Improving Ingot Quality Through Controlled Melt Flow: Industrial Application of Rotating Casting Mold (RCM) Technology

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The quality of steel ingots is strongly influenced by melt flow during solidification, which remains difficult to control in conventional ingot casting and often leads to segregation defects and porosity. While various flow-control strategies exist, no widely adopted industrial solution is available for ingot casting.
The Rotating Casting Mold (RCM) technology, developed by INTECO, introduces a mechanical approach to actively control melt flow during solidification. By inducing rotational motion of the mold, forced convection is generated throughout the ingot, promoting a more uniform grain structure and improving central soundness. In this study, industrial-scale casting trials were conducted on two 21-ton steel ingots to compare conventional ingot casting with the RCM technology. The results demonstrate a significantly improved solidification structure, characterized by a finer and more homogeneous grain structure, an increased equiaxed region, and reduced porosity. To support the experimental findings, a physics-based CFD model was applied. The simulations indicate that mold rotation promotes fragmentation and enhances equiaxed grain formation, leading to the observed structural changes. Good agreement between experimental and numerical results confirms the predictive capability of the model. Overall, the results highlight the strong potential of RCM technology for improving ingot quality and provide a basis for further process optimization.

KEYWORDS: ROTATING CASTING MOLD (RCM), MELT FLOW CONTROL, MECHANICAL STIRRING, CFD SIMULATION, COLUMNAR-EQUIAXED SOLIDIFICATION, MACROSEGREGATION

INTRODUCTION

Macrosegregation remains one of the major quality challenges in the production of large steel ingots. It originates from the relative movement of solute-enriched or solute-depleted liquid and solid phases during solidification. Depending on the local solidification conditions, several coupled transport mechanisms contribute to the resulting composition distribution, including thermo-solutal convection, shrinkage-induced interdendritic flow, and the movement or sedimentation of equiaxed grains [1–3]. These mechanisms lead to characteristic segregation patterns in large steel ingots, such as negative segregation in the lower part of the ingot and positive segregation towards the upper central region [2,3].
Since macrosegregation is closely linked to the transport of liquid and solid phases, externally induced flow can substantially modify both the solidification structure and the resulting solute distribution. Electromagnetic stirring is an established approach for generating forced convection during solidification and can promote dendrite fragmentation and the formation of an extended equiaxed zone [4,5]. However, forced convection does not necessarily improve all aspects of casting quality simultaneously. The induced multiphase flow can also modify the transport of liquid and equiaxed grains and may consequently intensify macrosegregation under certain operating conditions [4,6]. The effectiveness of a flow-control strategy therefore has to be evaluated with respect to both the resulting solidification structure and macrosegregation.
Mechanical mold rotation represents an alternative approach for generating forced convection during solidification. Previous investigations have demonstrated that rotating or oscillating the mold can influence interdendritic flow, grain structure, and macrosegregation, with the resulting effect strongly depending on the applied rotational conditions [7–9]. More recently, laboratory-scale experiments on steel showed that

alternating mechanical rotation can significantly refine the solidification structure and enlarge the equiaxed region, while strong rotational conditions were also associated with visible stirring bands [10]. These findings demonstrate the importance of the applied rotation scheme for both solidification structure and segregation behavior.

Despite these previous investigations, the influence of mechanically induced alternating rotation on macrosegregation in industrial-scale steel ingots remains insufficiently understood. The present study compares two 21-ton steel ingots produced under conventional and RCM conditions, with particular focus on the solidification structure and carbon macrosegregation. The experimental results are further compared with a multiphase numerical model. The objective is to evaluate the influence of the applied rotation scheme and to establish a basis for its further optimization.

ROTATING CASTING MOLD CONCEPT

The Rotating Casting Mold (RCM) technology is a mechanical stirring concept developed by INTECO to actively influence the solidification of steel ingots through controlled melt flow. While melt flow during conventional ingot casting is predominantly governed by thermal and solutal buoyancy, RCM introduces forced convection by mechanically rotating the mold. The RCM concept is subject to a pending patent application by INTECO. Therefore, only a schematic representation of the technology is provided, while detailed technical information regarding the mechanical rotation system is not disclosed.

The basic operational principle of the RCM system is illustrated in **Fig. 1**. The concept is designed for integration into the conventional ingot casting process without fundamentally altering the established casting procedure. After completion of casting, the connection between the ingot and the runner system is physically separated. The mold and the partially solidified ingot can subsequently be rotated around their common vertical axis while solidification continues.

