

409 Casting Trials with Parabolic Mold Taper at AK Steel's Mansfield Operations Using VAI's DIAFACE® Mold Technology

R.J. O'Malley* and J. Watzinger**

*AK Steel - Middletown, OH, USA

**VOEST-ALPINE Industrieanlagenbau GmbH & Co. - Linz, Austria

INTRODUCTION

The in-mold behavior of 409 stainless steel cast with parabolic narrowface taper was investigated using a combination of VAI's DIAFACE® Mold technology and supplemental mold instrumentation. The thermal behavior of the DIAFACE® Mold was documented and compared to the thermal behavior observed when casting 409 stainless with linear narrowface taper.

The parabolic narrowface taper was observed to have a pronounced effect on the thermal behavior of the mold over the entire mold perimeter, including the broadface. The observed effects included an increase in narrowface thermal stability, a reduction in broadface temperature rebound, and an increase in heat removal high in mold. No significant change in the 409 stainless internal slab structure was observed when using parabolic narrowface taper, but a slight increase in slab narrowface concavity was observed with the DIAFACE® Mold.

BACKGROUND

The medium-thin slab caster at AK Steel's Mansfield Operations, shown in **Figure 1**, employs a 1.2 meter long straight parallel mold to cast ferritic and martensitic stainless steels by a direct charge routing without slab conditioning. While this 1.2 m long mold provides some distinct operating benefits, it has also introduced some unique challenges during the development of casting practices for the production direct rolled stainless steels.

One area that appears to be negatively influenced by the length of the Mansfield mold is narrowface thermal stability. Previous studies⁽¹⁾ have shown that the mold narrowfaces are thermally much less stable than the broadfaces. The casting trials with the DIAFACE® mold that are reviewed in this paper were performed to determine if the parabolic narrowface shape could be employed successfully to improve the thermal stability of the narrowface on the Mansfield caster.

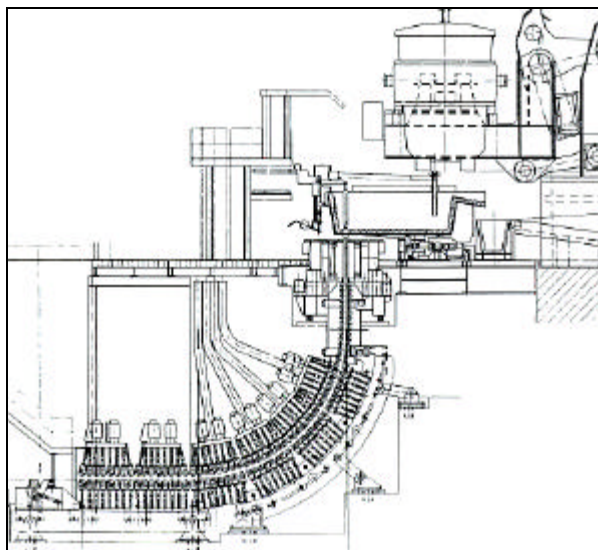


Figure 1: AK Steel's medium-thin slab caster at Mansfield Operations.

EXPERIMENTAL

DIAFACE® Mold Design

The parabolic narrowface configuration employed in this investigation was based on VAI's DIAFACE® Mold technology. The narrowfaces were designed, fabricated, and instrumented by VAI, and operated and evaluated at Mansfield as part of an ongoing joint cooperation project agreement⁽²⁾ with VOEST ALPINE Industrieanlagenbau GmbH. A drawing of the basic narrowface design is shown in **Figure 2**. Essentially, the narrowface copper plate is pre-machined to a parabolic shape, and supplemental edge relief is machined into the lower edges of the mold plate to minimize the binding of the slab corners in the lower part of the mold.

As shown in **Figure 3**, the narrowface plate angle is adjusted so that the combination of the machined taper and the plate angle produces the desired operating taper for the mold. In the current investigation, the operating taper of the DIAFACE® plate was set so that the magnitude of the taper from the meniscus to the mold bottom, in inches, was equal to the magnitude of the taper of a flat mold plate set to a 1%/m taper. As

shown in **Figure 3**, this taper setting resulted in approximately a 2%/m taper at the meniscus with a gradual decrease in taper to about 0.5%/m at the bottom of the mold.

