

CH02 - An Experimental and CFD Based Synergic Approach to Improve Productivity and Quality of Continuous Cast Aluminum Wire Rod

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Abstract

Continuous casting and rolling (CCR) is the most preferred route to manufacture the electrical conductor grade aluminium wire rod throughout the globe. Due to very high production speed and continuous nature of the CCR process, various quality issues like mechanical property variations and cast bar cracking are the major challenge for achieving a high productivity rate with stringent quality requirements. The main areas of improvement to address these quality issues are proper solidification of the cast bar and sufficient flow of liquid metal through tundish into the caster. The focus of present study is to resolve the wire rod UTS (Ultimate Tensile Strength) variation and cast bar cracking issues of Properzi™ wire rod mill at Hindalco Industries Ltd., and further improving productivity. While analyzing process data of Properzi™ mill, it was a mystery to understand variation in UTS properties after caster, while process parameters were quite stable before caster. During our investigation, we found that the unstable airgap formation between cast bar and mold surface during solidification is identified as the root cause for UTS variation of the wire rod and cast bar cracks. The cooling pattern optimization to achieve stable airgap during solidification of cast bar is successfully conducted at plant with systematic DOE (Design of Experiments) approach, and the optimal casting recipe at an increased casting speed is developed. The implementation resulted in reduction of UTS variation to approximately half, while cast bar crack instances were limited to assignable causes only. Later, to further improve the flow behavior of the liquid metal through tundish, the understanding was developed by developing a CFD (Computational Fluid Dynamics) model. The model is calibrated using the melt level fluctuation data at plant. The simulation results are used to understand the areas of recirculation, back flow and high turbulence regions. Also, the CFD model is used to compare various possible design modifications to improve the liquid metal flow through tundish.

Keywords: Electrical conductor (EC) grade wire rod, Aluminium continuous casting and rolling (CCR), Ultimate tensile strength (UTS) variation, Cast bar cracks, Computational fluid dynamics (CFD) modelling.

1. Introduction

Continuous casting is gaining popularity in the production of aluminium, copper, and steel billets, bars, and slabs due to its advantages of high productivity, excellent quality, and cost-effectiveness. The continuous casting and rolling (CCR) process, characterized by its continuous and rapid

nature, requires careful control of various parameters to ensure the desired quality of the wire rod. There are several configurations available for the Continuous Casting and Rolling (CCR) setup, which involve pouring liquid metal from a furnace into a circular mold with a trapezoidal or rectangular shape. To facilitate the solidification of the cast bar, water jets are used to cool the mold from all four sides. The cooling water for the caster is divided into multiple zones, each with a separate pressure control system. A bar cooler is employed to further adjust the temperature of the solidified cast bar to the desired level to produce varying ultimate tensile strength (UTS) wire rod as required by customer. Once the solidified cast bar reaches the desired temperature, it passes through multiple stands of rough and finish rolling mill to produce a wire rod of desired diameter. The rolled wire rod is then coiled and sent for wire drawing, where it is further processed.

Figure 1 illustrated a basic schematic of the CCR process with a circular configuration. Researchers have primarily focused on studying the flow behavior of the liquid metal as it moves from the tundish into the mold, as well as the heat transfer that occurs during the solidification process. These aspects are crucial as they significantly influence the quality of the solidified cast bar and the resulting wire rods.

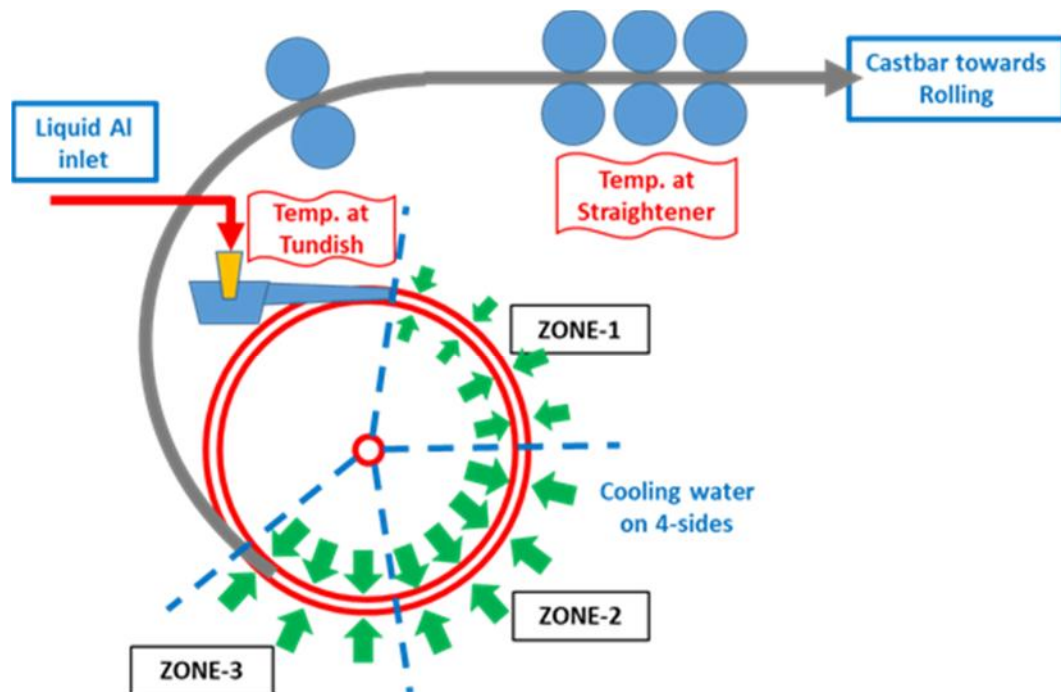


Figure 1. Schematic of CCR with circular configuration.

Researchers have extensively studied the transportation and solidification processes of the liquid metal pool in the continuous casting mold [1-3]. In order to simulate flow behavior, predict inclusion trajectories, inclusion removal fraction, free surface waves, and other relevant phenomena, researchers have employed various methods such as Volume of Fluid (VOF), Eulerian-Eulerian, and Lagrangian approaches [4]. A. Braun et al. compared the flow field obtained from a water model using Particle Image Velocimetry (PIV) in a steady-state condition with values predicted by a developed Computational Fluid Dynamics (CFD) model [5]. R Chaudhary et al. investigated the effect of stopper rod misalignment on nozzle and mold flow velocities using both a water model and a CFD model of continuous casting [6]. Z. He et al. demonstrated that incorporating a turbulence inhibitor in the tundish results in reduced metal velocity towards the tundish floor and lower turbulence kinetic energy on the melt's top surface compared to other designs [7]. Chouharia et al. focused on the impact of rolling energy inputs and

other process parameters on the physical properties of the wire rod [8]. Mohapatra et al. developed a two-dimensional transient thermal model to predict the temperature distribution in the cast bar and studied the effects of different operating conditions [9]. Grandfield et al. investigated the formation of air gaps, temperature distribution, and stress fields resulting from casting temperature and rotation speed variations using a three-dimensional thermo-mechanical model based on the finite element method (FEM) [10]. Berg & Fredriksson [11] proposed an experimental method to measure the heat transfer coefficient for pure copper wire casting in the Southwire process. Lindholm et al. [12] measured temperature on a rotating wheel and determined appropriate boundary conditions. Liu et al. [13] presented temperature profiles of the belt and wheel for dendritic arm spacing but did not measure the bar temperature. Ju et al. [14] studied the temperature profile of non-ferrous metal wire rods during continuous casting with a stationary mold. Shi and Guo [15] simulated casting geometry and processing parameters to investigate the solidification pattern of the wire rod. B. G. Thomas has contributed significantly to the field through numerous publications on continuous and DC casting of aluminum and steels, exploring the effect of surface temperature and changing nozzle orientation on heat transfer [1,16].

