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Development of Manufacturing Technology for High-Strength Hull Steel Reducing Production Cycle and Providing High-Quality Sheets

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The article presents the results of scientific research and industrial experiments aimed at the development of technology to reduce the production cycle of high-strength hull steel. The technology includes an improved reduced heat treatment of ingots made using rare-earth metals and uphill teeming of large sheet ingots.

The proposed technology for the preliminary heat treatment of ingots eliminates the high-temperature phase recrystallization operation, which is unnecessary, according to the authors, since it does not allow partial crushing (grinding) of the metal dendritic structure and homogenization. When using the proposed technology of reduced pretreatment, phase and structural stresses are sharply reduced. Experiments have shown that the modification of steel with rare-earth metals has a positive effect on the crystallization of ingots, changing the macro- and microstructure of alloy steel.

The developed manufacturing technology of high-strength hull steel provides a high level of sheet quality and a reduction in the production cycle time by 10-12 %.

Key words**:** high strength hull steel; heat treatment of ingots; uphill teeming of sheet ingots; rare earth metals; sheet quality; mechanical properties; production cycle length.

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Introduction. Large weight forging ingots for the production of high-strength hull steel sheets are produced at OJSC «OMZ-Spets Stal» by smelting steel in a DSP-120 electric arc furnace using out-of-furnace refining, vacuum treatment and uphill teeming under slag-forming mixtures with the protection of an argon metal stream. Due to the low hot deformability of forging ingots of high-strength steel, the technology uses preliminary heat treatment (PHT) of ingots [8-10, 12].

As a result of the application of this technology, a level of quality of sheet metal is ensured that meets the requirements of technical documentation and high hot deformability of ingots without sorting at the forge. At the same time, the production cycle of case steel is characterized by a considerable duration. It often limits the production capabilities of the enterprise due to the high workload of technological equipment when fulfilling orders of shipyards. In this regard, in recent years, the relevance of research work aimed at the development and development of technology to reduce the duration of the manufacturing processes of high-strength hull steel and high-quality products has significantly increased.

This paper presents the results of scientific research and industrial experiments performed to achieve this purpose in 2012-2016.

The challenge was met by solving the following issues:

- Improving the PHT technology for ingots of high-strength hull steel smelted using rare-earth metals (REM).
- Mastering uphill teeming of large sheet ingots, the use of which significantly reduces the production cycle as a result of eliminating further processing – forging ingots into slabs.

Improving the technology for the preliminary heat treatment of ingots of high-strength hull steel modified with rare-earth metals. After casting, forging ingots of high-strength hull steel have coarse crystalline structure of the cast metal and enrichment of crystallite boundaries with excess phases with a low crystallization temperature, which is explained by the alloying system of this type of steel.

The coarse crystalline structure and many excess phases can weaken the intergranular bonds and, as a result of thermal stresses during heating, lead to the formation of microcracks and their subsequent development during the forging of ingots [1, 7]. Similar processes can occur when the ingots are cooled to a certain temperature when they are transferred from the steelmaking shop to the forge.

At this time, with the possible cooling of the ingot metal, which is still in the austenitic state, precipitation processes can occur at the interdendritic boundaries along the axes of the order of 1-3 excess fusible phases, which weaken the interdendritic boundaries and lead to possible cracking during heating of the ingots due to forging due to thermal stresses. During forging, microcracks can develop into macrocracks, leading to intense cracking of the ingots in the early stages of the process.

The PHT of ingots is a prerequisite for low alloy steels doped with nickel, copper, and carbide-forming elements (molybdenum, vanadium). During PHT it is necessary to form a more dispersed structure due to phase transformations and a partial breakdown of the dendritic structure, as well as to dissolve in the solid solution the unstable phases of fusible impurities and carbide precipitates that were previously separated at the interdendritic boundaries. It should be noted that the PHT of case steel ingots is characterized by a significant process duration. An essential reduction of the production cycle of the hull at this stage may be the improvement of PHT to optimize it according to the processing time.

The treatment with rare-earth metals has a positive effect on the crystallization of ingots, changing the macro- and microstructure of alloy steel [4-6, 11]. According to the literature data, rare-earth metals are among the most surface-active elements, which, concentrating on phase boundaries, reduce interfacial tension, reduce the work of nucleation and increase the number of crystallization centers. It, possibly, is associated with the observed decrease in the size of dendrites and a narrowing of the columnar zone during crystallization of the ingot. In this case, crystallization conditions are improved with the formation of a uniform structure over the entire cross-section of the ingot. It follows that the physical and chemical processes involved in the processing of metals with REM additives are aimed at solving the same problems as the used PHT of ingots – increasing the dispersion of the dendritic structure of the ingot and its hot deformability. This task is solved at the 5th stage of the PHT flow chart for ingots of high-strength hull steel (phase recrystallization) (Fig.1, *a*).

