

WAVE Mould for Improved Billet Shape and Quality

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ABSTRACT

A new mould hot face geometry that incorporates a pattern of specially shaped longitudinal profiles running in the casting direction has been developed and tested for steel continuous casting applications. This new design, called the WAVE mould, utilizes its geometrical pattern to provide better guidance of the steel in the mould, more uniform shell growth, improved cast quality, as well as increased mould life. The special hot face geometry can be used with billet or bloom moulds of all standard copper alloys/coatings and is compatible with existing casting equipment.

This paper describes the rationale behind the WAVE hot face geometry, its design, and operation. Importantly, actual casting results from steel plants that have adopted this novel design will be presented.

INTRODUCTION

In the continuous casting of steel, the shape of the product is often a source of quality concerns. A common problem in billet casting is forming a non-square or rhomboid shape that can cause internal quality problems such as diagonal and off-corner hinge cracks. Another common billet shape issue is bulging of the section, typically caused by insufficient mould taper and/or strand support for a given section size and casting speed.

Clearly, the mould and its design have a role to play with regard to these shape issues. For example, it is well known that stronger tapers will reduce the degree of billet rhomboidity¹. Correspondingly, as a mould tube wears the amount of taper is reduced and this results in an increase in billet shape problems as well as an increasing risk of a breakout². A judgment as to the mould condition, either by measuring the inner profile or tracking the time (or tons) it has been used, is an important guide for when it should be replaced to prevent such problems.

The use of foot-rolls below the mould provides additional support that reduces bulging below the mould. Their use has also been found to lessen the degree of billet rhomboidity, even in cases where their application is not strictly required for strand support³. Foot-rolls will also

compensate for machine alignment problems that are also known to cause billet shape issues. Yet another cause of misshapen billets is inadequate mould water velocity and non-uniform flow⁴. This discovery led to major improvements in mould cooling, such as the use of CNC-machined baffles and other types of tight-tolerance water jacket designs. This change allowed for an increase in mould water velocity through a reduction in the water annulus dimension and greatly improved the uniformity of heat extraction from the copper mould.

Despite the many improvements to the mould system over the years, the problem of billet rhomboidity has not gone away, especially with regard to the mid carbon (0.2-0.4%) steels. In fact, rhomboidity can be considered the most vexing problem in billet casting and one that has regularly caused great consternation for machine operators. Past remedies have revolved around the belief that the source of the problem is related to cooling in the mould and thus could be rectified by improvements in taper, water velocity, oil lubrication and oscillator settings⁵. Other below-mould conditions such as spray water flow have not been thought to be a significant factor in this problem, despite clear instances where events such as plugged spray nozzles or low temperature spray water have led to misshapen billets.

With the preceding in mind, a comprehensive explanation as to the cause for billet rhomboidity is proposed as well as a potential solution. When liquid steel enters the mould tube the steel shell initially formed has no strength and acts like a water-filled balloon, taking the shape of the mould containing it. Further down the mould, the shell starts to develop strength and can shift position relative to the copper mould walls as it contracts while solidifying. As the vast majority of resistance to heat flow is governed by the air gap⁶, it is this shifting of position relative to the cooling surfaces that results in non-uniform shell growth, differential stresses and resultant shape problems below the mould. External factors such as oscillator wobble and machine misalignment will act to move the shell position relative to the mould wall and create a non-uniform cooling condition. Similarly, plugged or poorly designed sprays below the mould will act on the shell in a manner so as to pull or twist the strand and transmit this action right up into the mould, also causing non-uniform cooling. This effect can be confirmed by looking at mould wear in plants having spray problems where a strong pattern of non-uniform wear, such as shown in Fig. 1, is seen. It is these internal stresses, caused by non-symmetrical shell growth in the mould, that result in the strand distorting its shape upon exiting from the bottom of the tube. In addition, the accompanying tensile strain as a result of this shape distortion will often result in cracks forming at the solidification front.



Fig. 1 Severe and non-uniform mould wear associated with billet rhomboidity

With these arguments as to the cause of billet rhomboidity in mind, the challenge of developing a new mould design that would better centre the solidifying strand and ensure uniform cooling was undertaken.

WAVE MOULD DESIGN CONCEPT

The solution proposed is called the WAVE mould and its general design is shown in Fig. 2. The key feature of this new design is to superimpose a series of wave patterns onto the hot face side of the mould, causing a mirror image of this pattern to be formed on the billet surface as it begins to solidify. These two surfaces will interlock and guide the shell through the length of the mould, while restraining any movement from side-to-side. The mould and shell are thus “coupled” together to such a degree that a more equal heat extraction and hence uniform shell formation occurs during its critical time in the mould.