Although numerous experimental and modeling studies have been conducted individually, there is a lack of literature on a synergistic approach that combines experimental and modeling methods to address the issue of mechanical property variation and improve wire rod quality by achieving optimal cast bar solidification. This work aims to develop a CFD model to understand the flow behavior of the liquid metal through the tundish into the mold and evaluate potential design changes in the current setup present. Additionally, to achieve the sound cast bar solidification, an experimental approach has been presented to develop an optimal cooling water recipe for quality improvement while increasing productivity.

2. Technical Approach

Achieving optimal solidification of the cast bar relies on two crucial factors: ensuring proper liquid metal flow into the mold to compensate for solidification shrinkage and effective heat extraction through cooling water. The insufficient metal flow can result into shrinkage defects and pipe voids at the centre of cast bar as illustrated in Figure 2 (a). However, the examination of the flow of liquid metal through the lower tundish into the caster mold cannot be easily conducted through experimental means alone. As a result, a Computational Fluid Dynamics (CFD) model was developed to simulate the flow of the melt and gain insights into its behavior, identify regions of turbulence, and assess the presence of potential dead zones. This CFD model provides a valuable tool for studying and understanding the intricate flow dynamics of the liquid metal during the casting process, which would otherwise be challenging to observe experimentally. The development of the tundish Computational Fluid Dynamics (CFD) model involved four main steps. The first step consisted of an in-depth literature study of the flow behavior of the liquid melt, the selection of the most appropriate turbulence model to accurately represent the plant scenario. Additionally, dimensions and process data were collected from the plant to be used for model development. The Model development encompassed tasks such as geometry preparation, meshing, and setting up the physical case to accurately capture the flow behavior of the liquid melt, including near-wall flow. Once the model was prepared, the calibration and validation of the model was conducted using melt level fluctuations values at a particular casting speed. This step aimed to ensure that the model accurately represented the actual flow behavior within the tundish by comparing the model predictions with real-world plant data. The validated CFD model was then used to study the impact of various possible design changes of the tundish like increased bucket width, tapered walls, and the addition of a bottom hump on liquid metal flow behavior through tundish.

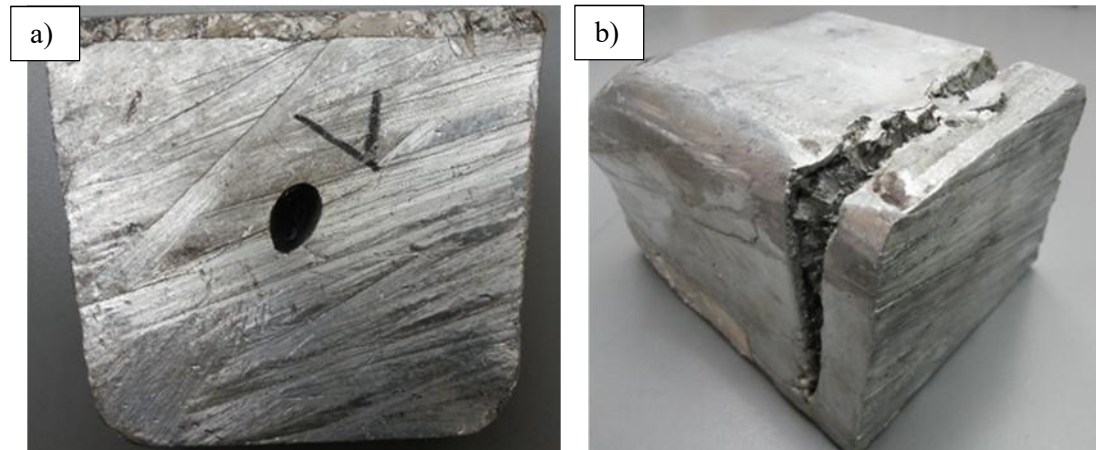


Figure 2. a) Central void due to insufficient melt flow, b) Cast bar crack due to improper heat transfer during solidification.

Improper heat transfer during cast bar solidification can lead to mechanical property variation and cast bar cracks as illustrated in Figure 2 (b). To achieve effective cooling to produce sound cast bar, the optimal cooling water recipe at different casting speeds were developed using an experimental approach. The optimization process involved a systematic and comprehensive Design of Experiment (DOE) to determine the ideal cooling water pattern as the casting speed increased progressively. During each trial, process data was collected and analysed to identify the optimal cooling water setting. The analysis focused on meeting the specific quality requirements for both the cast bar and wire rod. Samples of the cast bar and wire rod were obtained from each trial and subjected to microstructural characterization and mechanical testing to ensure that the quality requirements were met. This step served as validation for the effectiveness of the identified optimum cooling water setting. To further confirm the results, the DOE findings were implemented at the plant for an extended duration. This step aimed to verify the reproducibility and reliability of the results in an operational environment. Subsequently, the operational window for the remaining process parameters was estimated, enabling the design of a complete recipe that encompassed all the necessary process settings to achieve the desired quality and productivity goals. The impact of the implemented recipe was assessed through a within-coil variation test, wherein tensile samples were periodically tested within a coil at approximately 30 m intervals. This test evaluated the range of Ultimate Tensile Strength (UTS) variation within the coil, providing insights into the effectiveness of the optimal cooling recipe. By following the aforementioned methodology, the optimal cooling water recipe was developed and implemented for increasing casting speeds. The impact on wire rod quality was quantified, ensuring a comprehensive understanding of the improvements achieved.

3. CFD Model Development for Melt Flow Behavior Analysis

A VOF (Volume of Fluid) multiphase model was developed in ANSYS-Fluent™ to simulate the flow of two Eulerian phases, namely liquid aluminum and air, in an open channel setup to represent the actual plant conditions of liquid metal flow in the lower tundish. The outer geometry of the lower tundish was provided by the Original Equipment Manufacturer (OEM). However, over time, manual preparation of the tundish has caused alterations to the internal volume that holds the liquid metal. To address this, manual measurements were conducted at the plant to obtain the precise internal dimensions of the tundish. Figure 3 displays an image of the actual tundish and the tundish-spout geometry prepared for the model.