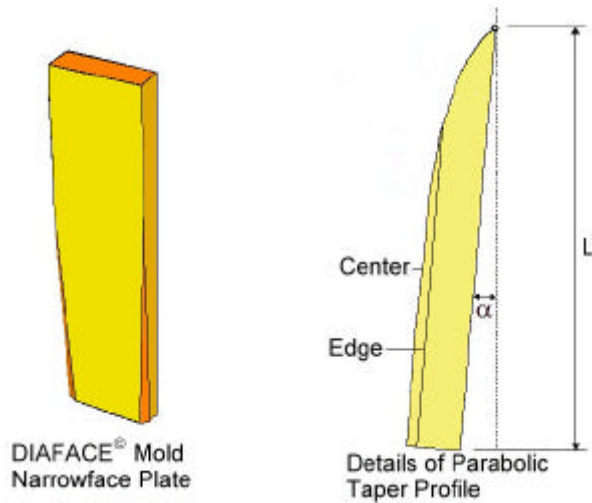


Figure 2: Overview of the VAI DIAFACE® narrowface plate design employed in this study.

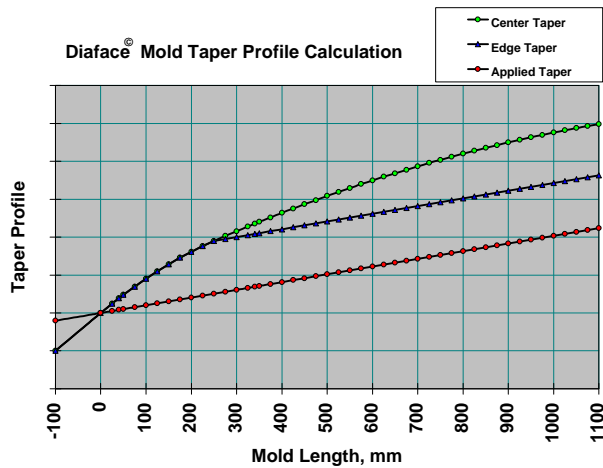


Figure 3: Details of taper settings employed in the DIAFACE® mold trials.

Mold Instrumentation

The instrumented mold that was employed in this study consists of a dedicated mold cassette assembly that is equipped with 106 thermocouples that measure the mold plate temperature at various positions within mold. In the current investigation, the standard narrowface plates were replaced with special DIAFACE® plates that were fitted with embedded thermocouples. Details of the thermocouple mounting configuration have been described previously⁽³⁾. The location of the thermocouples on each symmetrical pair of mold cassettes is shown in **Figure 4**.

Casting Trials

The DIAFACE® mold was employed to cast six trial heats of 409 stainless steel. Temperature data from the instrumented mold was collected for these six trial heats at 5 second intervals, along with supplemental process data, such as casting speed, mold level, mold water delta Ts, etc. Slab samples were also secured from select heats to evaluate slab macrostructure and slab shape. Similar process data and samples were also collected for several 409 heats cast with traditional linear mold tapers for comparison.

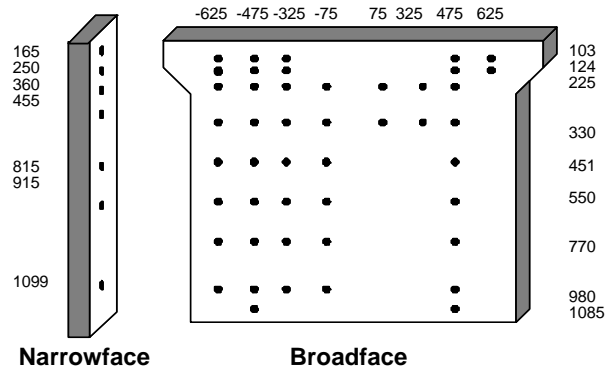


Figure 4: Location of thermocouples in the instrumented mold (in mm).