Of course, care has to be taken in the design of the WAVE geometry so that the shell and mould are not held so rigidly together that it is not possible to cast successfully. To ensure that this is not the case, a special wave shape is used with its height and length designed so that the billet shell can shrink inwards without the wave peaks on either the copper mould or steel shell binding. The WAVE geometry will therefore vary depending on the section size being cast and linear position in the mould. Typically, the wave heights are in the range of 0.5-5.0 mm and the wavelengths in the range of 1-30 mm; the exact values used are considered proprietary⁷.

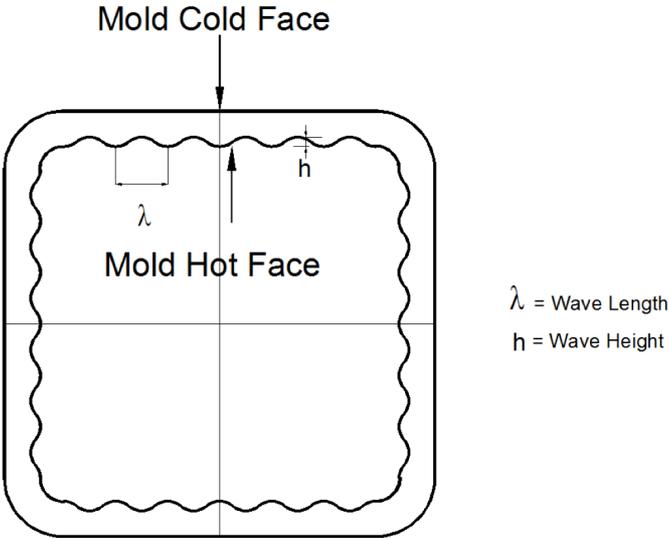


Fig. 2 WAVE Mould Design Parameters

Another benefit of the WAVE mould geometry is a more uniform distribution of oil at the steel meniscus. Current mould oil distribution systems all work by introducing lubricating oil through a plate at the top of the mould housing and letting it weep down the mould wall to the steel meniscus. While a great deal of emphasis has been placed on ensuring that the distribution of oil to the top of the mould is uniform⁸, the actual situation when it reaches the steel level is not certain. As the burning of the oil will affect heat transfer at the meniscus, it is clear that this uniformity is important. With the WAVE mould design providing “channels” for the oil to flow along the length of the mould, it can thus be assured that the uniformity of the oil at the meniscus will be maintained from the oil plate right to the steel level.

PLANT TESTING – CASTING

The first test of the WAVE mould was in late 2010 at a steel plant in the USA, designated as Company A. This plant produces rebar, merchant bar and forging quality steel grades using a relatively new casting machine with the following characteristics:

Table 1. Casting Machine Details

MACHINE DETAILS	COMPANY A	COMPANY B
Casting Machine	2006 Concast®	1986 Mannesmann Demag®
Ladle Size	109 t	159 t
Machine Radius	10.25 m	Vertical
Number of Strands	4 strands	6 strands
Oscillator Type	Hydraulic, retractable	Mechanical
Mould Lubrication	Oil, 35 ml/min	Oil, 40 ml/min
Section Size & Casting Speed	127 x 127 mm @ 4.0 m/min 134 x 194 mm @ 3.3 m/min	178 x 178 mm @ 1.65 m/min
Mould Type (standard)	Elbrodur® G AMT tubes	Elbrodur® G AMT tubes
Mould Taper (standard)	Parabolic	Parabolic
Meniscus level	115 mm	105 mm
Mould length	1000 mm	705 mm
EMS	Yes	Yes
Foot rolls	Yes	Yes
Sprays	Hydraulic, 3 zones	Hydraulic, 3 zones
Withdrawal Unit	Two-point unbending	Single-point unbending
Billet Cut-Off	Oxygen torches	Oxygen torches
Billet Discharge	Walking beam	Chain transfer

