# INVESTIGATION OF THE SOLIDIFICATION BEHAVIOUR OF 40CR STEEL INGOTS UNDER METAL HEATING AND STIRRING

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***Abstract.*** *To eliminate shrinkage defects in large steel ingots, a method of external influence combining electroslag heating and metal stirring during solidification has been proposed. Laboratory-scale experimental melts were carried out to produce 120 kg ingots of 40Cr steel. Longitudinal templates were cut from the obtained ingots, followed by macroscopic structure analysis, tensile tests and Brinell hardness measurements. The conducted studies demonstrate the elimination of shrinkage defects and an improvement in the physical homogeneity of the ingot as a result of the combined external influence, indicating the promise of this approach.*
***Keywords***: *steel ingot, solidification, external influence, electroslag heating, stirring.*

The production of large steel ingots is often accompanied by the formation of shrinkage defects in the central part of the ingot. These internal cavities, porous zones, and areas of looseness significantly deteriorate the mechanical properties of the metal and the quality of the final products. The primary cause of such defects is the insufficient feeding of the solidifying zones with liquid metal during the final stages of crystallization.

Over the past decades, numerous methods have been proposed to address these issues [1–2], including stirring of the liquid core during ingot formation, which is widely applied in continuous casting processes [3], mechanical vibration, metal modification, and various additional heating techniques applied to the hot-top region, such as electroslag heating [4]. However, none of these approaches alone has succeeded in fully eliminating shrinkage defects or ensuring sufficient homogeneity of the solidified metal, particularly in the case of large-tonnage ingots.

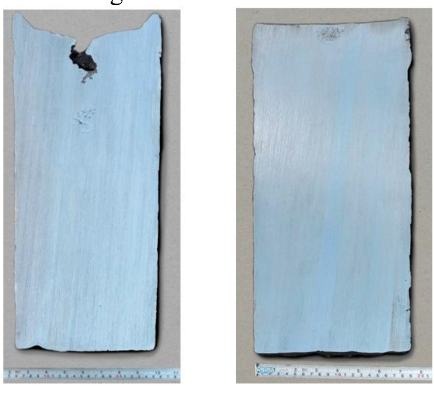
To overcome these challenges, a new approach has been proposed that combines external thermal and hydrodynamic effects: heating of the metal in the hot-top and periodic stirring of the liquid core by inert gas purging [5]. The simultaneous application of these two factors reduces the extent of the mushy zone during solidification and enhances the feeding of the solidification front, thereby improving the structural and physical homogeneity of the steel ingot [6].

This work is devoted to a further investigation of the above-mentioned external influence on the structure and physical homogeneity of 40Cr steel ingots. This steel grade is widely used as a structural material in various industrial applications, including the production of steel ingots.

Under laboratory conditions, 120-kg ingots were produced by pouring molten metal into sand–clay molds, which made it possible to simulate the solidification conditions of larger ingots cast in cast-iron molds. The applied external influence consisted of electroslag heating of the ingot hot-top using a non-consumable electrode and periodic stirring of the liquid metal pool by argon purging.

Two ingots were produced. The first ingot (control) was subjected only to hot-top heating after pouring, with the temperature of the slag bath maintained close to the liquidus temperature of the metal. The second ingot (experimental) was heated with a slag temperature of 1500–1530 °C, and its liquid core was stirred five times during the solidification process by argon purging. In this case, the stirring power ranged from 3 to 4 × $10^{-}$I W/kg.

Analysis of the ingot templates (Fig. 1) showed that the control ingot exhibits shrinkage-related defects typical for conventionally produced ingots. An open shrinkage cavity is located in the hot-top region, and a zone of increased porosity is observed further along the ingot axis at a distance of 150–200 mm from the top (approximately one third of the ingot height). According to macroscopic examination, such defects are nearly completely absent in the experimental ingot.



*a* *b*

**Fig. 1. Appearance of the polished surface of vertical axial templates of 40Kh steel ingots: (*a*) control; (*b*) experimental**

To evaluate the physical homogeneity of the steel ingots, Brinell hardness measurements were performed across the ingot cross-section. Both the control ingot (No. 1) and the experimental ingot (No. 2) demonstrate a common trend toward decreasing hardness from the surface toward the axis and from the bottom toward the top of the ingot (Fig. 2).

However, in the control ingot, a sharp decrease in hardness is observed in the zone of increased porosity, and in the upper axial region the hardness could not be measured due to the presence of shrinkage cavities. In the experimental ingot, no significant drop in hardness was detected in the upper axial zone. Tensile tests were also carried out, and the results are presented in Fig. 3.

