WAVE Mold Results at Nucor Jackson Mississippi

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ABSTRACT

In 2011, Nucor Mississippi had severe problems with off-square billets that could not be controlled with the usual operating and maintenance adjustments. A test with a new KME mold design was made that had outstanding results in terms of both billet shape and mold life. In addition, there were significant cost savings achieved by reducing the amount of Manganese and Vanadium added to the steel in an effort to control the billet shape. This paper will present information on the operating, quality, and cost saving results when using the new WAVE mold design.

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 mold taper and/or strand support for a given section size and casting speed.

Clearly, the mold 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 rhomboidity[1]. Correspondingly, as a mold tube wears the taper is reduced and this results in an increase in billet shape problems, as well as an increasing risk of a breakout[2]. A judgment as to the mold condition, either by measuring the inner profile or tracking the time (or tons) it has been used, is an important guide as to when it should be replaced to prevent such problems. The use of foot-rolls below the mold provides additional support for the relatively thin shell that will reduce bulging and improve billet shape. Their use has been found to lessen the degree of billet rhomboidity, even in cases where they are not strictly required for strand support[3]. Additionally, foot-rolls will compensate for machine alignment problems that are also known to cause billet shape issues.

Yet another cause of misshapen billets is inadequate mold water velocity and non-uniform flow[4]. This finding led to major improvements in mold cooling, such as the use of CNC-machined baffles and other types of tight-tolerance water jackets. The improved designs allowed for an increase in mold water velocity, through a reduction in the water gap dimension, that prevented boiling of the cooling water and greatly improved the uniformity of heat extraction from the copper mold.

Despite the many improvements to the mold 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 much consternation for machine operators. Past remedies have revolved around the belief that the source of the problem is related to cooling in the mold and thus could be rectified by improvements in taper, water velocity, oil lubrication and oscillator settings[5]. Other below-mold 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 mold tube the steel shell initially formed has no strength and acts like a water-filled balloon, taking the shape of the mold containing it. Further down the mold, the shell starts to develop strength and can shift position relative to the copper mold walls as it contracts while solidifying. As the vast majority of resistance to heat flow is governed by the air gap[6], 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 mold. External factors such as oscillator wobble and machine misalignment will act to move the shell position relative to the mold wall and create a non-uniform cooling condition. Similarly, plugged or poorly designed sprays below the mold will act on the shell in a manner so as to pull or twist the strand and transmit this action right up into the mold, also causing non-uniform cooling. This effect can be seen by looking at molds at steel plants having rhomboid shape problems where a strong pattern of non-uniform wear, such as shown in Figure 1, is seen. It is the non-symmetrical heat extraction and resultant stresses in the forming steel shell that result in the strand distorting its shape upon exiting the bottom of the mold tube. In addition, the accompanying tensile strain as a result of this shape distortion will often result in cracks forming at the solidification front.

Figure 1. Severe and non-uniform mold wear associated with billet rhomboidity

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

WAVE MOLD DESIGN CONCEPT

The solution proposed is called the WAVE mold and its general design is shown in Figure 2. The key feature of this new design is to superimpose a series of wavy undulations onto the hot face side of the mold, causing a mirror image of the pattern to be formed on the billet surface as it begins to solidify. These two surfaces will then interlock and guide the shell through the length of the mold, while restraining any movement from side-to-side. The mold 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 mold.

Of course care must be taken in the design of the WAVE geometry so that the shell and mold 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 profile is used with its height and length designed so that that the billet shell can shrink inwards without the wave peaks on either the copper mold or steel shell binding. The WAVE geometry will therefore vary depending on the section size being cast and linear position in the mold. Typically, the wave amplitude is 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 proprietary[7].