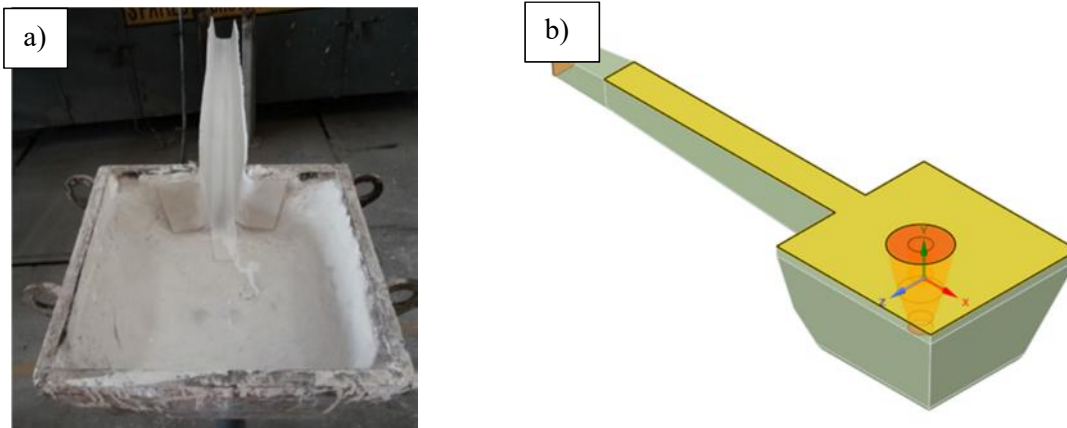


Figure 3. Geometry of lower tundish a) actual figure b) model geometry.

To compare mesh quality and the total number of elements, both tetrahedral and polyhedral meshing techniques were employed. Figure 4 illustrates the tetrahedral and polyhedral meshes generated for the tundish geometry. Upon evaluation, it was observed that the polyhedral mesh generated using the Fluent meshing module exhibited a minimum orthogonal quality of 0.5. Additionally, the polyhedral mesh required only 0.16 million as compared to 0.26 million in case of tetrahedral elements. Considering the better mesh quality and reduced computational time offered by the polyhedral mesh, it was selected for use in the final model. This choice ensures improved simulation accuracy and computational efficiency during the analysis of the tundish system.

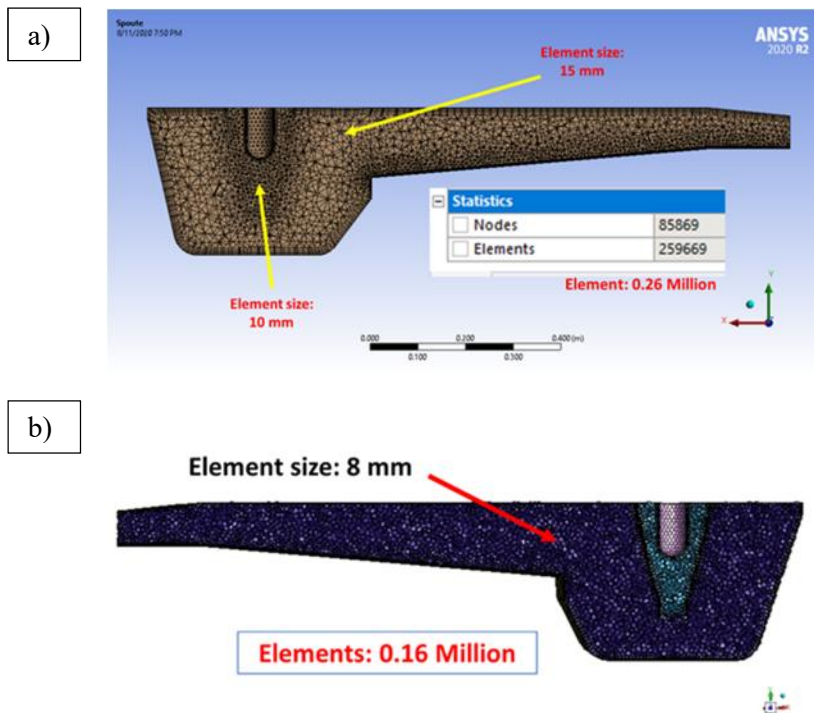


Figure 4. Meshed tundish geometry with a) tetrahedral mesh b) polyhedral mesh.

3.1 Governing Equations

ANSYS-Fluent™ employs the solution of conservation equations for mass and momentum as the foundation for solving various flow problems. In cases where heat transfer or compressibility is

involved, an additional equation for energy conservation is solved. If the flow involves species mixing or reactions, a species conservation equation is solved, or alternatively, if the non-premixed combustion model is utilized, conservation equations for the mixture fraction and its variance are solved. Furthermore, when the flow is turbulent, additional transport equations are also solved to account for turbulent effects. These comprehensive solution approaches ensure accurate and robust simulations of a wide range of flow phenomena within the ANSYS-Fluent™ software. The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad (1)$$

Equation 1 represents the general form of the mass conservation equation, which is applicable to both incompressible and compressible flows. The source term S_m accounts for the mass added to the continuous phase from the dispersed second phase, such as the vaporization of liquid droplets, and any additional user-defined sources. Conservation of momentum in an inertial reference frame, where there is no acceleration, is described by the equation [18].

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (2)$$

where:

- ρ Density
- v Velocity
- p Static pressure,
- $(\bar{\tau})$ Stress tensor,
- $\rho \vec{g}$ Gravitational body force,
- \vec{F} External body forces that may arise from interaction with the dispersed phase. \vec{F} also encompasses other model-dependent source terms, including porous-media effects and user-defined sources.

The stress tensor, $(\bar{\tau})$ is described by the following expression:

$$\bar{\tau} = \mu [(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I] \quad (3)$$

where:

- μ Molecular viscosity,
- I Unit tensor.

The second term on the right-hand side captures the effect of volume dilation.

The k- ω SST (Shear Stress Transport) model was employed to account for turbulence in the flow of liquid metal through the tundish. This model incorporates all the refinements of the baseline (BSL) k- ω model and includes the transport of turbulence shear stress in the definition of turbulent viscosity. The original k- ω model was proposed by Wilcox [19] and incorporated modifications to account for effects such as low Reynolds number, compressibility, and shear flow spreading. However, the 1998 Wilcox model had a weakness in that its solutions were sensitive to values for k and ω outside the shear layer, which could significantly affect the results, particularly in free shear flows. To address this, the standard k- ω model was further improved by introducing empirical production terms in the turbulence kinetic energy (k) and specific dissipation rate (ω) equations. This enhanced the accuracy of the model in predicting free shear flows over time. The SST k- ω model, developed by Menter [20], offers additional refinements and is considered more accurate and reliable for a broader range of flows. It exhibits improved performance in various scenarios, including adverse pressure gradient flows, air foils, and transonic shock waves. These

advancements make the SST $k-\omega$ model preferable due to its enhanced accuracy and applicability across different flow conditions.