This paper proposed an improved flow chart for the solid-state ingot formation (Fig.1, *b*) for high-strength hull steel treated with rare-earth metals; it did not include the phase recrystallization stage.

At stage 1 of the developed flow chart, the ingots are accumulated in the thermal furnace, and the temperature is equalized over the cross-section since high-strength hull steel has increased austenite stability, the ingots are in a supercooled state without noticeable transformations. Upon cooling (stage 2), a bainitic transformation begins, which continues under isothermal conditions (stage 3). In this case, a mixed bainitic-martensitic transformation occurs. Further heating, austempering, and cooling of the ingots (stages 4, 5, and 6) contribute to the tempering of the resulting structures and a significant reduction in structural and temperature stresses, which significantly reduces the duration of the heat treatment process.

The research aimed at developing and mastering the manufacturing technology of high-strength hull steel, which

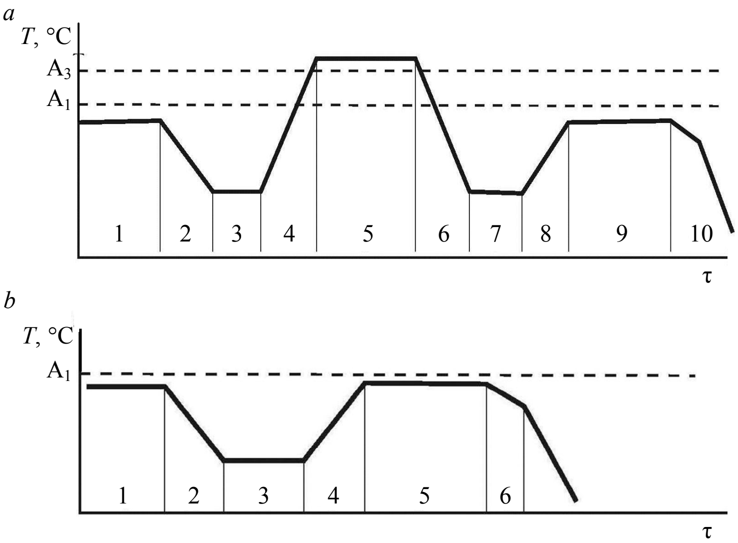

Fig.1. Scheme of preliminary heat treatment of ingots of high-strength hull steel: *a* – standard; *b* – pilot

reduces the duration of the production cycle by improving the PHT of ingots treated by rare-earth metals, was performed on gross smelting of current production line.

The technology to produce ingots of high-strength hull steel, providing a reduction in the duration of the production cycle, basically corresponded to the previously developed methods [9, 12]. The difference was in the materials used during out-of-furnace processing and in the applied advanced reduced regime of ingot PHT (Fig.1, *b*).

The complex microcrystalline modifier was used to produce test samples of metal; it contained 7-9 % cerium and 9-12 % calcium, as well as ferrocalcium with a content of 40 % calcium. At the end of the treatment, a flux-cored wire with ferrocalcium was first introduced into the metal, then a wire with a complex modifier based on the calculation of calcium and cerium in steel within 0.002-0.004 % of each. The actual content of calcium and cerium in the metal of the ladle samples, determined on a high-precision X-ray fluorescence spectrograph AXIOS Advanced by PANalytical B.V., was within the specified limits.

Previously [2, 3], it was shown that the modification of high-strength shipbuilding steel together with ferrocalcium and rare-earth metals with the calcium and cerium content in the metal within the indicated limits allows to reduce the pollution of steel by inclusions and increase the level of mechanical properties of the sheets. In addition, we can expect a decrease in the physical and chemical heterogeneity of the metal of large ingots treated with rare-earth metals, with an increase in their hot deformation.

Forged ingots made according to the developed technology had a high surface quality when forging them on slabs.

Mechanical tests of impact hardness and ductility in the *Z*-direction of the sheets of experimental melts were carried out on samples cut from samples taken from the middle third and both edges in width from the upper and lower ends of one sheet from the heat. The test results of the mechanical properties of the three test sheets showed a high level and stability along the width of the sheet (Table 1).

The study of the macrostructure was performed on macro sections made from samples taken from three sheets of different heats. A sample for the manufacture of a macro section was taken from the head of the sheet in the middle third of the width over the entire thickness of the sheet. The macrostructure of all sheets in thickness is dense, uniform, there are no macrostructure defects.