The CuAg alloy WAVE mould in size 127x127 mm was installed into strand #4 toward the end of a 1022 steel grade (0.19-0.23% carbon) campaign, using the retractable oscillators. Prior to this, care had been taken to position the foot rolls further out from the usual set point to accommodate the changed billet exterior profile. A check had also been made to ensure proper clearance of the dummy bar head inside the mould, which should not be an issue in most cases. While a slight “jerking” of the strand was noted on start-up, this quickly went away and was judged similar to that typically seen when a new mould is installed. Just over two heats were cast with the strand speed starting at 3.5 m/min and moving to a high of 4.5 m/min. The various casting machine parameters were the same between the WAVE and control strand, including the mould water ΔT values. However, visual observation of the billet colour seen in the upper spray zone showed a hotter surface temperature, although this impression disappeared by the time the strand was at the machine discharge. It is speculated that this was due to the scale not being as tightly adhered to the WAVE billets and its subsequent removal by the water sprays. Another important observation was that the WAVE billets tracked down the machine in a straighter line, without any “snaky” problems often associated with rhomboidity. As you would expect, oscillation marks were still present, although more difficult to see with the wave pattern superimposed on the billet surface.

Three sets of billet samples from the WAVE and control strands were obtained for evaluation. A light etching, dimensional measurements, and scarfing on the billet corners was done. Figure 3 shows billet cross-sections from one pair of samples.



Fig. 3 First WAVE billet samples, #4 is WAVE (left) and #1 is Control (right)

The test billets retained the WAVE shape of the mould as their outer surface matched that on the inside of the mould. The overall shape was very square, with just 0.1 mm rhomboidity measured. A slight convexity of 0.4 mm on the mid faces was seen but there were no off-corner depressions or cracking. In comparison, the control strand had measured rhomboidity values ten times greater (although very acceptable at <1.5 mm) as well as some off-corner depressions and cracking. Scarfing on the billet edges did not reveal any quality problems.

Table 2. Measured Billet Rhomboidity with 1022 Steel Grade

Casting Speed (m/min)	WAVE Mould Rhomboidity (mm)	Control Mould Rhomboidity (mm)
3.5	0.1	1.0
4.0	0.1	1.5
4.5	0.1	1.0

Information from the second steel plant to run the WAVE mould was equally encouraging. Plant B introduced one WAVE mould into operation in January 2013, making a 4130 grade of steel. Again, there were no operational issues with the new mould design and strand start-up was very smooth. Over the next months, as the success with the WAVE mould continued, additional strands were converted until today they are operating with five of their six strands using the new design. Billet rhomboidity measurements are routinely taken and the values reported in Fig. 4 show a decrease during this period of time, reflecting the gradual changeover to the WAVE mould design and consequent improvement in shape.

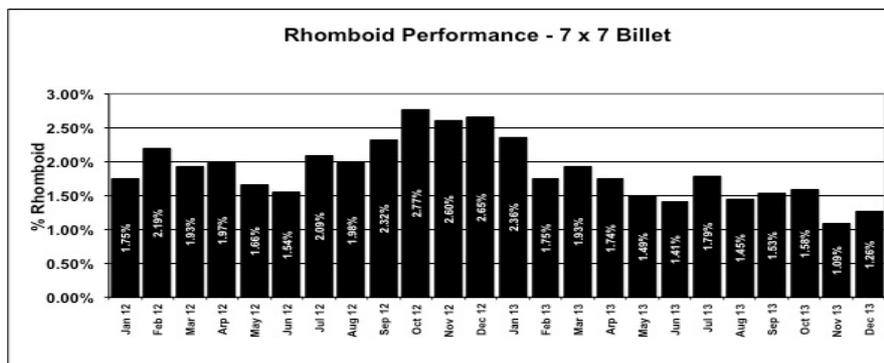


Fig. 4 Rhomboidity Results at Company B

Testing at Company A moved to their primary billet size of 134x194 mm, used to produce billets for rebar and merchant bar quality grades. As before, a WAVE mould in CuAg alloy was installed into one strand of the machine, with another strand again being the control reference. Photos of the WAVE mould before and during casting are shown in Figure 5.



Fig. 5 WAVE mould installed and running at Company A

Once again, start-up and casting with the mould was completely normal and uneventful. The steel grade being cast was a 0.45% carbon grade used for rebar applications. Looking inside the mould during casting, there were no signs of shell sticking to the copper and liquid steel was seen flowing into the wave pattern on the tubes. This latter point is reflected on the billets being cast, with the WAVE pattern being well formed on the surface as seen in Figure 6.