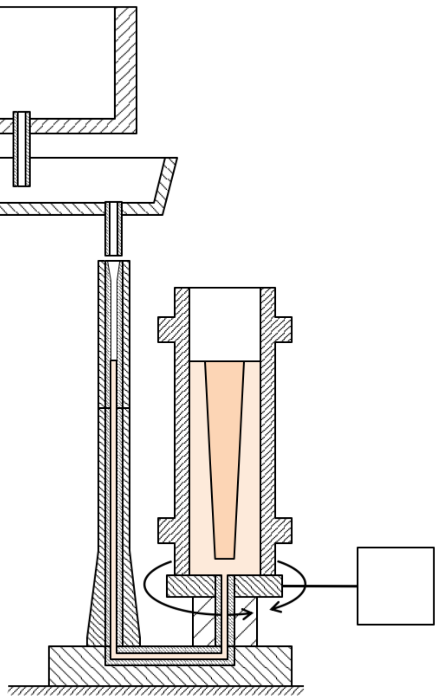

Fig. 1: Schematic illustration of the Rotating Casting Mold (RCM) technology

A key feature of the RCM concept is the flexibility of the applied rotation strategy. The mold can be rotated continuously or intermittently, while alternating directions of rotation can be applied as schematically illustrated in **Fig. 2**. The rotational velocity can additionally be varied throughout the solidification process to account for the continuously decreasing liquid region as the solidification progresses from the mold wall towards the ingot center. Consequently, the rotation strategy can be adapted to the ingot geometry, steel grade, solidification progress, and targeted metallurgical effect.

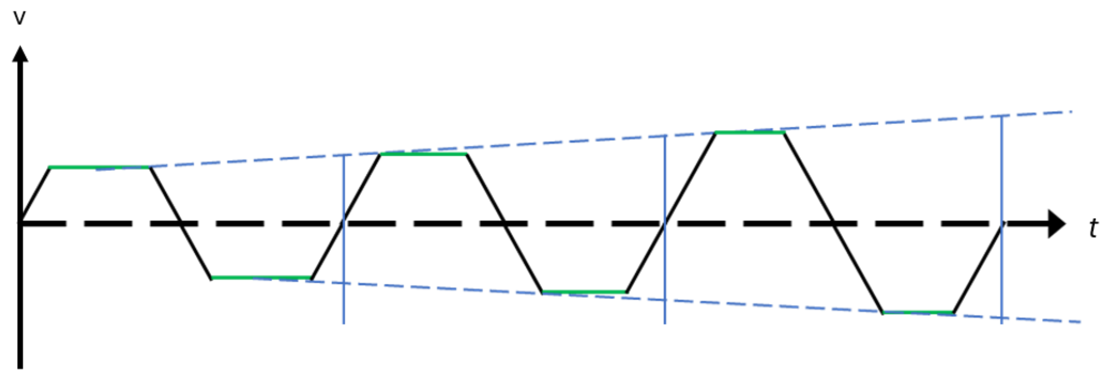

Fig. 2: Schematic representation of an alternating mold rotation sequence.

From a metallurgical perspective, the rotational movement transfers momentum from the mold through the already solidified shell to the liquid melt, generating forced convection at the solid-liquid interface. Under RCM operation, the imposed forced convection dominates the melt flow and suppresses the naturally occurring convection. As a result, heat and, in particular, mass transport during solidification are significantly altered compared with conventional ingot casting.
The induced flow is intended to promote grain refinement and the formation of a more pronounced equiaxed region while improving the homogeneity and central soundness of the as-cast structure. The magnitude of these effects, however, depends strongly on the applied rotation strategy. Consequently, the selection of suitable rotational parameters represents an essential aspect of the RCM process and provides a basis for tailoring the solidification conditions to the specific requirements.

SIMULATION MODEL DESCRIPTION

The present work builds upon a three-phase volume-averaged solidification model previously developed by the authors [11,12]. While the fundamental framework and its application to mixed columnar-equiaxed solidification are described in detail in these publications, a concise overview of the key features relevant to the present study is provided here. The model has previously been applied to investigate the formation of both the as-cast structure and macrosegregation in steel ingots.
The model solves the volume-averaged conservation equations of mass, momentum, species, and enthalpy for three interpenetrating phases: the liquid melt (f_ℓ), the columnar dendrites (f_c), and the equiaxed crystals (f_e). The corresponding volume fractions satisfy the closure relation $f_\ell + f_c + f_e = 1$. To describe growth kinetics, the columnar and equiaxed morphologies are idealized as cylinders and spheres, respectively, with solidification and remelting rates governed by diffusion-controlled kinetics. The columnar phase represents a stationary dendritic network growing from the mold walls, while the equiaxed phase consists of mobile crystals transported by the melt flow.
The model considers a prescribed density difference between the solid and liquid phases, leading to grain sedimentation and sedimentation-induced melt convection. In addition, the Boussinesq approach is employed to account for thermo-solutal convection in the melt. Melt flow and the motion of equiaxed crystals are fully coupled with energy, species, and mass transport and therefore influence the solidification sequence. Bulk and interdendritic flow as well as crystal sedimentation are key mechanisms for the formation of macrosegregation in steel ingots [12].
To capture the flow conditions induced by the RCM technology, the momentum equations were extended by volumetric source terms representing the rotational forces, namely Euler, centrifugal, and Coriolis forces, in combination with the Boussinesq approximation for buoyancy. This formulation follows the generalized framework proposed by López et al. [13]. The model domain and corresponding boundary conditions are presented in **Fig. 3**.

