishtails, which are subject to strict requirements on the mechanical properties and linearity. The final operation specified by State Standard GOST 4133–73 in the production of R65 and R50 fishtails is thermal strengthening by quenching in oil. At OAO VNIIMT, a water-jet system has been developed for this purpose.

Analysis of experimental data provides the basis of mathematical simulation of oil cooling of fishtails, which indicates different cooling rates of the head and neck on account of the nonuniform mass distribution. On the basis of heat-transfer data obtained at OAO VNIIMT on laboratory and industrial accelerated-cooling systems, multivariant modeling of the rail cooling by water jets with differential intensity in different sections is possible [1, 2].

Such modeling permits the design of a controlled-cooling system of pass-through type, consisting of two sections separated by an air gap (Fig. 1). In bench tests, heat-transfer data required for adaptation of the mathematical model are obtained, and the operating conditions (water flow rate, rail speed through the cooling zone, etc.) ensuring the required mechanical properties and linearity of the fishtail are determined [2, 3]. The bench-test data are used in developing an industrial system for thermal strengthening (quenching) at OOO Nizhnesaldinskii Metallurgicheskii Zavod (NSMZ). To permit the industrial introduction of this system, the Stavan-Test research center at Ural institute of Metals has developed Technical Specifications TU 14-2R-463–2011 for the production of fishtails using a water-jet system.

In introducing the production of R65 and R50 fishtails at OOO NSMZ, the following equipment is used (Fig. 2): a cold-cutting press *10*; heating furnace *13*; a hot hole-piercing press *15*; a quenching unit *17*; transport equipment; and an autonomous water-supply system for the quenching unit.[1] Hot-rolled strip (length up to 11.5 m) is supplied to intake table *3*. On reaching roller conveyer *5*, the strip is inspected on all sides by means of a tipping system, so as to assess its surface quality and linearity, and is marked. Where necessary, the strip may be sent to stripping table *4* for defect removal. On roller conveyer *8*, the strip passes through drive unit *9* and is sent to the cold-cutting press so as to obtain blanks of the required length (0.54–1.00 m). The blanks are sent to the furnace, where they are heated to 840–880°C and then to the

[1] The general configuration of this production system and the transport equipment were developed by OAO KKO VNIImetmash.

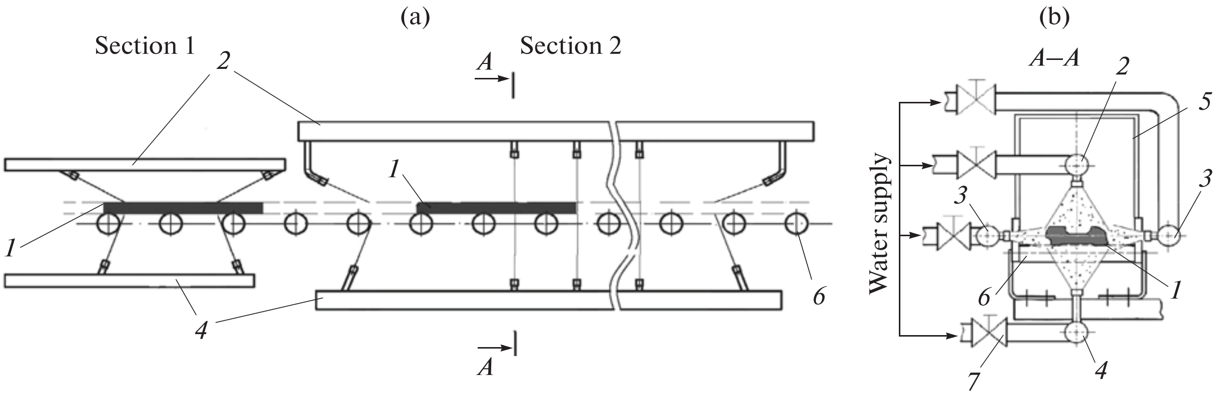

Fig. 1. Side view of controllable cooling system for fishtails (a) and a single cooling loop (b): *1*) fishtail; *2*) upper supply line; *3*) lateral supply line; *4*) lower supply line; *5*) protective housing; *6*) rollers; *7*) valve.