Fig. 6 Rectangular WAVE billets at Company A

Observing the strand, it was apparent that the cast billets were quite square compared to the control strand. In fact, at one point the control strand was having severe problems due to a misalignment of the spray risers. To test the impact of the WAVE mould on such a machine problem, it was decided to swap the test and control moulds while the melt shop was down for power demand reasons. The billets produced with the WAVE mould in strand #1 immediately

improved, with no other changes having been made. An example of the improved shape obtained with the WAVE mould is seen in Figure 7.

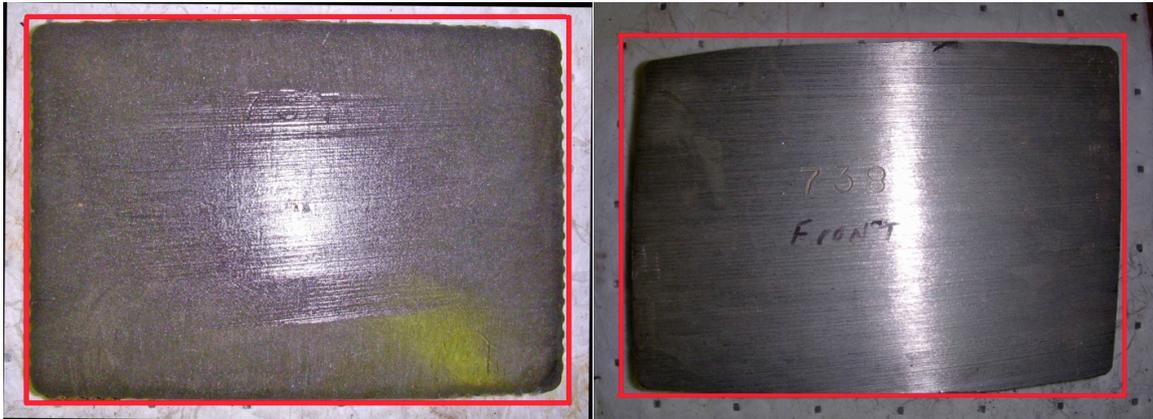


Fig. 7 WAVE mould billet slice (left) compared to the test strand (right)

As the casting with the WAVE mould was proceeding smoothly, it was decided to keep it in use for a longer period. Over time the operators came to view the WAVE mould as their best operating strand, making consistently good billets no matter the casting conditions. By the time the mould was taken out of the machine, an astonishing 1795 heats or about 50,000 tons had been cast with the CuAg alloy WAVE tube. Fig. 8 shows this mould at the end of its life. By comparison, average mould life with the conventional Elbrodur® G (CuCrZr) alloy tubes is a very good 1050 heats but still far less than with the WAVE mould. While mould life was not the primary goal for this new design, it was important to learn that the WAVE patterns in the mould would not wear away quickly, which was an initial concern. This result is also a strong indication that movement by the steel shell in the WAVE mould has been much reduced, leading to lower wear and longer service life.



Fig. 8 WAVE mould at end of its life having cast 1795 heats or 50,000 tons

During the extended period of time this mould was in continual service, there was only one casting incident that resulted in a breakout. This was due to inadvertently using an oversized nozzle that allowed the metal level to rise quickly, causing a sudden acceleration of the strand that then pulled itself apart just below the mould. The nature of this breakout left a very nice shell that provided an accurate representation of its growth in the mould. The excellent shell uniformity around the perimeter, as well as the lack of re-entrant corners, is seen in Fig. 9. The latter observation is a very important point as re-entrant corners, with their characteristic thinning of the shell, often result in cracks or even breakouts in the off-corner region⁹. The well-formed wave pattern around the periphery of the billet surface is also clearly seen.