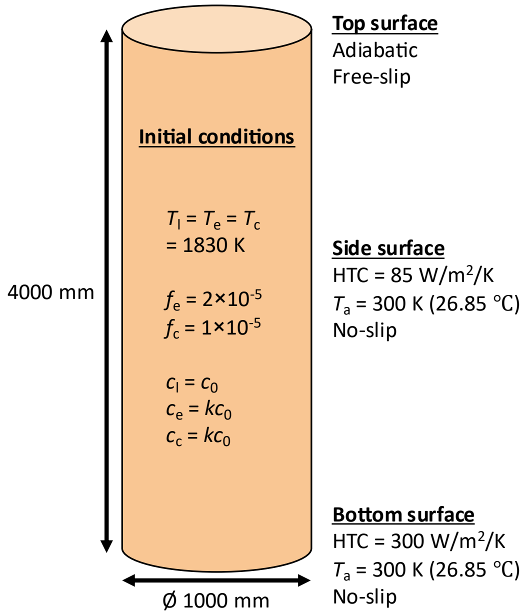

Fig. 3: Domain and boundary conditions of the numerical model.

The model is applied to both the conventional and RCM cases to investigate the influence of mold rotation on the resulting solidification structure and macrosegregation.

EXPERIMENTAL RESULTS AND MODEL VALIDATION

Industrial Casting Trials

Two 21-ton steel ingots of 42CrMo4 were produced at Breitenfeld Edelstahl AG in Austria. The ingots had a height of approximately 3750 mm and a diameter of 970 mm. Two casting conditions were investigated: a conventional (static) ingot and an ingot produced using the RCM technology.

To ensure comparable boundary conditions, all relevant process parameters were kept within a narrow range. Both ingots were produced as single-cast bottom-poured ingots using the same mold. The casting temperature was identical, while casting speed, casting time, and the use of casting and exothermic powders were closely matched. Furthermore, the chemical composition was maintained within a narrow range, as summarized in **Table 1.**

These conditions provide a suitable basis for a direct comparison between conventional and RCM casting.

Tab. 1: Chemical Composition in mass %

	C	Si	Mn	P	S	Cr	Mo	Ni	Al	N
Analysis [%]	0.44-0.46	0.25-0.30	0.80-0.85	<0.005	<0.005	1.05-1.15	0.25-0.30	0.47-0.52	0.01-0.02	<0.01

For the RCM trial, an alternating rotation scheme, as schematically illustrated in **Fig. 2**, was applied. After the formation of a sufficiently solid shell, rotation was initiated at 60% of the maximum rotational speed. As the solidification front advances towards the ingot center, the radius of the remaining liquid region decreases, resulting in a lower circumferential velocity and consequently reduced flow intensity at a constant rotational speed. Therefore, the rotational speed was progressively increased to maintain the induced melt flow towards the ingot center and thereby improve central soundness. Rotation continued until complete solidification of the ingot.

After stripping, both ingots were sectioned longitudinally and transversely for post-mortem analysis. The overall sectioning and sampling scheme is illustrated in **Fig. 4**. For the present study, two longitudinal sections at 500-1000 mm (sample 2) and 3000-3500 mm (sample 3) from the ingot bottom were selected for the investigation of the solidification structure and macrosegregation. The corresponding cross-sectional investigations are not discussed in the present work, as a detailed comparison of the experimental and numerical results is presented in a separate work [14].