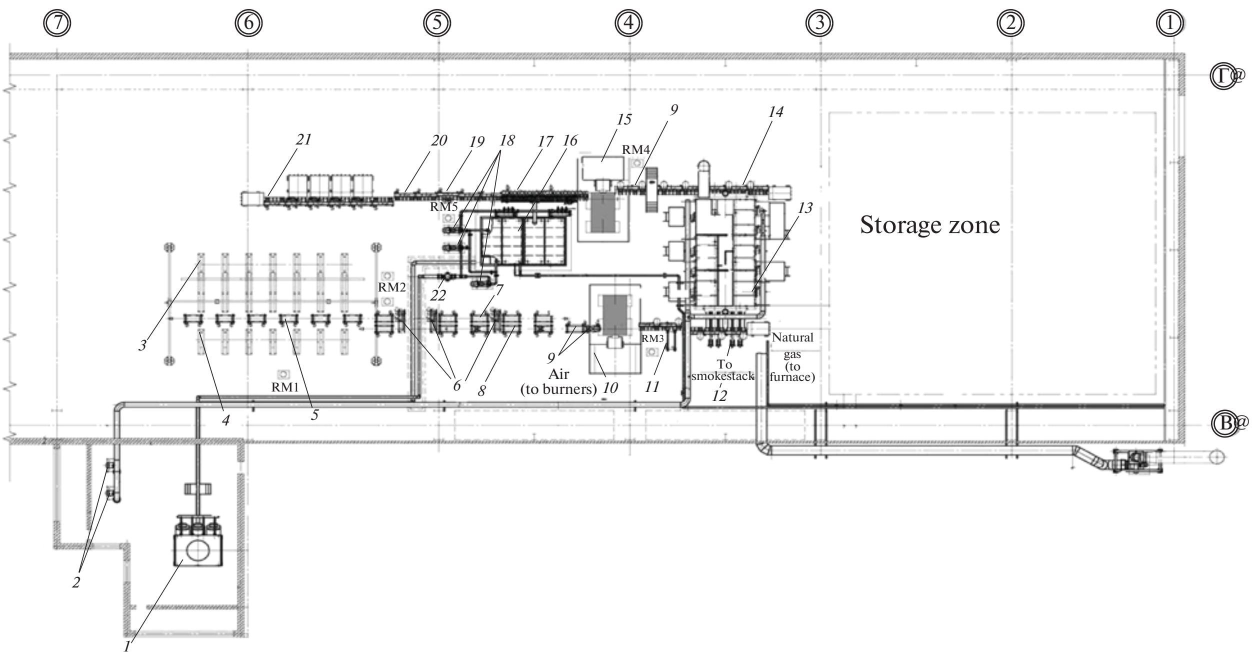

Fig. 2. Department for quenching of fishtails at OOO NSMZ: *2*) furnace fan; *6*) tipping system; *7*) roller conveyer for inspection of blank; *11*) reversing unit; *12*) furnace-charging conveyer; *14*) discharge roller conveyer; *16*) water tank; *18*) pumps; *19*) tipping unit; *20*) roller conveyer. The other notation is explained in the text.

hot hole-piercing press. From there, they proceed to the quenching unit, which has its own roller conveyer. In the quenching unit, the fishtails undergo thermal strengthening by means of water jets. The strengthened profiles are sent to sorting roller conveyer *21* and then sent for storage. All the operations in this system are governed by an automatic control system.[2] The basic operations—cutting, transportation, furnace heating, hole piercing, water-jet cooling, and storage—are controlled by the automatic system. The water circulating in the autonomous supply system for jet cooling passes through filter *1* and is cooled in tower *1*. The closed water-supply system for the quenching unit is shown in Fig. 3.