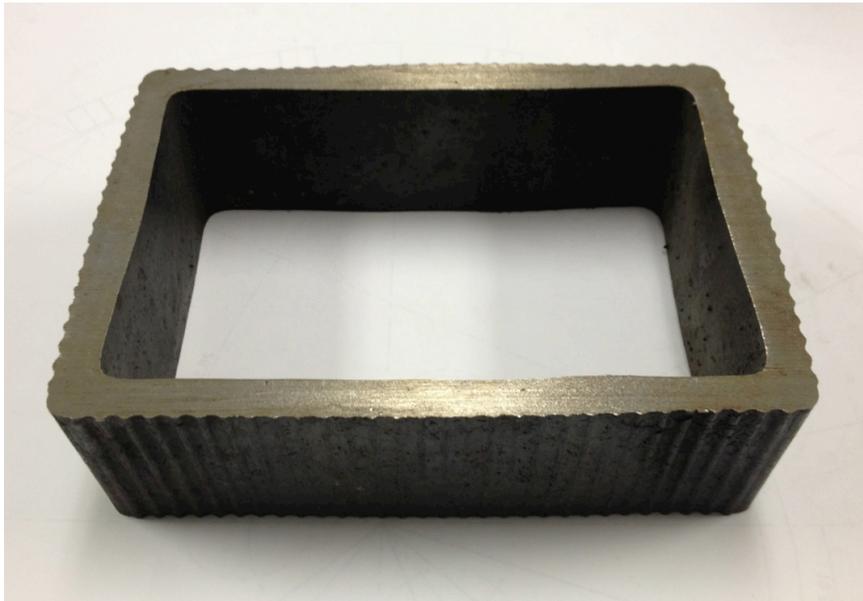


Fig. 9 Breakout shell from 0.45% carbon steel cast with WAVE mould.

This wave pattern that forms on the outside surface does not continue into the solidifying steel shell for any significant distance, as determined by macro-etch analysis. A finite element analysis also confirmed that this solidification front would become linear after a very short time period due to the thermal diffusivity properties of the steel shell. Figure 10 shows the macro-etch on the left while the temperature contours calculated using a two-dimensional FEA model is on the right.

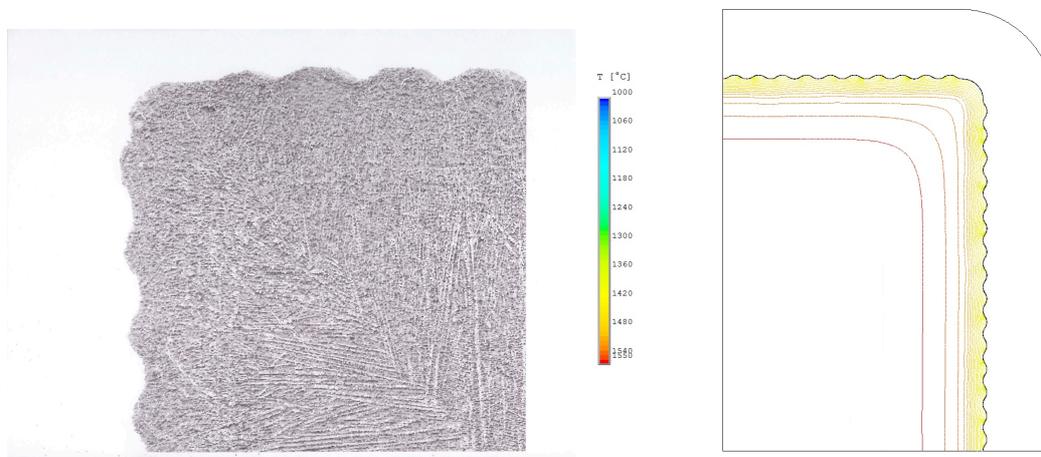


Fig. 10 WAVE mould solidification front quickly becoming linear

PLANT TESTING – ROLLING

While the WAVE pattern on the billets is the key to the success of this novel mould design, there was concern with regard to its influence on the surface quality of the finished rolled product. However, given the relatively shallow depth and special form of the waves, it was anticipated that this would not be a problem. To check this, the first WAVE billets were tracked through the rolling mill to determine if there were any quality issues with the product.

Observations and burn tests in the rolling mill proved that the WAVE striations were rolled out after the first two passes of about 30% reduction each. This is seen in photos presented in Figure 11 and later confirmed by examination of the finished bar products. It should be noted that even the force of the caster withdrawal rolls on the curved side of the billet can significantly reduce the WAVE pattern on those two sides, depending on the pressure used.