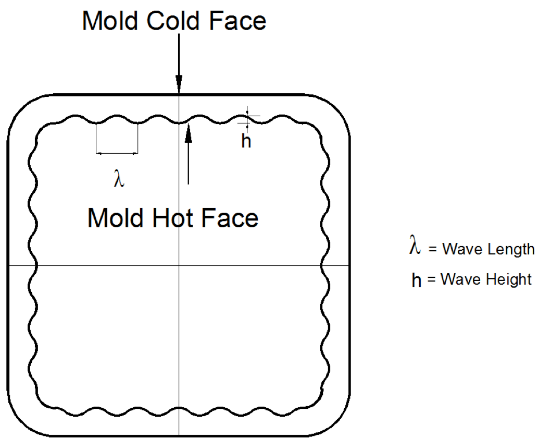

Figure 2. WAVE Mold Design Parameters

Another benefit of the WAVE mold geometry is a more uniform distribution of mold oil at the steel meniscus. Current mold oil distribution systems all work by introducing lubricating oil through a plate at the top of the mold housing and letting it weep down the mold 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 mold is uniform[8], 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 mold design providing "channels" for the oil to flow along the length of the mold, it can 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

In July 2013, a test of the WAVE mold in the 140x140mm billet size was begun at the Jackson, Mississippi plant of Nucor Steel. Products produced here are rebar, merchant bar and forging quality steel grades using a 1993 billet continuous casting machine that was revamped in 2009, with the following characteristics:

Table 1. Nucor Jackson Mississippi Casting Machine Details

Casting Machine	SMS Concast (2009)
Ladle Size	50 t
Machine Radius	7.92 m
No. Strands	3 strands
Oscillator Type	Electro-Mechanical
Mold Lubrication	Oil lubrication, 25 ml/min
Section Size & Casting Speed	100 x 100 mm @ 4.5 m/min 115 x 115 mm @ 3.8 m/min 130 x 130 mm @ 3.3 m/min 140 x 140 mm @ 3.0 m/min 160 x 160 mm @ 2.2 m/min
Mold Type (standard)	KME CuAg AMT
Mold Taper (standard)	Parabolic
Meniscus level	115 mm
Mold length	812.8 mm
EMS	No
Foot rolls	No
Sprays	Hydraulic, 2 zones (later 3 zones)
Withdrawal Unit	Two-Point Unbending
Billet Cut-Off	Oxygen Torches
In-Line Weighing System	Not at time of testing
Billet Discharge	Pusher

The impetus to try the WAVE molds was a "snaky" billet problem that started in April 2011. Even today, there is no explanation as to why steel grades that cast without difficulty prior to this suddenly could not be cast without shape issues afterwards. As detailed below, numerous steps were taken to identify and correct the problem, all without complete success.

Fig. 3: "Snaky" billets cast with standard molds seen on the cooling bed

"Snaky" billets are an indication of off-square shape (rhomboidity) in cross-section and are a problem commonly seen at this plant when casting steels in the ranges of 0.18-0.24% carbon. The distorted shape will almost always result in an off-corner hinge crack at the solidification front. If the shape problem is severe enough, the cracking will continue below the mold, often resulting in a breakout in this off-corner region[9].

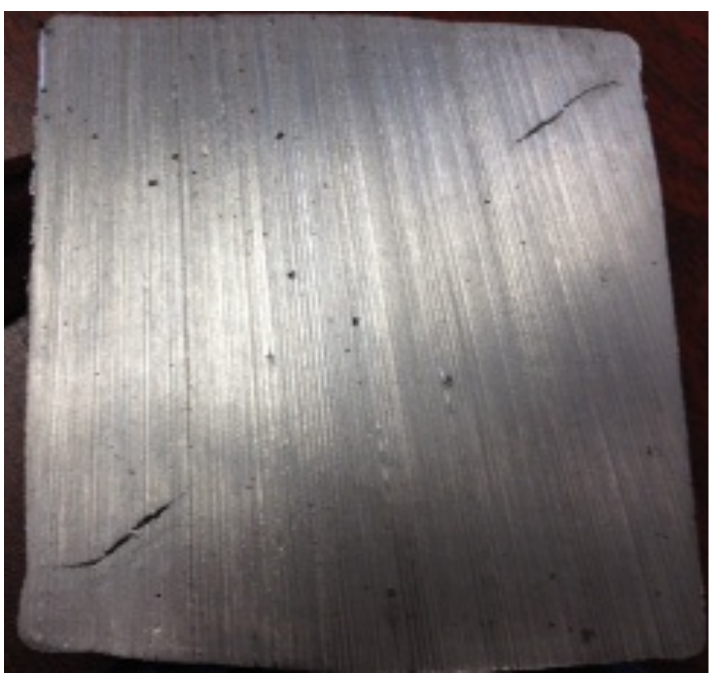

Fig. 4: Off-corner hinge cracks from rhomboid billet shape

After the “snaky” billet problems began, various operating/maintenance parameters were checked and adjusted in an effort to control the shape problems. This included:

Table 2. Casting Machine Parameters Checked/Adjusted

- Verified tundish stream alignment
- Check mold lube flow
- Tried different mold level settings with different speed combinations
- Replaced mold tubes
- Check mold tapers
- **Trialed new mold taper**
- Reviewed mold level control program
- Reviewed thermocouple level control installation process
- **Verified stroke settings**

- Measured water jacket distortion
- Replaced water jacket spacer pins
- Verified spray water alignment
- **Changed out spray water pumps (pulsing)**
- **Redesigned zone 1 spray water pipes due to water pulsing**
- Checked spray water curves
- Replaced all spray nozzles with OEM
- Adjusted scrap mix to increase Mn/S ratio
- **Shot caster alignment**
- **Checked oscillation motion**

The one factor that proved effective in controlling the billet shape problem was to adjust the steel chemistry so as to have minimum manganese to sulfur ratio of 30:1. This was achieved by lowering the carbon to allow for the increased manganese addition. For some grades, vanadium had to be added to meet the mechanical properties required of the steel. A considerable economic drawback to this solution is that the additional manganese and vanadium represents a substantial alloy cost increase of up to $6.00 USD per ton. Clearly, there was a need to find another solution.

Thus when there was an opportunity to try a new mold technology, designed with this problem in mind, a quick decision was made to move ahead with a test as soon as possible. After an agonizingly long wait for the first WAVE molds to arrive, the first cast was made without any difficulties. While mold lube had been increased from 25 to 35 ml/min to compensate for the greater billet surface area, there was a slight amount of jerking initially. However, this was no worse than sometimes occurs when running a new mold and, in any case, went away after a short time. The chemistry cast was the problematic Grade 40 (0.25 C, Mn/S=20) steel. Right from the very first WAVE billet on the cooling bed, it was clear that the billet shape was greatly improved compared to the other two strands and rhomboidity was effectively gone!

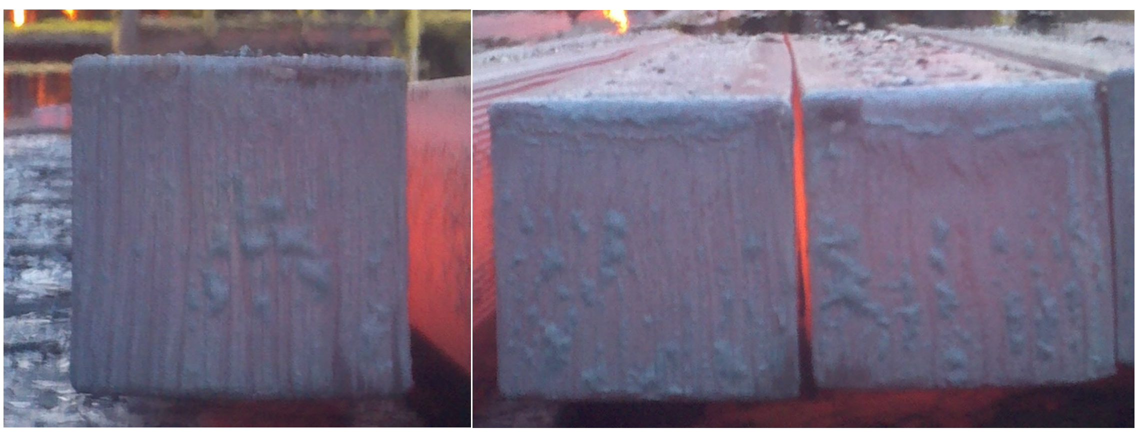

Fig. 5: WAVE mold billet (left) with excellent shape compared to standard mold billets (right)