3.2 Physics and Boundary Conditions

An implicit formulation was utilized, incorporating implicit body forces and interfacial anti-diffusion. The volume fraction cut-off was set at $1e-08$ to accurately capture the interface between the two phases. Additionally, a constant surface tension force of 0.87 N/m and wall adhesion were considered in the model to account for the behavior of the liquid melt.

To simulate the turbulent viscosity of the liquid melt, the $k-\omega$ SST (Shear Stress Transport) turbulence model was applied. This model provides an improved representation of the turbulent behavior and accurately predicts the behavior of the liquid melt. To define the boundary conditions in the model, four conditions were specified to replicate the actual plant setup. The spout inlet boundary condition was set as a mass flow rate dependent on the casting speed. The tundish nose outlet was defined as a pressure outlet with open channel flow to capture the height of the melt inside the tundish. The spout walls were assigned a wall boundary condition to allow fluid flow through the bottom opening of the spout. Lastly, a pressure outlet boundary condition was applied to the top free surface of the tundish to capture the interaction between the liquid melt and atmospheric air. The details of all the boundary conditions can be observed in Figure 5.

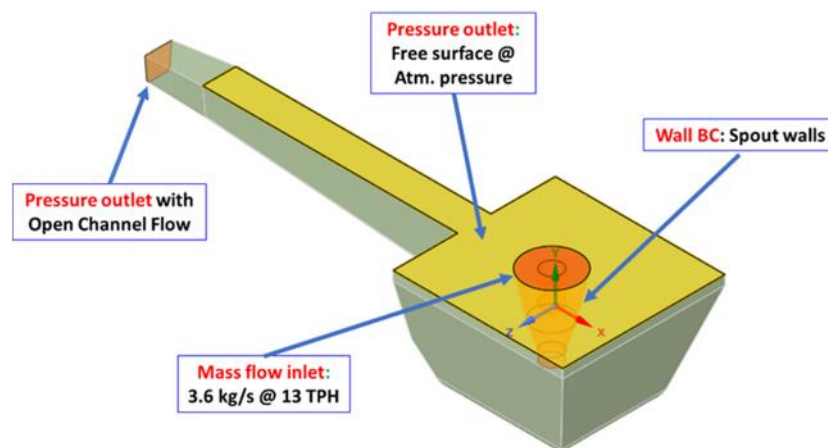


Figure 5. Boundary conditions for CFD model for lower tundish and spout.

To simplify the simulation process and reduce computational time, the liquid aluminum phase was initially filled in the spout and tundish up to the outlet height at the start of the simulation. This was achieved by patching these regions with liquid aluminum. To facilitate this liquid patching, a new region was defined using mesh registration, extending up to the height of the actual liquid metal in the tundish. A PISO (Pressure Implicit with Splitting of Operators) scheme was implemented for pressure-velocity coupling, ensuring accurate calculations without introducing any skewness or neighbor corrections.

For spatial discretization, several methods were employed. A Green Gauss node-based gradient was used for spatially differentiating variables. The body force weighted pressure and compressive volume fraction schemes were applied to accurately calculate pressure and volume fraction, respectively. To handle momentum, turbulent kinetic energy, and specific dissipation rate, a first-order upwind method was utilized. These discretization schemes and methods were selected to balance accuracy and computational efficiency, ensuring reliable simulations while minimizing the computational time required for the analysis.

3.3 Model Validation

At the plant, the only flow-related parameter that could be measured directly was the melt level fluctuation. Due to the high temperature of the liquid melt, it was not possible to measure velocity profiles inside the tundish inlet or outlet. As a result, the developed model was validated by comparing the actual melt level fluctuation data, obtained from plant measurements, with the predicted fluctuation amplitude from the model for a constant casting speed.

The results of the validation showed excellent agreement between the predicted melt level fluctuation value from the model and the actual melt level fluctuation data captured at the plant. The predicted fluctuation amplitude was 6.1 mm, while the measured plant data recorded a value of 5.5 mm. This close correspondence between the model prediction and the plant data, as depicted in Figure 6 demonstrates the accuracy and reliability of the developed model in capturing the melt level fluctuation behavior in the tundish.

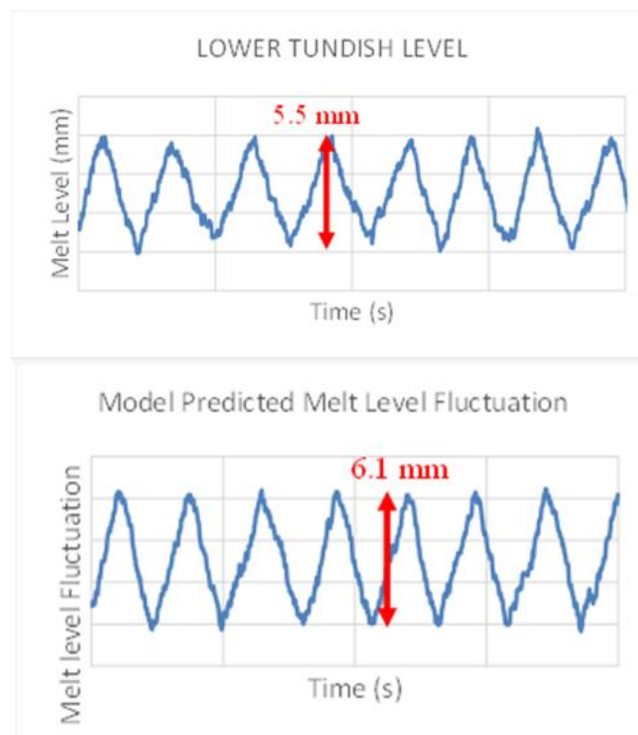


Figure 6. Melt level fluctuation with time a) Actual plant data b) Model predicted data.

4. Process Optimization and Recipe Development for Effective Heat Transfer

Achieving optimal cooling is crucial for ensuring uniform solidification of the cast bar. Inadequate cooling, below the optimal level, can lead to the formation of liquation pockets within the cast bar. This, in turn, may cause deformations or shrinkage of the cast bar, making it difficult to separate from the mold and potentially leading to cracks. On the other hand, excessive cooling beyond the optimal level can result in sudden shrinkage of the metal shell, leading to the formation of air gaps. Once unstable air gap formation occurs, inconsistent cooling will cause severe cracks in the cast bar due to the rapid formation of thermal gradients. Therefore, maintaining the optimal cooling level is essential to avoid issues such as liquation pockets, cast bar deformation, shrinkage, difficulties in mold separation, and cracks caused by sudden thermal gradients. Proper control and monitoring of the cooling process are necessary to ensure the quality and integrity of the cast bar during solidification.