The water supply to the upper, lower, and lateral lines in the quenching unit is regulated independently. For uniform cooling over the perimeter of the fishtail, flat fan-shaped water fluxes are supplied to the top, bottom, and sides from OAO VNIIMT sprayers, which ensure the required spread of the water jets (Fig. 1). For more efficient water use in heat transfer at different components of the fishtail, the plane of the lines supplying the upper and lower fluxes is shifted relative

[2] The automatic control system was developed and supplied by ZAO VNIPI SAU-40.

Table 1. Dependence of the heat-flux density q, MW/m^2, on the density of water irrigation, m^3/m^2 h, for the surfaces of the fishtail

Surface	Formula	R*
Topsurface	$q = 0.0618\omega - 0.4567$	0.95
Bottomsurface	$q = 0.0356\omega - 0.3561$	9.94
Lateralsurface	$q = 0.0524\omega - 2.0999$	0.95
upper head		
lowerhead	$q = 0.0203\omega - 1.9801$	0.93

* Here R denotes the reliability of the approximation.

to the lateral lines. The system permits the quenching of R50 and R65 fishtails without replacement or redistribution of the cooling-system components. The thermal strengthening is controlled on the basis of the final cooling temperature by regulation of the speed of the fishtails in the system.

In the first stage of introduction of the quenching unit, the fishtails are cooled in one and two sections. That permits determination of the heat-flux density using the mathematical model in [1, 2]. Experimental data on the temperature of the fishtail are obtained for use in the control software [1]. The interface of the software that solves the two-dimensional nonsteady heat-conduction equation permits the specification of initial data for different components of the fishtail. Accordingly, the heat-flux density for the upper, lower, and lateral surfaces of the fishtail may be calculated. On the basis of the water flow rate in each line, the irrigation density of different surfaces may be determined. From the results for each surface, the corresponding dependence of the heat-flux density on the irrigation density may be established (Fig. 4, Table 1). That permits the calculation of the thermal-strengthening conditions corresponding to specified final cooling temperature.

Assessment of the influence of different ratios of the water flow rate G on the linearity of the fishtail shows that the best results correspond to $G_B/G_T = 1.4$ and $G_{LL}/G_{LU} = 2.0$. Here G_B and G_T are the flow rates at the bottom and top surfaces of the fishtail; G_{LL} and G_{LU} are the flow rates at the lateral surfaces for the lower and upper heads, respectively. Thus, twice as much water is required at the side surface for the lower head as for the upper head. This may be attributed to the complex geometry of the fishtail, since the heat-flux density at the surfaces of both heads is practically the same. This conclusion is confirmed by bench tests.

In the second stage of its introduction, the operating conditions of the quenching unit in the thermal strengthening of fishtails made from M54 steel with different carbon content are investigated. The quenching conditions are selected so as to create mechanical properties of the fishtails that comply with the corresponding standards. The initial conditions—the water flow rates in the sections, their ratios, and the speed of the fishtails in the system—are selected on the basis of bench tests [1, 2]. As we see in Table 2, mechanical properties that comply with the standards are obtained for metal with different carbon content in R65 fishtails of type 1 based on strip from different manufacturers. Industrial tests with OAO NTMK steel are consistent with test data for steel from West Siberian Metallurgical Works with 0.53% C [1]. In Fig. 5, on the basis of results for more than 50 experimental and industrial batches, we show the dependence of the mechanical properties on the final temperature in cooling for fishtails with 0.56–0.57% C (West Siberian steel) and 0.485% C (OAO NTMK steel). We see that, with increase in the final temperature in cooling, the strength declines, while the plasticity increases. Thus, to attain the required mechanical properties, the final temperature in cooling must be increased as the carbon content rises. On that basis, the operating conditions for steel of different composition such that the mechanical properties consistently meet the necessary standards may be determined. Data for industrial batches show that the curvature of the initial strip has a great influence on the linearity of the final fishtail. Therefore, the tolerances on the initial hot-rolled strip must be more stringent than for the final product.