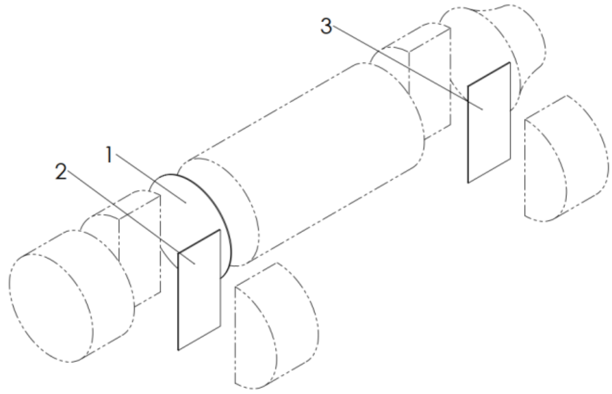

Fig. 4: Sectioning and sampling scheme of the investigated 21-ton steel ingots.

Solidification Structure

A detailed analysis of the experimentally observed solidification structure, including the comparison with the numerical model, is presented in a separate work [14]. Therefore, only a brief overview of the longitudinal sections relevant to the present study is provided here. The selected sections at 500-1000 mm and 3000-3500 mm from the ingot bottom are shown in **Fig. 5** and **6**.

The selected longitudinal sections were prepared and etched according to standard industrial practice to reveal the as-cast solidification structure. At 500-1000 mm, the conventional case exhibits a coarse solidification structure with a relatively limited equiaxed region. In contrast, the RCM case shows a considerably finer and more homogeneous structure with an extended equiaxed region and improved central soundness.

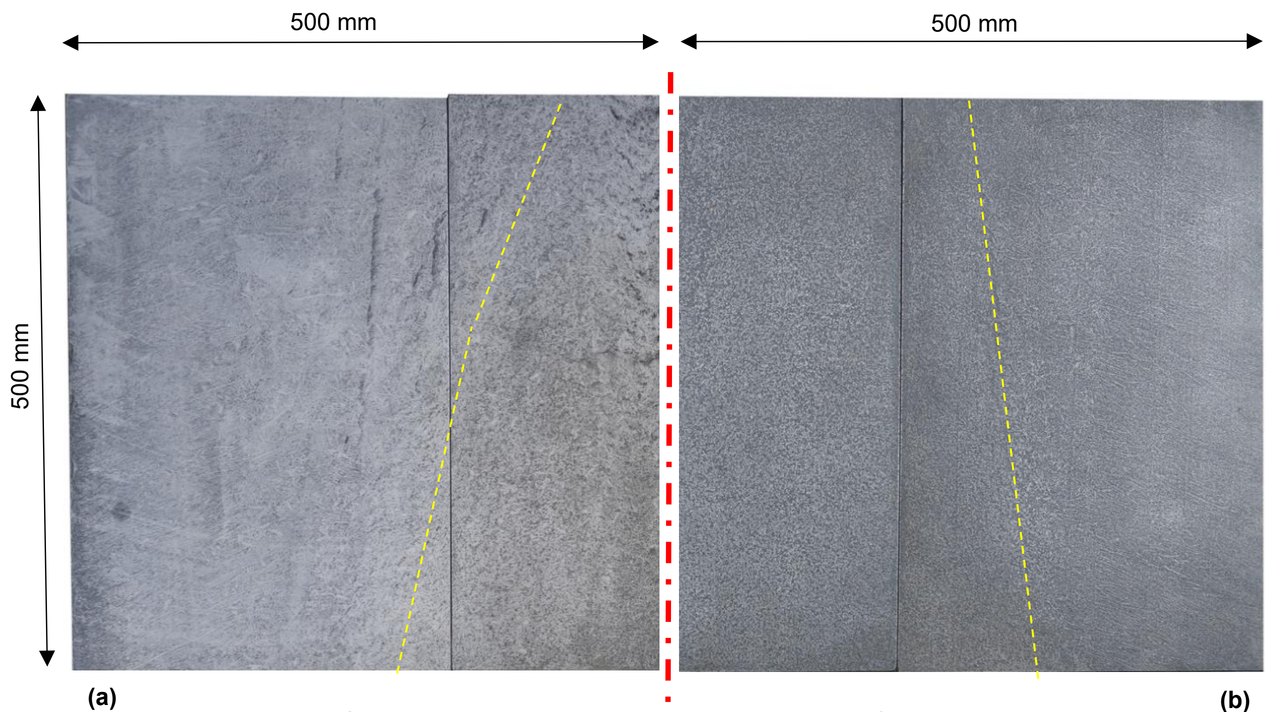

Fig. 5: Sample 2: Longitudinal section at 500 – 1000 mm from the ingot bottom:
(a) conventional (static) case, **(b)** RCM case

Similar differences are observed at 3000-3500 mm. While the conventional case is dominated by coarse columnar dendrites extending towards the ingot center, the RCM case exhibits a more homogeneous structure with refined columnar dendrites and an extended equiaxed region towards the center. The central soundness is substantially improved.