4.1 Air-Gap Formation

Cooling in the continuous casting process is achieved by employing water sprays and nozzles directed at three sides of the wheel and the belt. As the cast bar undergoes solidification, it undergoes shrinkage, resulting in the formation of a non-uniform air gap between the bar and the wheel/belt interface. This air gap reduces the efficiency of heat extraction during solidification. Typically, air gap formation occurs rapidly upon contact between the molten metal and the mold or belt, as heat is rapidly conducted. It primarily arises from the contraction of the thin solid metal shell away from the wheel mold walls and/or the belt, which could be due to combination of solidification shrinkage and shell bending driven by thermal stresses. So, when air gap formation is developed due to rapid cooling at start, it drastically reduces heat transfer to wheel-belt from solid shell. Then, solidified shell starts reheating due internal molten metal heat, which softens and reduces shell strength, which is eventually pushed again back on wheel-belt. After touching wheel-belt, it will again have rapid cooling and air gap formation, and hence the cooling-heating cycle will continue to repeat causing cycling variation in cast bar temperature. In wheel-belt continuous casting processes, several factors can exacerbate air gap formation. These include the expansion or distortion of the wheel mold due to temperature gradients during the initial stages of bar solidification, as well as belt buckling, and "cold framing" caused by cyclic thermal conditions and temperature gradients along the belt during the solidification process [17]. Unstable air gap formation has detrimental effects on heat transfer rates and, consequently, impacts the quality of the cast bar and fluctuations in the mechanical properties of the wire rod. The presence of an unstable air gap leads to inconsistent and reduced heat transfer at the interfaces between the bar and the wheel or belt, resulting in irregularities such as sine waves and kinks on the cast bar's surface. Moreover, the reduction in heat transfer can contribute to the formation of liquation and surface cracking on the bar as presented in Figure 7.

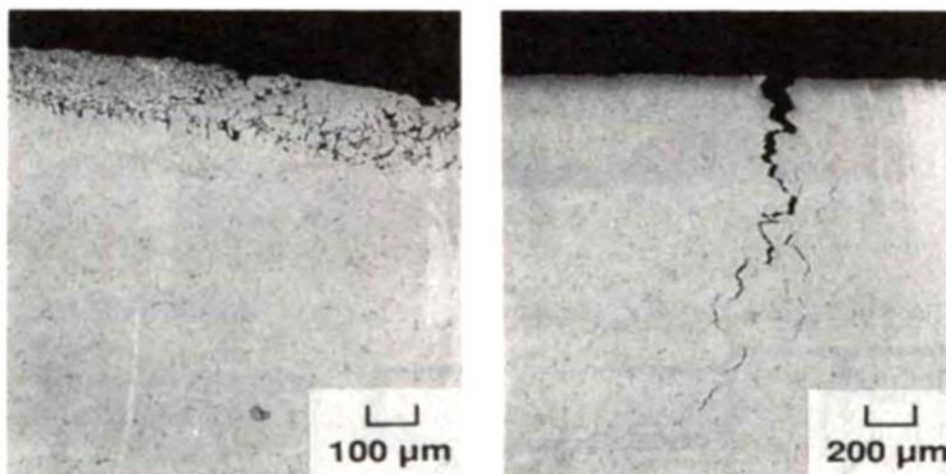


Figure 7. Liquation and cracking defects caused by air gap formation [17].

4.2 Design of Experiments (DOE) for Cooling Water Optimization

Two crucial parameters for ensuring proper heat extraction during solidification are the nozzle opening and cooling water pressures. In the continuous casting process, the circular caster is divided into three zones (1-3), each with separate water feeding systems and pressure control, as depicted in Figure 8 (a). To facilitate the formation of a uniform and stable shell (thin film) at the beginning of solidification, a gradually increasing water flow pattern known as "tapering" is employed by controlling the nozzle openings in zone 1. To achieve an optimal cooling pattern, a systematic Design of Experiment (DOE) was developed, consisting of different combinations of water pressures at various zones and sides. The selection of water pressures was based on feasible

levels at the plant that would not lead to line stoppage. For the internal pressure in zone 1, four levels were chosen as it exhibited the highest sensitivity during the optimization activities conducted by the plant team.

A full factorial design was employed to prepare the DOE, considering the nozzle opening and zone-1 water pressures. Once all possible permutations were obtained, constraints were imposed to ensure that the lateral side had lower cooling than the internal side (Lateral Z1 cooling < Internal Z1 cooling). Permutations that violated these constraints were eliminated from the DOE. These trials were successfully conducted at the plant, and process data was collected at 1-second intervals corresponding to each trial. A direct correlation was discovered between the temperature fluctuations of the cast bar and the variations in ultimate tensile strength (UTS), primarily due to strain hardening during the rolling process, which serves as the primary method of strengthening for EC (Electrical Conductor) grade wire rods. Therefore, a decrease in the cast bar temperature at the straightener stage was deemed indicative of a reduction in UTS variation. The variation in cast bar temperature was compared, and the optimum water pressure setting (Trial 3a) was identified. This setting resulted in the lowest variation in cast bar temperature with no cast bar crack instances, as illustrated in Figure 8 (b).

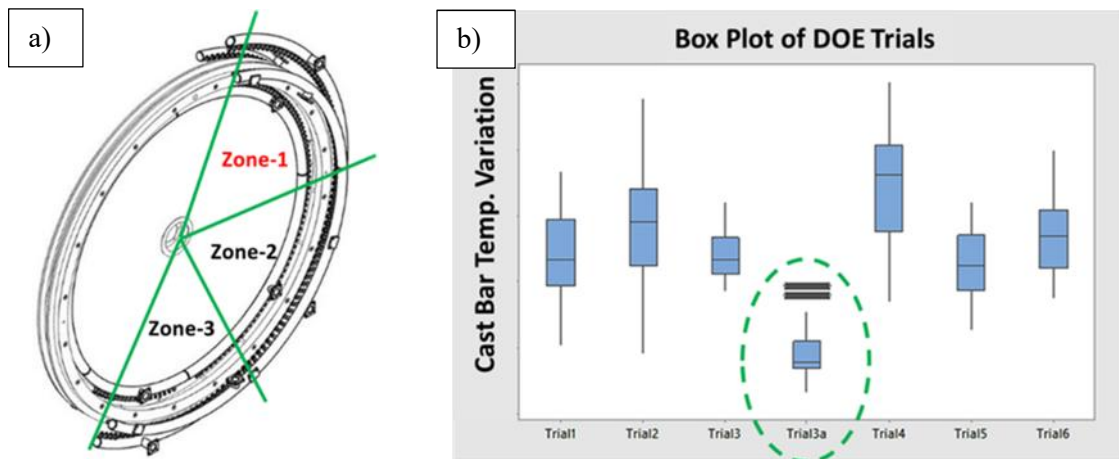


Figure 8. a) Various zones of cooling nozzles in circular caster, b) Boxplot showing the cast bar temperature variations for different DOE trials.