Industrial research focuses on R65 fishtails of type 1, which are in most demand. In the manufacture of industrial batches of R65 fishtails, transition from type 1 to type 2 is underway. The standard documentation does not impose requirements on the microstructure of the fishtails. Research at OAO NKMK on quenching in aqueous solution of a polymer (the iron-bearing salt of polyacrylic acid) shows that the product performance may be improved by reducing the distance between the pearlite plates and the quantity of structure-free ferrite in the surface layer of metal [4]. After bulk quenching in oil and thermal strengthening by water jets, samples are taken for assessment of the microstructure. In all cases, the structure consists of pearlite with ferrite along the grain boundaries. The

Table 2. Mechanical properties of fishtails after thermal strengthening ($\varphi > 20°$)

Metal	σ_u, N/mm^2	sy, N/mm^2	δ, %	ψ, %	HB
OAO NTMK steel, 0.485% C	855–923	570–620	12–16	31–44	241–269
West Siberian steel, 0.56–0.57% C	850–912	530–555	13–19	31–41	241–321
Technical Specifications TU 14-2R-463–2011	≥844	≥530	≥10	≥30	235–388

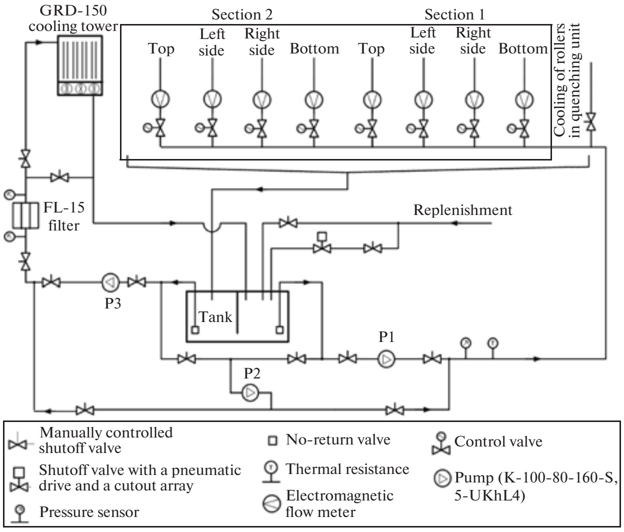

Fig. 3. Water-supply system to the quenching unit at OOO NSMZ.

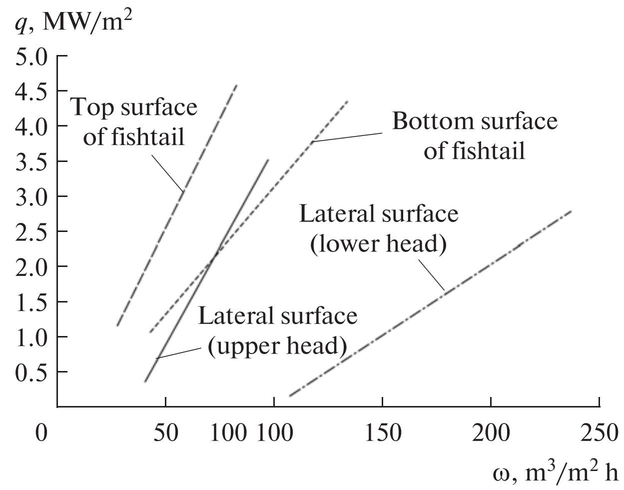

Fig. 4. Dependence of the heat-flux density on the irrigation density according to experimental data for the top, bottom, and lateral surfaces of the fishtail in an industrial system.

only difference is that the pearlite is more disperse after thermal strengthening by water jets than after bulk quenching. In Fig. 6, we show an X-ray diffraction pattern from the middle section of the neck. The tall narrow peaks correspond to ferrite [5, 6]. The X-ray diffraction pattern obtained for the middle section and edges of all regions of the fishtail are of the same form as Fig. 6.