Specimens taken from different regions of the axial template underwent standard heat treatment for 40Cr steel. Quenching was performed at 850 °C with a holding time of 15 minutes, followed by cooling in water. This was followed by high-temperature tempering at 500 °C with a holding time of 1 hour, and subsequent cooling in air.

According to the mechanical tests, the metal exhibits sufficiently high strength values. A clearly pronounced decrease in strength is observed in ingot No. 1 in the zone of increased porosity. In ingot No. 2, such a decrease in the upper axial region is absent.

The results of mechanical testing and hardness measurements indicate improved physical homogeneity in the 40Cr steel ingot obtained under the combined action of heating and stirring of the metal. Thus, the external influence combining electroslag heating of the hot-top metal and stirring of the liquid pool by argon purging represents a promising method for enhancing the physical homogeneity of steel ingots.

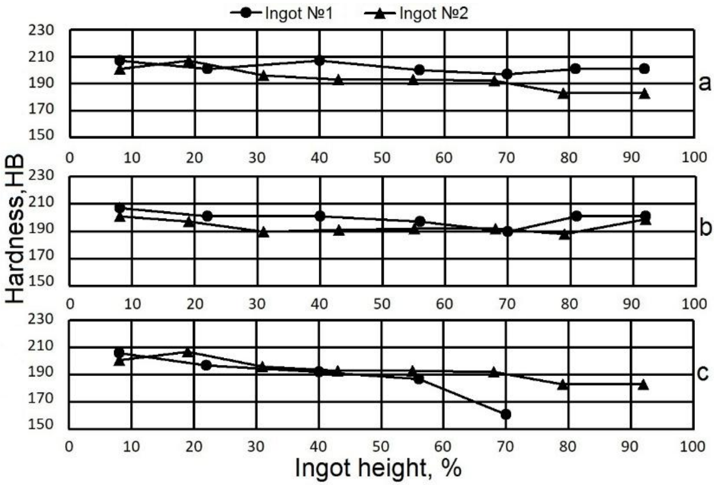



**Fig. 2. Brinell hardness at the ingot template edge (*a*), at 2/3R (*b*), and along the axis (*c*)**

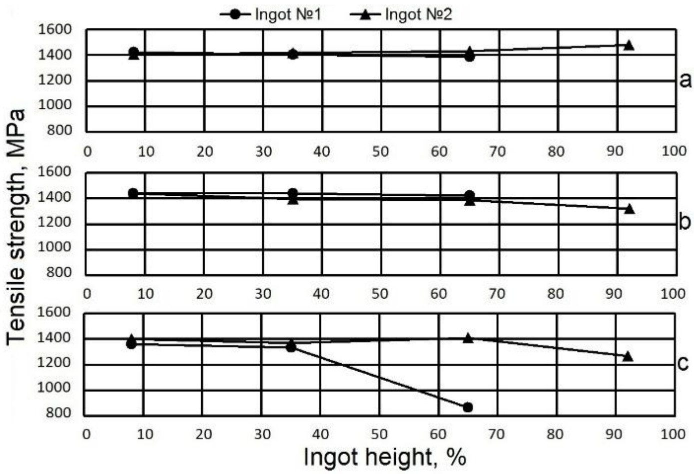



**Fig. 3. Tensile strength at the ingot template edge (*a*), at 2/3R (*b*), and along the axis (*c*)**

## References

1. Tarasevich, N. I., Nuradinov, A. S., & Taranov, E. D. (2006). The influence of vibration treatment on the solidification parameters of steel workpieces. Casting processes, (1), 64. [in Russian]

2. Nuradinov, A. S., & Efimov, V. A. (2002). Study of thermophysical conditions of solidification of steel ingots in the field of elastic waves. Casting Processes, (4), 30. [in Russian]
3. Verzilov, O., Smirnov, O., & Semenko, A. (2022). Influence of electromagnetic stirrer operating modes on the structure of the billet in modern micro-plants. Metal and casting of Ukraine, 30 (3). URL: https://doi.org/10.15407/steelcast2022.03.048 [in Ukrainian]
4. Biktagirov, F. K., Shapovalov, V. A., Efimov, M. V., Selyutin, A. A., & Padalka, V. G. (2011). Improving the quality of large ingots. Electrometallurgy Today, (1), 7–11. [in Russian]
5. Barabash V. V., Biktahirov (2024) F. K. Application of external influence in the production of steel ingots. Overview. Electrometallurgy Today, (1), 40–48. https://doi.org/10.37434/sem2024.01.05 [in Ukrainian]
6. Barabash V. V., Biktahirov F. K., Shapovalov V. O., Hnatushenko O. V. The Influence of Metal Heating and Stirring on the Conditions of Steel Ingot Solidification. Proceedings of 18th International Conference on Science and Education, January 04–11, 2024. Hajduszoboszlo (Hungary). P. 70–74.