4.3 Confirmation Trials and Result Repeatability

After observing the lowest cast bar temperature variation during the DOE trials, it was necessary to conduct confirmation trials at the plant with the same water recipe sustained for a longer duration. These trials aimed to validate the results and estimate feasible operational windows for various process parameters. The corresponding Supervisory Control and Data Acquisition (SCADA) data was collected and analysed. The analysis revealed that the minimum variation range in cast bar temperature at the straightener was reproducible when the same water recipe was used with no cast bar crack instances. However, it also unveiled interesting findings regarding the optimal window for the lower tundish temperature, which is critical for minimizing cast bar temperature variation.

As depicted in Figure 9, it became evident that maintaining the lower tundish (caster inlet) temperature within a specific range resulted in the minimum cast bar temperature variation. Conversely, operating the tundish outside this optimal window led to an increased cast bar temperature variation (with a lag corresponding to the time needed to reach the material from caster to straightener), as observed at the beginning of the plot in Figure 3. Furthermore, an

analysis was conducted on a week's worth of data at the same water setting and casting speed. The results conclusively indicated that the most effective reduction in cast bar temperature variation occurs when the lower tundish temperature is maintained within the specified range. It was also observed that any variation in the lower tundish temperature directly impacted the variation in cast bar temperature. Therefore, it is crucial to maintain a stable temperature in the lower tundish to ensure consistent casting performance and minimize temperature variations in the cast bar.

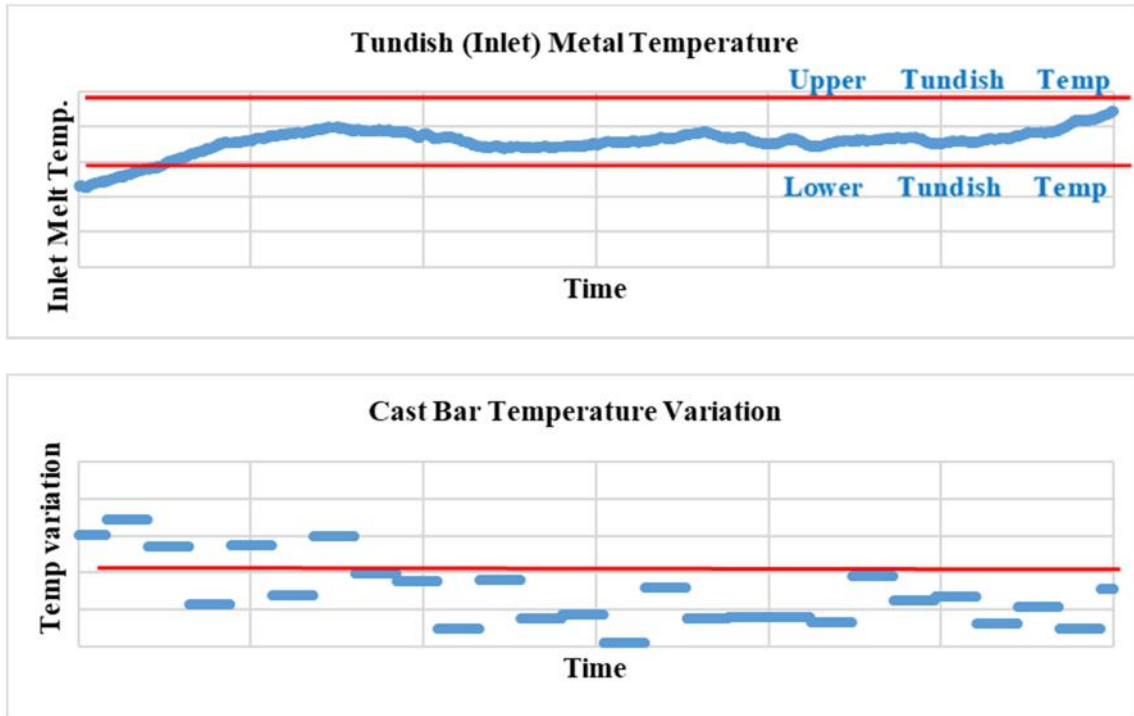


Figure 9. Cast bar temperature variation corresponding to lower tundish temperature variation.

In addition to measuring the lower tundish temperature, the mold temperature was also monitored multiple times during the trial. As the optimal water pressure, mill speed, and lower tundish temperature settings were implemented, an optimal range for the mold temperature was specified. This ensured that all essential parameters were controlled within the optimal ranges for effective casting. Furthermore, apart from optimizing the cooling water, lower tundish temperature, and mold temperature, various other process variations were also taken into consideration to achieve the best results. These included optimizing factors such as mold lubrication, melt chemistry, belt temperature, grain refiner addition, mold maintenance frequency, and more. By fine-tuning and optimizing these additional parameters, the overall casting process was further improved, leading to enhanced quality and productivity. By implementing the optimal ranges for cooling water, tundish temperature, mold temperature, and optimizing other process variations, a comprehensive approach was taken to ensure the best possible results in terms of cast bar quality, reduced variations, and overall process efficiency.

4.4 Quantification of UTS Variation Reduction with Recommended Settings

To assess the impact of reducing cast bar temperature variation on the Ultimate Tensile Strength (UTS) variation, a within-coil test was conducted at the plant. A baby coil weighing approximately 1400 kg was produced for this purpose. From the coil, 100 tensile test samples were cut at intervals of approximately 30 m, with each sample being approximately 1.5 m in

length. Additionally, 100 spare samples were collected at intervals of 15 m between consecutive samples to allow for retesting, if necessary. The collected samples were straightened, and tensile tests were performed using a gauge length of 250 mm. Similarly, for comparison, 100 samples were cut at approximately 30 m intervals from an older coil in which the optimal recipe was not implemented. Tensile tests were conducted on these samples as well. The UTS variation for both the coil produced after implementing the optimal recipe and the coil without the optimal recipe was analyzed and compared to quantify the reduction in UTS variation.

5. Results and Discussions

To analyze the behavior of liquid metal flow from the tundish into the caster mold, a VOF (Volume of Fluid) multiphase model was developed using ANSYS-Fluent™. The accuracy of the model was verified by comparing the predicted fluctuations in melt level with the measured values obtained at the plant. Once validated, the model was employed to predict velocity profiles, turbulent viscosity, and liquid level fluctuations at various casting speeds and tundish designs. Post-processing techniques were applied to investigate the flow behavior at different horizontal and vertical planes of interest. Velocity vectors and turbulent viscosity profiles served as the primary tools for post-processing, enabling a comparison of flow behavior under different process and design conditions. Figure 10 illustrates the comparison of velocity vectors and turbulent viscosities for the base tundish designs with bottom hump at casting speeds of 13 and 14 TPH (tonne/hour). At both casting speeds, vertical recirculation within the tundish and minor backflow at the tundish tip were observed. Although the fluid flow pattern and the location of fluid recirculation were consistent across both casting speeds, an increase in turbulence was noted as the casting speed was raised. However, in both the cases a small back flow was observed near the entry to the tip of the tundish nose which can be attributed to the top ceramic paper.