Fishtails produced by thermal strengthening by water jets at OOO NSMZ performed well in bench tests and track tests at OAO VNIIZhT. On the basis of these test results, a certificate of compliance was

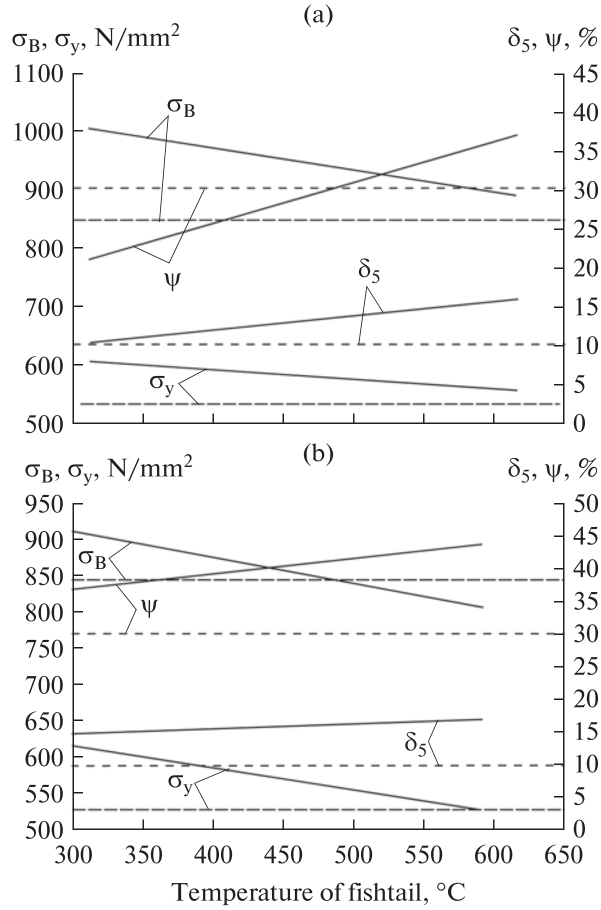

Fig. 5. Experimental (continuous curves) and standard (dashed curves) dependence of the strength and plasticity of fishtails with 0.56–0.57% C (a) and 0.485% C (b) on the final temperature in spray cooling.

issued, permitting the supply of such fishtails to OAO RZhD.

The introduction of thermal strengthening by cooling in water jets is promising for components of complex structure. Traditional bulk quenching of fishtails in oil cannot ensure the same cooling of rail components that differ greatly in mass. Therefore, the design of systems based on cooling in water jets and the determination of corresponding operating conditions is a priority today. Accelerated cooling of asymmetric fishtails with components of different mass may be developed on the basis of the relation between the heat-flux density and the irrigation density obtained in the present work, the proposed method of selecting the cooling parameters in the final stages of production (confirmed by industrial experience), and systems for thermal strengthening by cooling in water jets.

CONCLUSIONS

A system for accelerated water cooling of fishtails has been developed and tested in industrial conditions.

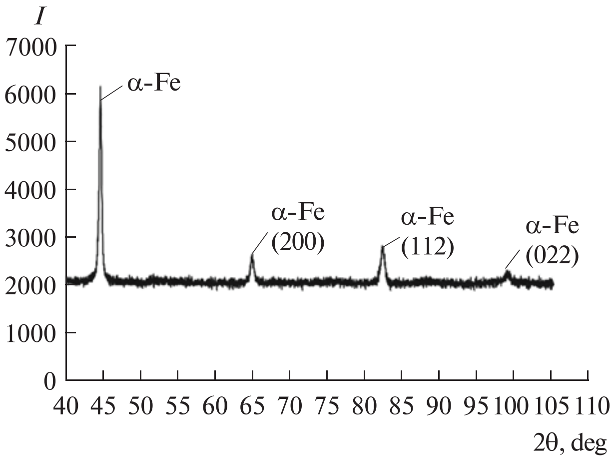

Fig. 6. X-ray diffraction pattern from the middle section of the fishtail's neck: *I*, intensity; 2θ, disorientation angle.

The dependence of the heat-flux density on the irrigation density has been determined for surfaces with different orientation. The proposed operating conditions ensure the required mechanical properties of steel with different carbon content and linearity of the fishtails, thanks to independent regulation of the water flow rates.

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Translated by Bernard Gilbert

SPELL: 1. fishplate