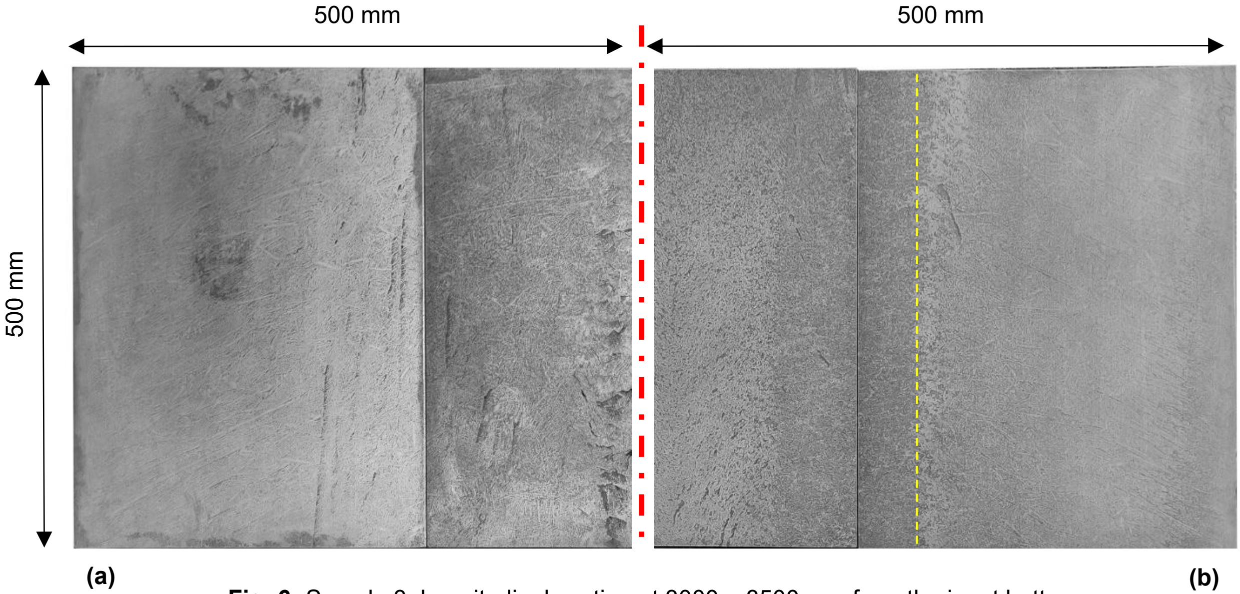

Fig. 6: Sample 3: Longitudinal section at 3000 – 3500 mm from the ingot bottom: **(a)** conventional (static) case, **(b)** RCM case

The numerical model reproduces the experimentally observed changes in the solidification structure with good agreement. The corresponding numerical validation is discussed in detail in [14].

Macrosegregation

To evaluate the influence of mold rotation on macrosegregation, chemical analyses were performed on samples systematically taken from the two longitudinal sections presented in **Fig. 5** and **6**. The measured carbon concentrations were used to determine the relative carbon segregation, expressed as $(c - c_0)/c_0$. **Fig. 7** compares the resulting experimental segregation maps for the conventional and RCM ingots using a consistent scale ranging from −0.2 to +0.2. The experimentally investigated regions are shown within the full ingot geometry, while the remaining areas are greyed out to indicate regions not included in the present experimental analysis.

At 500–1000 mm from the ingot bottom, the conventional case shows the upper part of the typical cone-shaped region of negative segregation, gradually narrowing towards the top of the investigated section. This distribution is consistent with the segregation-related features observed in the macroetched longitudinal section shown in **Fig. 5**. In particular, the beginning of the pronounced negative segregation approximately coincides with the transition from the columnar to the equiaxed region.

The RCM case exhibits a generally similar negative segregation pattern; however, the upper end of the cone is less clearly distinguishable. Instead, a pronounced band of negative segregation becomes visible at approximately half radius, which again corresponds to the transition between the columnar and equiaxed regions observed in the macroetched section, shown in **Fig. 5.**

At 3000–3500 mm, directly below the hot-topped region, the conventional ingot exhibits the characteristic region of positive segregation towards the center. This distribution is consistent with the segregation-related features observed in the macroetched longitudinal section shown in **Fig. 6**. In the RCM ingot, positive segregation in the central region is considerably more pronounced. In addition, a band of negative segregation at approximately half radius can again be observed, corresponding to the transition between the columnar and equiaxed regions in the macroetched section.