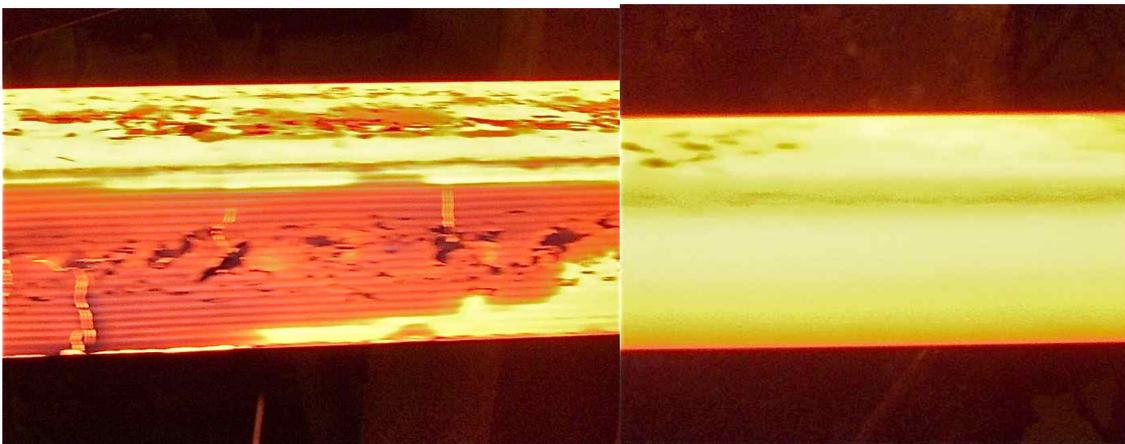


Fig. 11 Billet WAVE marks visible when entering the mill but gone after second pass

After many months of operation with the WAVE mould at three steel plants, it can be stated that there are no quality concerns regarding the surface pattern on the billets, when used for rebar and merchant bar steel grade products. The use of the WAVE mould for SBQ steel grades is pending, awaiting testing of the products produced for these applications.

ALLOY SAVINGS POTENTIAL

As discussed earlier in the paper, one of the most effect strategies to control billet rhomboidity in the mid-carbon grades is to change the steel chemistry slightly, within the boundaries of the alloy specification. Moving the aim carbon either one or two points up or down will often provide some relief. Another very successful strategy in this regard is to ensure that a Mn/S ratio of 30 is maintained. A considerable economic drawback to the latter approach is that substantial quantities of manganese, above that required to meet the grade specification, is often needed and this represents a substantial cost increase. The alternative of using the WAVE mould to control billet shape can be a lucrative one and early adopters have indeed been able to lower their alloy costs accordingly. By one steel plant's calculation, a cost saving of \$6.00 USD per ton was obtained by reducing the Mn addition to the minimum required, while still being able to cast a good billet having a Mn/S ratio of just 15. Clearly, using the WAVE mould has the potential for significant alloy cost savings.

CONCLUSIONS

A billet mould tube with a new hot face geometry is being tested at a number of steel plants. The new design, called the WAVE mould, is achieving improvements in billet shape, internal quality, and alloy costs. At this time there are three steel plants that are routinely casting with WAVE moulds, another six conducting evaluations, and a further nine that have placed orders. While there have been some obstacles to using the special mould, such as the different outer shape of the billets, the benefits for those adopting the WAVE design are significant. Going forward, there are plans to incorporate this special mould geometry to cast other products such as bloom, round and beam-blank shapes.



Fig. 12 Four WAVE mould strands in continuous operation

REFERENCES

1. V. Krujelsis and J. Cook, "The Influence of Mould Tube Taper and Distortion of Cast Billet Quality", *1988 Steelmaking Conference Proceedings*, pp. 349-352.
2. I.V. Samarasekera and J.K. Brimacombe, "The Continuous-Casting Mould", *Continuous Casting Vol. Two: Heat Flow, Solidification, and Crack Formation*, The Iron & Steel Society of AIME, 1984, pp.33-44
3. I. Bakshi, "KME internal Report", 28 Aug 1997.
4. R. Berryman, I.V. Samarasekera, and J.K. Brimacombe, "Cooling Water Flow in Continuous Casting Billet Moulds", *Iron & Steelmaker*, March 1988, pp. 69-77.
5. R. Bommaraju, I.V. Samarasekera and J.K. Brimacombe, "Optimum Design and Operation of Moulds for the Continuous Casting of Steel Billets", *69th Steelmaking Conference Proceedings*, April 1986, pp. 409-423.
6. AIST, "The Making, Shaping and Treating of Steel– Casting Volume, 11th Edition 2010, pp.94
7. D.P. Lorento, US Patent Application Publication US 2013/0277006 A1
8. I. Bakshi, A. Perri, J.K. Brimacombe, I.V. Samarasekera, and R.P. Smith, US Patent 5027887, 1991.
9. J.E. Lait, and J.K. Brimacombe, "Solidification During Continuous Casting of Steel", *Continuous Casting Vol. Two: Heat Flow, Solidification, and Crack Formation*, The Iron & Steel Society of AIME, 1984, pp.171-183.