The study of the content and distribution of non-metallic inclusions (NMI) was carried out by optical metallography in accordance with GOST 1778 using optical microscopes Olympys BX-51 and Axiovert 40MAT from ZEISS.

Impurities of NMI metal were determined by comparison with scales according to GOST 1778 (method SH4) with a 100-fold increase on six microsections from each sample, made in the longitudinal direction of rolling perpendicular to the plane of the sheets, in a state without etching. The results of pollution assessment by inclusions of experimental steel are presented in Table 2.

Steel made according to the developed technology has a high degree of purity, NMI in all samples are evenly distributed and do not exceed a score of 3 according to GOST 1778. The largest inclusions are non-deformable silicates (NDS) (Table 2, Fig.2). For other types of inclusions, the pollution does not exceed a score of 1 according to GOST 1778. X-ray microanalysis of NMI showed that round inclusions, classified according to GOST 1778 as non-deformable silicates, are oxysulfides.

Thus, the processing of metal with complex modifiers with rare-earth metals made it possible to ensure low pollution of steel with hazardous non-deformable silicates, which could lead to microcracks.

The performed experiments showed that steel made with the use of rare-earth metals and an improved PHT mode for ingots has a high level of quality.

Table 1

Test results of the mechanical properties of the width of the sheets of high-strength hull steel made of forging ingots with the use of rare-earth metals and an improved PHT mode

Sheet number index/sheet thickness, mm	Place of sampling along the width of the sheet		Impact hardness KCV^{+20}, J/cm^2	Contraction in Z-direction Ψ_z, %
1/57	Top of sheet	Sheet edge	213-215	64-58-65
		Middle part	198-211-	60-54-62
		Sheet edge	201-227	57-62-63
	Bottom of sheet	Sheet edge	200-203	60-63-62
		Middle part	210-211	56-54-54
		Sheet edge	215-223	56-58-58
2/64	Top of sheet	Sheet edge	233-236	61-66-63
		Middle part	207-210	59-59-63
		Sheet edge	225-233	58-61-62
	Bottom of sheet	Sheet edge	242-248	66-65-67
		Middle part	213-218	63-59-64
		Sheet edge	236-245	66-58-66
3/42	Top of sheet	Sheet edge	202-211	58-57-59
		Middle part	230-249	55-53-54
		Sheet edge	200-206	59-61-61
	Bottom of sheet	Кромка	208-215	59-63-63
		Sheet edge	200-220	52-57-58
		Кромка	203-215	65-59-60

Table 2

Pollution assessment results for non-metallic inclusions, points[*]

Melting number index	Top of sheet						Bottom of sheet					
	Oxides		Sulfides	Silicates			Oxides		Sulfides	Silicates		
	OS	SO	S	SC	SP	NDS	OS	SO	S	SC	SP	NDS
1	0.0	0.5	0.0	0.3	0.0	1.7	0.0	0.5	0.0	0.5	0.0	2.7
2	0.0	1.0	0.2	0.2	0.0	2.3	0.0	1.0	0.0	0.2	0.0	2.5
3	0.0	0.5	0.0	0.0	0.0	2.3	0.0	0.5	0.2	0.0	0.0	1.3

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[*] Average values of pollution for six samples.