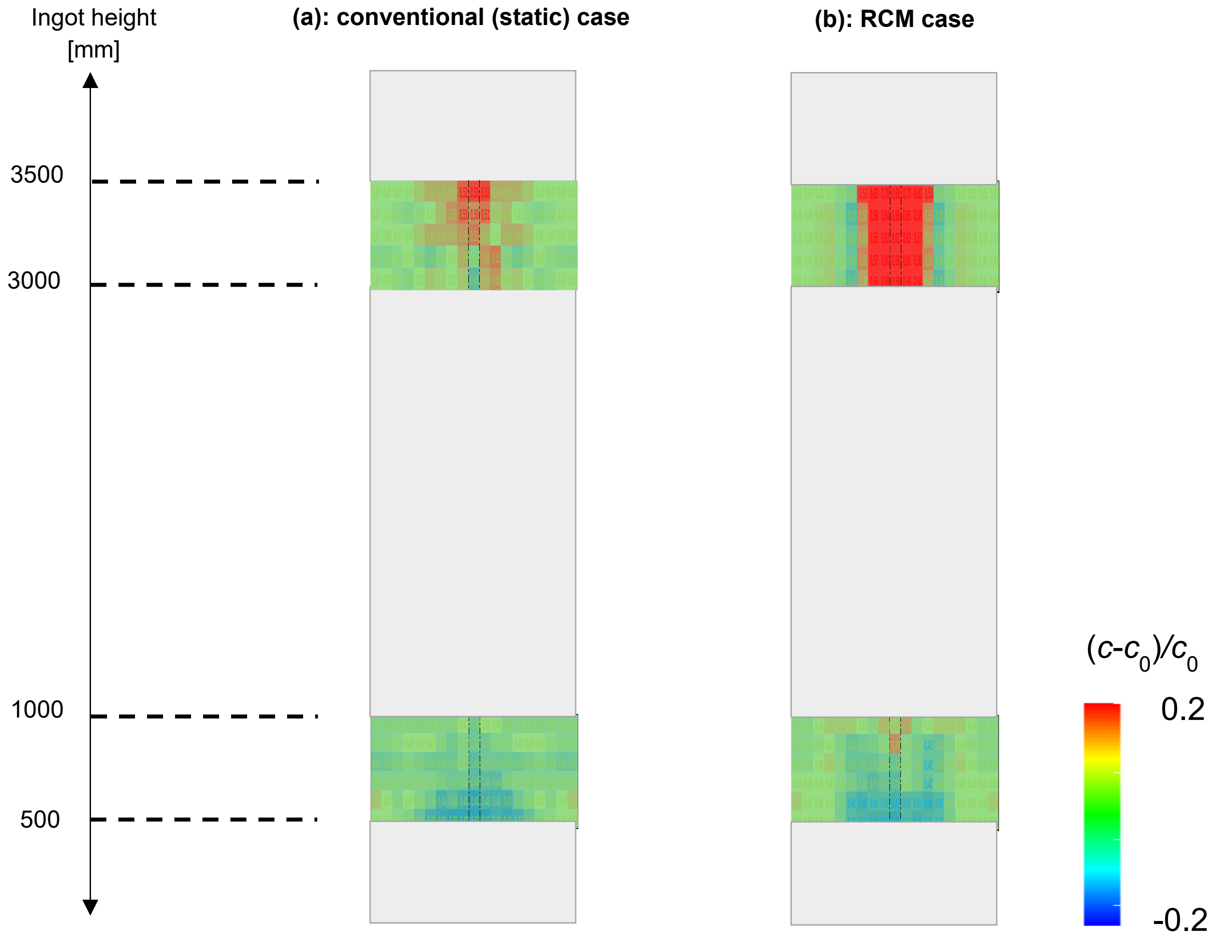

Fig. 7: Experimental relative carbon segregation, $(c - c_0)/c_0$: **(a)** conventional (static), **(b)** RCM case. The experimentally investigated longitudinal sections at 500–1000 mm and 3000–3500 mm are shown within the full ingot geometry; grey areas indicate regions not included in the present experimental analysis.

The corresponding numerical results are shown in **Fig. 8** for the entire ingot. The model reproduces the experimentally observed macrosegregation behavior with good, respectively very good agreement for the RCM case. Both the increased positive segregation towards the center and the negative segregation band observed experimentally are captured by the simulation. For the conventional ingot, the overall segregation behavior is also reproduced well, although local deviations, particularly in the central region, occur due to phenomena that are not fully captured by the present model. In particular, mini-ingotism and the formation of solidification bridges within the remaining liquid region are observed experimentally, but their local effects are not sufficiently resolved by the current mesh resolution. These phenomena locally modify the solute distribution and lead to porosity and enhanced segregation in the ingot center. Consequently, the simulated carbon map appears comparatively smooth in the central region and does not reproduce the local variations observed experimentally.