RESULTS

The six heats of 409 stainless that were produced with the DIAFACE® mold all cast well with no operating problems. The coils produced from the trial heats were all shipped as prime material, with no degradation in surface quality. The only minor difficulty encountered was with the mold taper calibration procedure using Mansfield's existing taper gauge. This issue was overcome by preparing a translation table for the taper gauge to correct for the machined parabolic profile on the DIAFACE® mold.

The temperature data collected from the 409 trial heats and the control heats were examined in several different ways. Temperature profiles from the trials with the DIAFACE® mold were compared to the profiles obtained using the standard linear tapered mold at comparable steady state casting conditions, as shown in **Figures 5 and 6**. The temperature variability for each test condition was also evaluated by plotting the standard deviation in temperature for the steady state time period, as shown in **Figures 7 and 8**. The dynamic behavior of the thermal profiles for the two molds was also compared by reviewing time-stepped animations, using procedures described elsewhere⁽¹⁾.

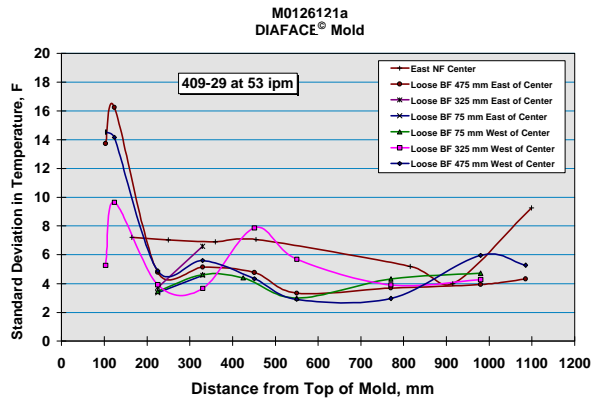
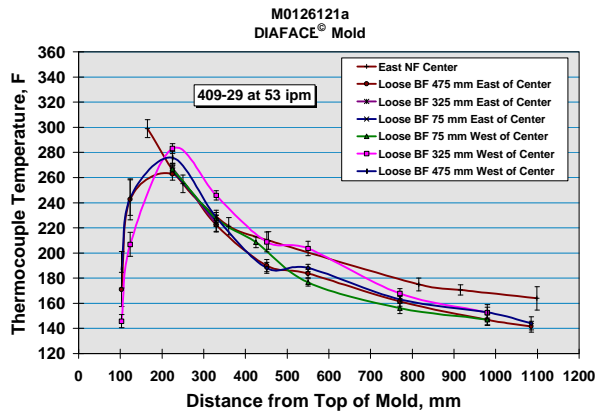
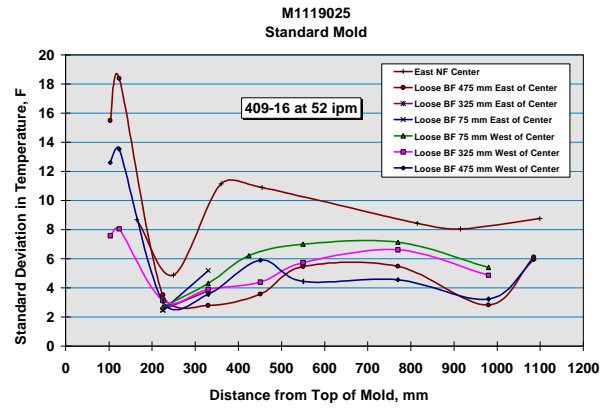
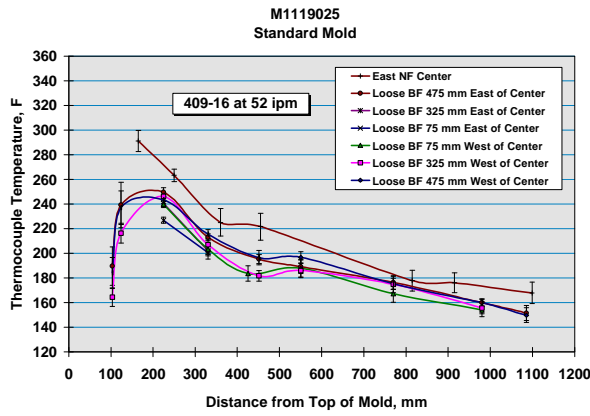


Figure 5: Comparison of steady state temperature profiles on loose broadface and east narrowface.