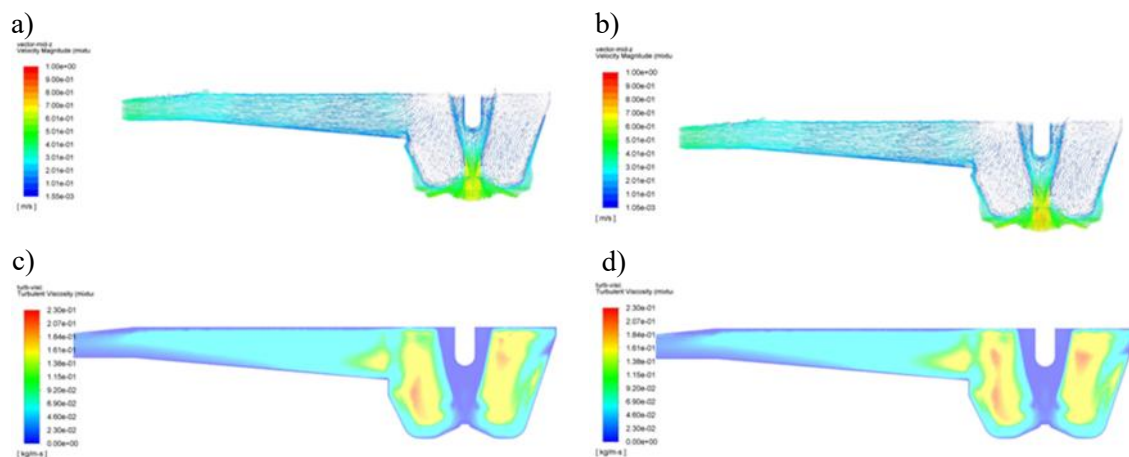


Figure 10. Comparison of velocity vector and turbulent viscosity on vertical mid-plane at 13 TPH (a, c) and 14 TPH (b, d) respectively.

5.1 Possible Modification in Tundish Design

In order to enhance the flow profile, the validated model was utilized to investigate the viability of incorporating design alterations in the lower tundish. After considering the available space for implementing a modified tundish at the plant, three design modifications were selected in collaboration with the plant team. These modifications included the addition of a bottom hump, an increased bucket width, and wall tapering. For each modification, a revised geometry was created, and simulations were conducted to analyze the flow patterns and turbulence. Figure 11 illustrates the potential design changes in the lower tundish.

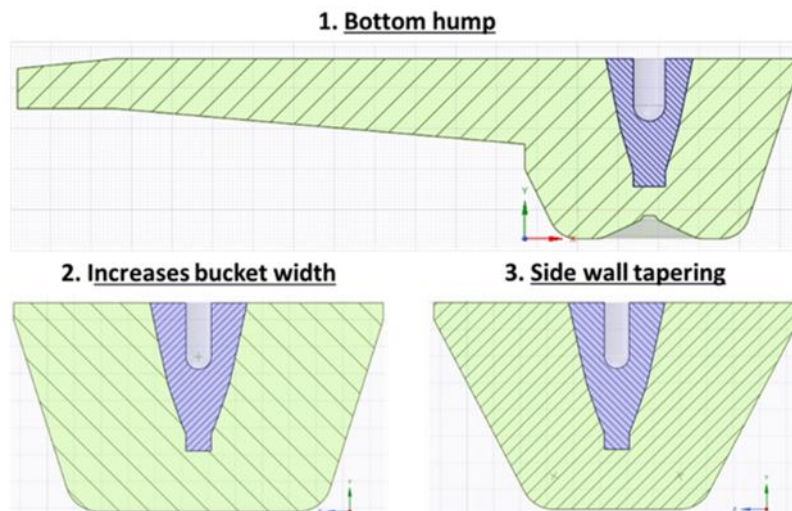


Figure 11. Various design modifications in lower tundish design to reduce turbulence in liquid melt flow.

The flow characteristics of the suggested modified tundish designs were examined by analyzing the velocity vector and turbulent viscosity profiles on different cutting planes within the tundish at 14 TPH casting speed. A comparison between the velocity vector and turbulent viscosity profiles of the base design and the proposed modifications, including the designs with a hump, wider bucket, and tapered walls, is presented in Figure 12 on the vertical mid-plane.

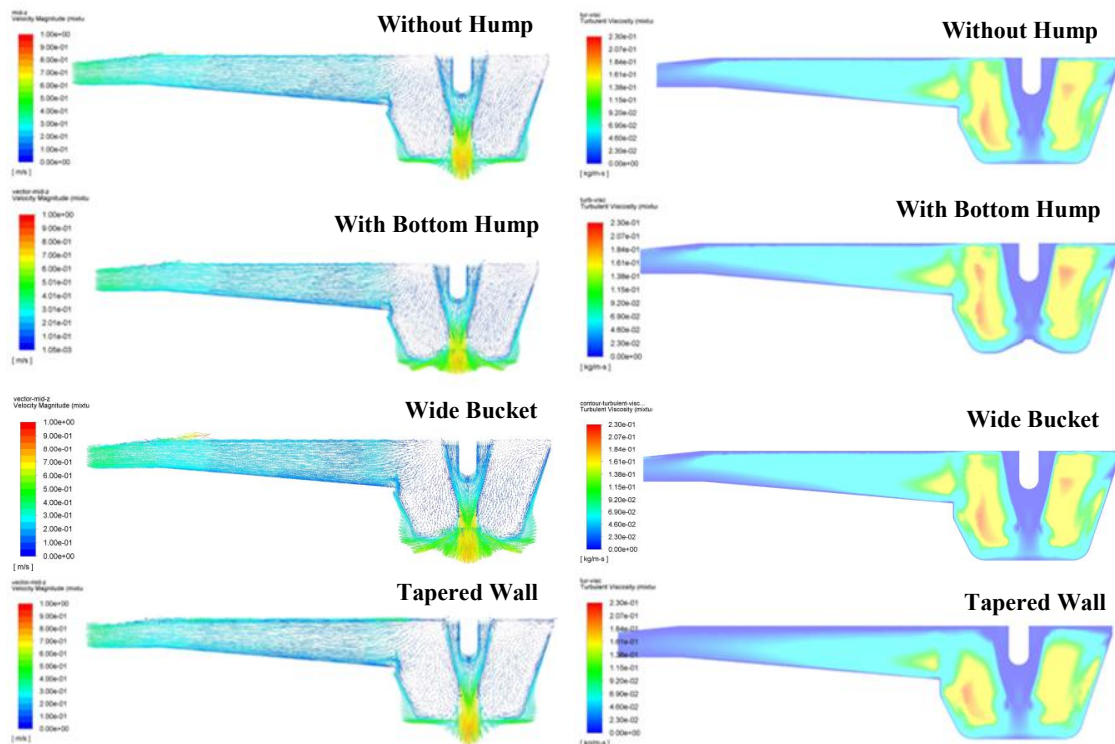


Figure 12. Comparison of velocity vector and turbulent viscosity profile for modified designs.