The experimental and numerical results demonstrate that the strong modification of the solidification conditions by RCM also has a pronounced influence on macrosegregation. The observed behavior is attributed to the rotation-induced flow, which promotes fragmentation and thereby enhances the transport of solid fragments and enriched melt ahead of the advancing solidification front towards the ingot center while suppressing the upward-directed natural convection. Consequently, the enriched melt becomes increasingly concentrated in the central region, resulting in the stronger positive segregation observed in the RCM ingot.

The rotation strategy applied in the present industrial trial was intentionally selected to generate a pronounced influence on melt flow and solidification. While this strategy resulted in the significant refinement of the solidification structure and improvement in central soundness, the macrosegregation results indicate that the applied rotation scheme exceeded the optimum with respect to macrosegregation.

(a): conventional (static) case

(b): RCM case

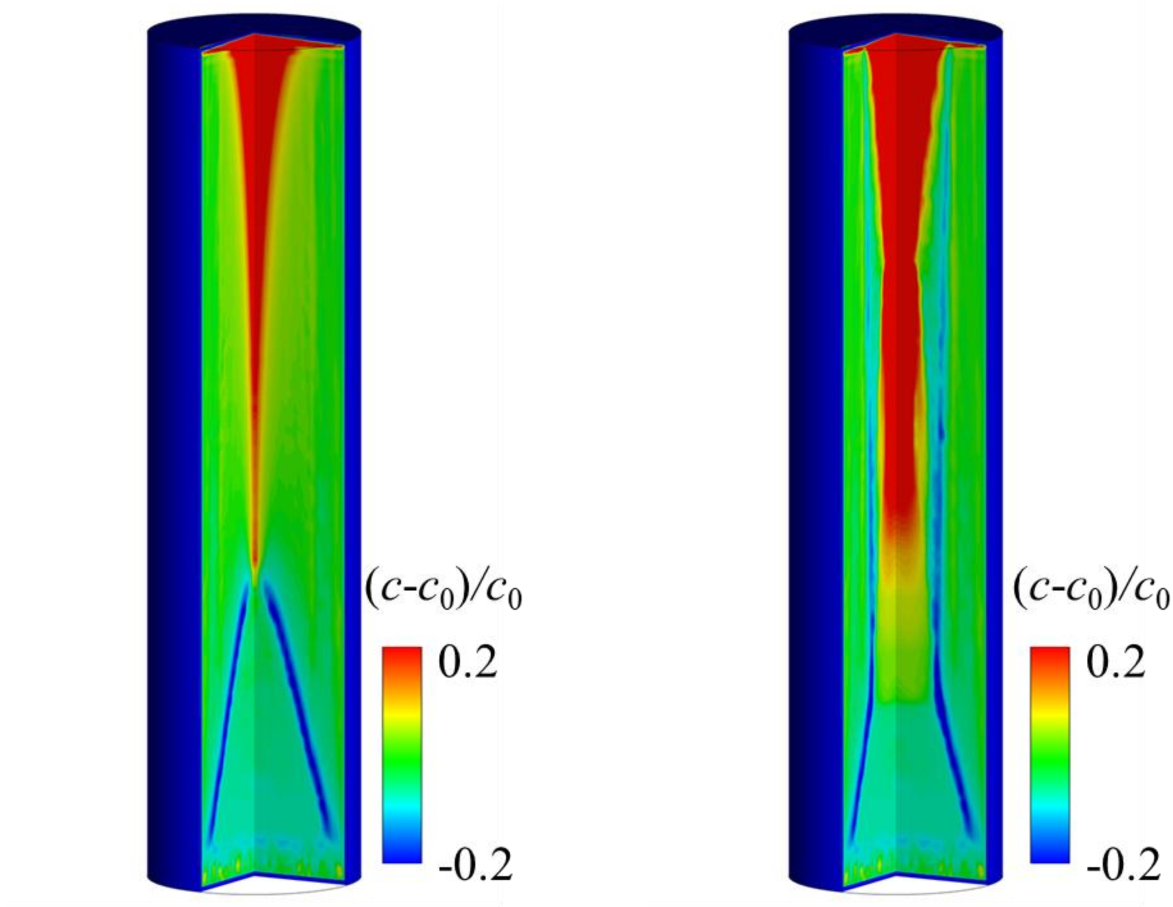

Fig. 8: Simulated relative carbon segregation, $(c - c_0)/c_0$: **(a)** conventional (static) case, **(b)** RCM case.