A later measurement found that the diagonals were 194.8 mm, a variation of 1.3% from the theoretical value of 197.4 mm. The measured billet dimensions wear 139.7-140.0 mm on the two sides, with the nominal value being 139.7 mm

The next step in the evaluation was to cast with the WAVE molds in all three strands. A wide variety of steel chemistries were cast without any operational difficulty. The rebar grades cast included:

Table 3. Chemistry of Rebar Grades Cast with WAVE Mold

Chemistry	Grade 40	Grade 60
% Carbon	14-18, 20-24, 26-30	40-44
% Manganese	70, 80, 100	1.20

It was also seen that the wave pattern on the billet was well formed and a mirror image of the inside mold profile.

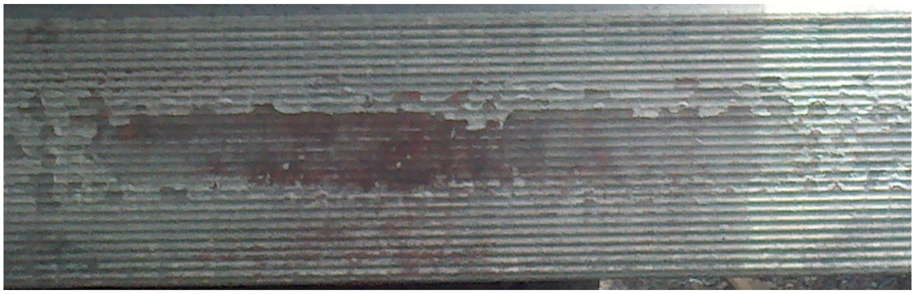

Fig. 6: Well-formed pattern on billet cast with WAVE mold

As has been the case with other users of WAVE molds, a substantial increase in mold life was obtained. While the life of the standard AMT molds in the 140x140 mm billet size had been a very good 800 heats, it increased to an astounding 2400 heats after converting to the WAVE molds. This tripling of mold life can be attributed to improved strand guidance in the mold that reduces movement of the shell and resultant abrasive wear. Of course, such high mold life cannot be obtained without having excellent overall caster maintenance and operating practices.

PLANT TESTING – ROLLING

While the WAVE pattern on the billets is the key to the success of this novel mold design, there is naturally 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 as was the case with earlier steel plants to use the WAVE mold design. To check this, the WAVE billet rolled were tracked for each of the critical product shapes to verify there were indeed no quality issues. Specifically, the finished product categories analyzed and the results were as follows:

Table 4. Rolling Trial Results

Section	Results
Rounds 0.906”	No upset failures or other visible defects, waves not visible after stand two
Angles	No defects reported
Strips	No defects reported
Rebar	No defects reported
Flats	No defects reported
Squares	No defects reported

Interestingly, a reduction in the amperage drawn by the roughing stands of between 50-100 A was measured. The drop in power input with the WAVE billets was attributed to their improved shape entering the mill. This in turn has allowed the reheat furnace temperature to be reduced by 30º C, with corresponding energy savings. Other benefits reported by the rolling mill with the WAVE billets are that split noses have “all but gone away” and there is better “spread” control between passes. So, rather than being a reluctant customer of the differently shaped billets, today the rolling mill operators are enthusiastic supporters of the WAVE mold.

Fig. 7: WAVE billet exiting the second roughing stand

CONCLUSION

A billet mold tube having special hot face geometry was tested at the Nucor Steel plant in Jackson, Mississippi. This new design, called the WAVE mold, is achieving improvements in billet shape, internal quality, and alloy cost savings. The excellent results obtained, both in the melt shop and rolling mill, have led to the opinion that "*the WAVE mold is the best thing in casting since oscillation*".

Fig. 8: All three WAVE mold strands in continuous operation

REFERENCES

1. V. Krujelsis and J. Cook, "The Influence of Mold 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 Molds", *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 9,393,614B2, Jul 2016.
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.