Figure 7: Comparison of temperature standard deviations on loose broadface and east narrowface.

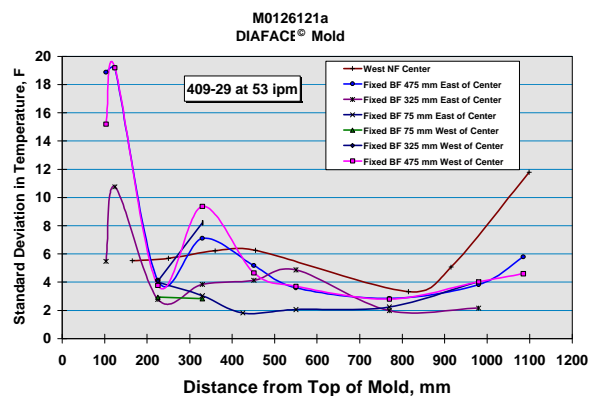
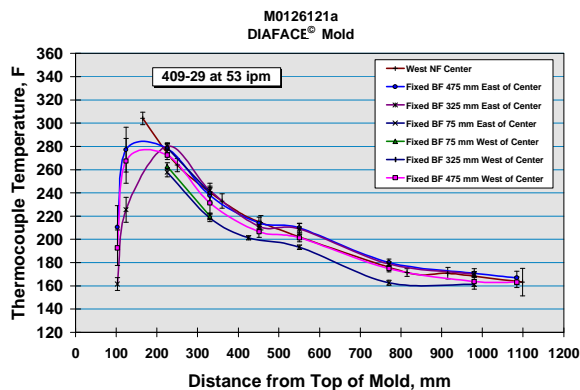
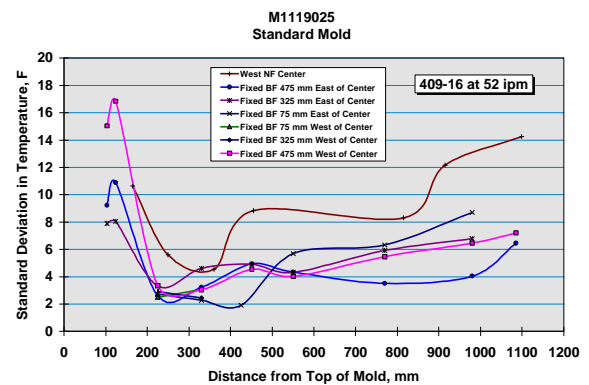
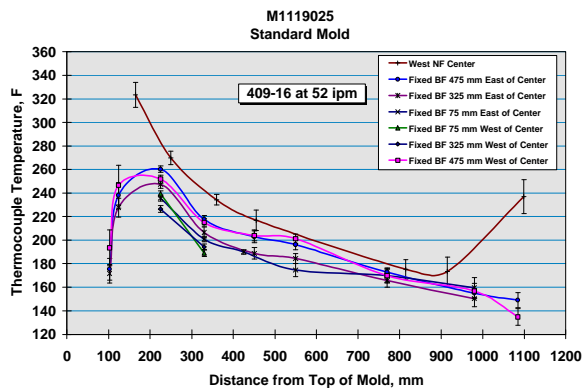


Figure 6: Comparison of steady state temperature profiles on fixed broadface and west narrowface.

Figure 8: Comparison temperature standard deviations on fixed broadface and west narrowface.

In general, the steady state broadface temperature profiles with the DIAFACE® mold were observed to be about 20-40 C hotter in the top third of the mold than the temperature profiles observed with the standard mold. Also, the strong temperature rebound observed on the loose broadface at about 400 mm below the meniscus with the standard mold (**Figure 5**) was much less evident with the DIAFACE® mold. In addition, the standard deviations in narrowface temperature were much lower with the DIAFACE® mold. Smaller thermal fluctuations were also observed with the DIAFACE® mold in the transient profile animations of the mold narrowface.