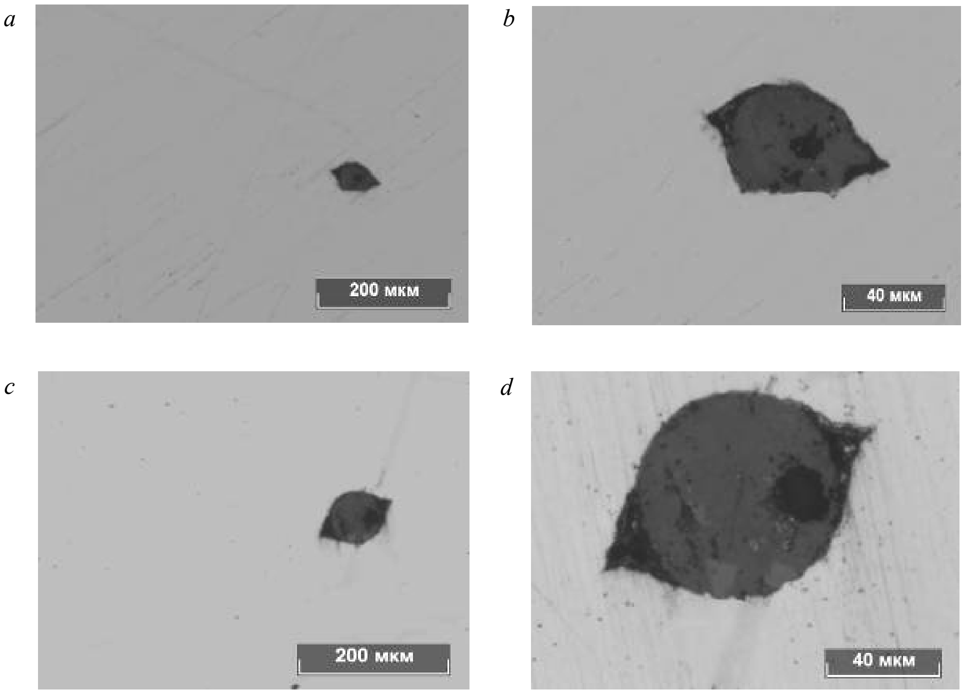

Fig.2. Non-metallic inclusions – non-deformed silicates in the metal of samples of experimental melting of high-strength hull steel at different magnifications: *a*, *b* – top of sheet; *c*, *d* – bottom of sheet

We produced 15 pilot melts to confirm the results of the developed technology and rolled 93 sheets out of this steel. The data were processed on 13 gross heats (75 sheets), manufactured using standard technology at the same time as the pilot ones.

The analysis of the results of certification tests of mechanical properties (impact hardness and ductility in the *Z*-direction) of the sheets of pilot and standard melts of high-strength hull steel showed that they are almost at the same level of quality and meet the requirements of the current technical documentation (Table 3).

Table 3

The results of certification tests of the mechanical properties of sheets of high-strength hull steel[*]

Technology	Number of sheets	Place of sampling	Mechanical properties	
			Impact hardness KCV $^{+20}$, J/cm^2	Contraction in *Z*-direction Ψ_z, %
Pilot	93	Top Bottom	210.6 214.6	54.2 55.1
Standard	75	Top Bottom	207.2 211.6	54.5 54.9

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[*] Average values.

The application of the advanced manufacturing technology of high-strength hull steel, including the processing of rare-earth metals and PHT of ingots according to the reduced mode, provides high hot deformability of ingots, reduces the PHT duration of ingots by 25-30 % depending on their weight and significantly reduces the cost of sheet production.

Flat products manufactured according to the developed technology fully comply with the requirements of the current technical documentation.

Uphill teeming of sheet ingots. Ingot casting is an established technology, but there are potential opportunities for its improvement. Over the past 6-10 years, at OJSC «OMZ-Spetstsal», casting technology for high-strength hull steel has undergone significant changes. They developed and mastered the technology for casting large forging ingots from above at atmospheric pressure in an argon atmosphere using high-quality warming mixtures, which made it possible to significantly reduce the pollution of sheets by clusters of oxide stringers, as well as to optimize casting technology, improve working conditions in the casting shop and reduce steel production costs [12].

The development of the technology of uphill casting of ingots in argon without intermediate devices and vacuum, the availability of high-quality materials, casting, and heat-insulating mixtures of foreign manufacture at the enterprise allowed us to start mastering the casting of ingots by the uphill teeming method.

The application of the technology of casting large forging ingots by the uphill teeming method compared to vacuum casting made it possible to increase the plasticity in the *Z*-direction by 1.2-1.3 times, eliminate this type of defects and significantly increase the yield in the production of high-strength hull steel [8, 12].

Based on the results of studies carried out during the development of uphill teeming of forging ingots, pilot industrial work was carried out to develop and introduce uphill teeming of sheet ingots weighing up to 34 tons of high-strength hull steel, which significantly reduced the production cycle due to the exclusion of process stages previously used for forging ingots into slabs. This, in turn, leads to additional savings in the production of hull metal.

The aim of the paper is to study the quality of sheets of high-strength hull steel made of large sheet ingots cast by an uphill teeming under slag-forming mixtures with protection of a stream of metal with argon.

The metal of the studied melts was manufactured using standard technology, except the casting of experimental large sheet ingots. These ingots were cast using the uphill teeming method with argon protection of the metal stream. The metal was poured into unpainted molds under a slag-forming mixture with a flow rate of 2 kg/t through a nozzle, a slide gate with a diameter of 60 mm. Immediately after the end of the casting of the ingot, 5-7 kg of slag-forming mixture was uniformly poured into the rising head to create an intermediate layer, after which the warming mixture was poured into the top part of the ingot at the rate of 1.5-2.0 kg/t of steel.