CONCLUSION

The industrial-scale trials demonstrate the strong potential of the RCM technology to actively influence the solidification of large steel ingots. Compared with conventional ingot casting, the applied rotation scheme resulted in a considerably finer and more homogeneous solidification structure, an extended equiaxed region and improved central soundness.

At the same time, macrosegregation analysis demonstrates that a strong rotational influence does not exclusively result in improved ingot quality. The applied rotation scheme led to increased positive segregation in the central region and the formation of pronounced negative segregation bands. These results indicate that maximizing the rotational influence on the melt is not necessarily beneficial with respect to the overall ingot quality.

The numerical model shows very good agreement with the experimental observations, particularly for the RCM case. In addition to reproducing the observed changes in the solidification structure, the model successfully captures the characteristic macrosegregation behavior resulting from the applied rotation scheme. This agreement provides a strong basis for using the model as a tool for further development of the RCM process. Future work will therefore focus on the optimization of the rotation scheme to identify an appropriate process window that provides sufficient forced convection to promote grain refinement and improve central soundness while simultaneously reducing macrosegregation. The combination of industrial-scale experiments and numerical modeling therefore enables the development of tailored rotation strategies that achieve an optimum balance between solidification structure, central soundness and macrosegregation.

REFERENCES

[1] M.C. Flemings, Our Understanding of Macrosegregation. Past and Present. ISIJ Int. 40 (2000), 9, pp. 833–841. doi:10.2355/isijinternational.40.833

[2] G. Lesoult, Macrosegregation in steel strands and ingots: Characterisation, formation and consequences. Materials Science and Engineering: A 413-414 (2005), pp. 19–29. doi:10.1016/j.msea.2005.08.203

[3] J.P. Gu and C. Beckermann, Simulation of convection and macrosegregation in a large steel ingot. Metall Mater Trans A 30 (1999), 5, pp. 1357–1366. doi:10.1007/s11661-999-0284-5

[4] M. Wu, L. Könözsy, A. Ludwig, W. Schützenhöfer and R. Tanzer, On the Formation of Macrosegregations in Steel Ingot Castings. steel research international 79 (2008), 8, pp. 637–644. doi:10.1002/srin.200806177

[5] J. Li, X. Xu, N. Ren, M. Xia and J. Li, A review on prediction of casting defects in steel ingots: from macrosegregation to multi-defect model. J. Iron Steel Res. Int. 29 (2022), 12, pp. 1901–1914. doi:10.1007/s42243-022-00848-7

[6] Z. Zhang, M. Wu, H. Zhang, S. Hahn, F. Wimmer, A. Ludwig and A. Kharicha, Solidification Principle in Large Vertical Steel Casting Under the EMS Effect. Metall Mater Trans B 54 (2023), 4, pp. 1870–1885. doi:10.1007/s11663-023-02801-9

[7] M.J. Stewart, L.C. MacAulay and F. Weinberg, Macrosegregation in castings rotated and oscillated during solidification. Metall Trans 2 (1971), 1, pp. 169–173. doi:10.1007/BF02662653

[8] Yu Q and Y. Zhou, Influence of mould rotation on macrosegregation in ingot. Acta Metallurgica Sinica (1988)

[9] A. Ohno, Solidification: The separation theory and its pract. applications. Berlin, Heidelberg, New York, London, Paris, Tokyo (1988), Springer.

[10] T. Holzgruber, H. Holzgruber, A. Scheriau and S. Baf, Influence of the rotation parameters on the solidification conditions during mechanical stirring. LMPC Proceedings 2024

[11] M. Wu and A. Ludwig, A three-phase model for mixed columnar-equiaxed solidification. Metall Mater Trans A 37 (2006), 5, pp. 1613–1631. doi:10.1007/s11661-006-0104-0

[12] M. Wu, A. Ludwig and A. Kharicha, Volume-Averaged Modeling of Multiphase Flow Phenomena during Alloy Solidification. Metals 9 (2019), 2, pp. 229. doi:10.3390/met9020229

[13] J.M. López, F. Marques and M. Avila, The Boussinesq approximation in rapidly rotating flows. J. Fluid Mech. 737 (2013), pp. 56–77. doi:10.1017/jfm.2013.558

[14] T. Holzgruber, C. Rodrigues, M. Wu, H. Holzgruber, A. Scheriau and C. Bernhard, Industrial-Scale Rotating Casting Mold: Experiments and Model Validation for As-Cast 21-Ton Steel Ingots. LMPC Proceedings 2026, in press