The vector profiles of the different modified designs exhibit comparable flow directions, recirculation patterns, and turbulent regions, along with minor backflow near the tip of the tundish nose. However, in the designs with a wider bucket and tapered walls, the recirculation area had a

relatively larger diameter, resulting in a decrease in the turbulent viscosity intensity. This observation is clearly depicted in Figure 12. The model predicted values of melt level fluctuations were in the range of 5.9-6.2 mm during the flow behavior analysis for the above four cases which illustrate that the proposed design modifications does not significantly impact the melt level fluctuation values. Therefore, implementing all three design modifications is expected to improve the flow profile.

5.2 Results of Implementing Optimal Casting Recipe

At the Hindalco plant, a series of systematic Design of Experiments (DOE) trials were conducted to determine the optimal cooling water profile and operational process parameters. The objective was to reduce both the variation in ultimate tensile strength (UTS) and the occurrence of cast bar cracks. The study revealed a direct correlation between cast bar temperature variation and UTS variation, as strain hardening during rolling serves as the primary strengthening mechanism for EC grade wire rods. To achieve the desired reduction in UTS variation, the optimal cooling recipe was identified as the water setting that resulted in the maximum reduction in cast bar temperature variations at the specific casting speed. It was also observed that other process parameters, such as lower tundish temperature (inlet melt temperature), mold lubrication, melt chemistry, belt temperature, grain refiner addition, and mold maintenance frequency, needed to fall within specified ranges.

A comprehensive recipe was progressively developed, taking into account the optimal window for all the aforementioned parameters, as casting speeds increased in different phases. Figure 13 illustrates the reduction in UTS variation achieved by implementing the optimal recipe at increasing casting speeds. However, as casting speed increased, it was observed that the belt, tundish, and mold life decreased. Consequently, maintenance frequency needed to be increased to accommodate higher production rates.

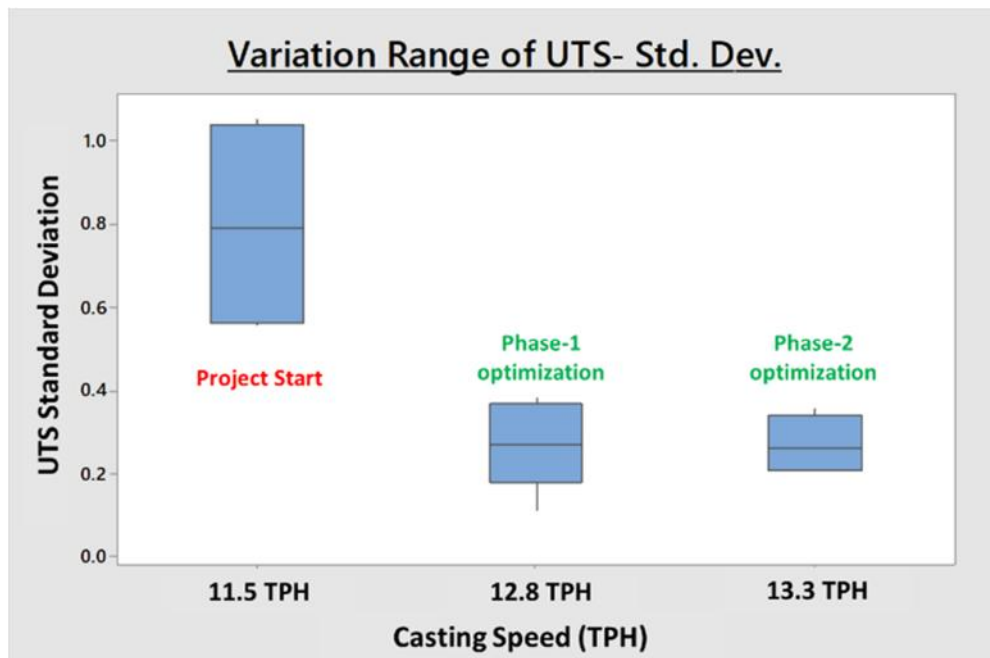


Figure 13. Reduction in UTS variation with various phases of optimization.

6. Conclusions

A computational fluid dynamics (CFD) model was created for the lower tundish to comprehend the flow behavior of liquid metal through the tundish and into the caster mold. The model's accuracy was confirmed by validating it against plant data, specifically the fluctuation measurements of melt level. Furthermore, the validated CFD model was utilized to assess the feasibility of potential design modifications in the lower tundish, aimed at enhancing flow behavior and turbulence. In addition, to address the issues of UTS variation and cast bar cracking, a synergic approach combining experimental and modeling techniques was employed. The investigation pinpointed the instability in air gap formation during cast bar solidification as the underlying cause for these quality concerns. To tackle this, a systematic design of experiments (DOE) was devised, involving variations in cooling water pressures across different zones and directions. By evaluating the reduction in cast bar temperature variation, an optimal cooling pattern was identified. Furthermore, the study estimated the optimal processing parameters for the remaining variables, leading to the development of a complete casting recipe. This recipe was implemented gradually, with casting speeds increasing progressively. In conclusion, the study yielded several important findings and insights which are as follows:

- The developed CFD model proved to be a valuable tool for visualizing the flow behavior of liquid metal, as well as identifying regions of recirculation and turbulence at different casting speeds.
- The CFD model was validated using the measured actual amplitude of liquid melt level fluctuation values obtained at the plant, showing close agreement between the model and the measurements (5.5 mm vs. 6.1 mm, respectively).
- All three design modifications, including the addition of a bottom hump, increased bucket width, and wall tapering, demonstrated promising reductions in turbulence levels when applied at increased casting speed of 14 TPH.
- Achieving a stable air gap during cast bar solidification is crucial for obtaining a defect-free cast bar and high-quality wire rod.
- Reduction in cast bar temperature is the metric to evaluate the most optimal cooling water setting among all the DOE trials conducted at the plant.
- In addition to the optimal water setting, it is essential to identify the optimal operational ranges for the remaining process parameters in order to design a comprehensive recipe.
- The implementation of the optimal casting recipe resulted in a significant reduction in cast bar temperature variation, nearly halving it, and the elimination of cast bar crack occurrences.

Based on above findings, the process improvement done in Properzi™ mill has resulted in stable UTS properties with higher productivity, and benefits found with changes are consistent and valuable.

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