The quality of the metal was investigated on sheets of high-strength hull steel with a thickness of 80 and 100 mm, made using uphill teeming out of sheet ingots weighing 33.3 and 20.4 tons.

The results of tests of impact hardness and ductility in the *Z*-direction along the width of the top and bottom of the sheets (the axis of the transverse impact samples passes at 1/3 of the thickness of the sheet from the surface) are given in Table 4. A cross-sectional view of technological samples from the top and bottom of a sheet 100 mm thick is shown in Fig.3.

The above results show the high quality of sheets with a thickness of 80 and 100 mm both along the perimeter and in thickness.

The study of the macrostructure was carried out on macro sections of two sheets with a thickness of 80 mm. A sample for the manufacture of a macro section was taken from the head end of the sheet in the middle third of the width over the entire thickness of the sheet. The macrostructure over the entire thickness of both sheets is dense and uniform; there are no defects in the macrostructure.

Table 4

Test results of impact hardness and *Z*-properties in width above and below three sheets of high-strength hull steel

Ingot weight, t	Sheet thickness, mm	Sampling place		Impact hardness KCV^{+20}, J/cm^2	Contraction in *Z*-direction Ψ_z, %
20.4	80	Top of sheet	Sheet edge	231-234	64-65-65
			Middle	215-217	61-63-63
			Sheet edge	222-224	63-65-67
		Bottom of sheet	Sheet edge	233-234	64-64-66
			Middle	230-244	60-63-63
			Sheet edge	235-237	63-65-65
20.4	100	Top of sheet	Sheet edge	215-216	63-64-65
			Middle	209-210	61-62-64
			Sheet edge	209-213	62-64-67
		Bottom of sheet	Sheet edge	211-216	66-66-66
			Middle	223-224	61-61-66
			Sheet edge	217-228	63-64-64
33.3	80	Top of sheet	Sheet edge	179-191	50-54-56
			Middle	187-191	48-48-49
			Sheet edge	178-185	51-52-56
		Bottom of sheet	Sheet edge	200-216	55-56-55
			Middle	197-207	60-61-64
			Sheet edge	197-201	57-60-61

Fig. 3. Cross-sectional view of technological samples from the top and bottom of a sheet 100 mm thick, made of a sheet ingot of high-strength hull steel weighing 20.4 tons.

Table 5

The results of the evaluation of pollution by nonmetallic inclusions*

Sheet number index	Type of nonmetallic inclusion	Amount of inclusions, points					
		Top of sheet			Bottom of sheet		
		Sheet edge	Middle	Sheet edge	Sheet edge	Middle	Sheet edge
4	Spot oxides	0.7	0.8	0.8	0.8	0.7	0.8
	Non-deformed silicates	1.8	1.7	1.8	1.6	1.7	1.7
5	Spot oxides	1.0	0.8	0.9	1.0	1.0	0.9
	Non-deformed silicates	2.3	2.3	2.3	2.2	2.3	2.3
6	Spot oxides	0.6	0.7	0.7	0.8	0.7	0.8
	Non-deformed silicates	1.9	2.0	1.8	1.7	1.8	1.9

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* Average values of pollution for six samples.

The study of the content and distribution of NMI was carried out by optical metallography following GOST 1778 on three sheets with a thickness of 80 mm, made of metal of three melts. The results of the assessment of pollution by inclusions of experimental steel are presented in Table 5.

Based on the studies performed, it can be concluded that hull steel made of large sheet ingots produced using the uphill teeming has a high degree of purity inclusions are evenly distributed across the width of the top and bottom sheets. The most dangerous inclusions of non-deformable silicates do not exceed a score of 2.5, according to GOST 1778.

The use of the uphill teeming technology for casting sheet ingots under a slag-forming mixture with the protection of a metal stream of argon provides a high level of quality of sheets of high-strength hull steel.

Conclusion. As a result of the research, the basic provisions of improved manufacturing technology for high-strength hull steel have been developed, which provide a reduction in the production cycle:

- metal processing with complex modifiers containing rare-earth metals;
- improved reduced ingot pre-heat treatment;
- uphill teeming of sheet ingots weighing up to 34 t.

Tests of metal made using elements of improved technology have shown a high degree of purity of rolled metal for non-metallic inclusions. The quality level of the sheets fully complies with the requirements of the current technical documentation. The duration of the technological cycle of production of high-strength hull steel due to the implementation of the developed measures is reduced by 10-12 %, and in individual phases of the cycle to ~ 30.0 %.

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