Steady state hot face heat flux profiles were calculated for the two mold configurations using a two dimensional thermal model of the mold⁽⁴⁾. The calculated heat flux profiles shown in **Figure 9** highlight the differences observed in the loose broadface heat flux profile for the two mold types. The results mirror the broadface temperature results, with the DIAFACE® mold showing a smaller thermal rebound and a higher heat flux high in the mold. The average broadface heat removal was also observed to be about 14% higher with the DIAFACE® mold (at 1.25 MW/m²) than with the standard mold (at 1.10 MW/m²).

The slab samples that were secured from select trial heats and the control heats were macro-etched using hot HCl to examine the slab internal structure, as shown in **Figure 10**. These samples were also traced to document the slab shape in the vicinity of the narrowface, as shown in **Figure 11**.

The slab tracings show a slight increase in narrowface concavity with the DIAFACE® mold compared to the standard mold. This small change in concavity had no negative impact to the direct rolling operation. In addition, the macroetched slab samples all possessed a sound internal structure with no internal defects.

DISCUSSION

The observed influence of the DIAFACE® narrowface mold plate design on the thermal stability of the narrowface suggests that the parabolic shape does a much better job of matching the steel shell shrinkage along the 1.1 meter effective mold than does a linear mold taper. A closer comparison of the narrowface temperature profiles, shown in **Figure 12**, indicates that the parabolic taper tends to reduce the mold-shell contact near the bottom of the mold without significantly impacting other aspects of the temperature profile. The strong impact of the parabolic narrowface taper on the observed narrowface temperature fluctuations, which is shown more clearly in **Figure 13**, also suggests that the narrowface shell is better supported in the mid-length portion of the mold with parabolic taper than with linear taper.

The strong influence of the parabolic narrowface taper on the thermal behavior of the mold broadfaces observed in this investigation was somewhat surprising. The difference in the loose broadface heat flux profiles for the two mold designs, **Figure 9**, suggests that the broadface shell's tendency to pull away from the mold plate is influenced by the amount of shell support provided by the narrowface plate in the mid-length portion of the mold. The influence of the narrowface support extends all the way to the center of the broadface, as shown in **Figures 14 and 15**. Apparently with linear narrowface taper, the ferrostatic pressure on the broadface shell is still not sufficient to fully overcome the broadface shell's tendency to pull away from the mold wall for the first 400 mm that the shell forms in the mold.

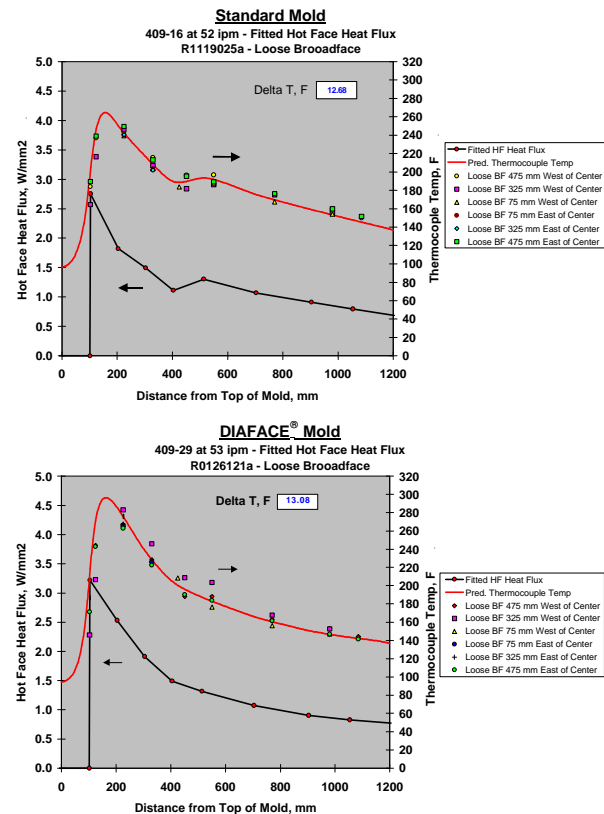


Figure 9: Calculated hot face heat flux for the two mold designs.

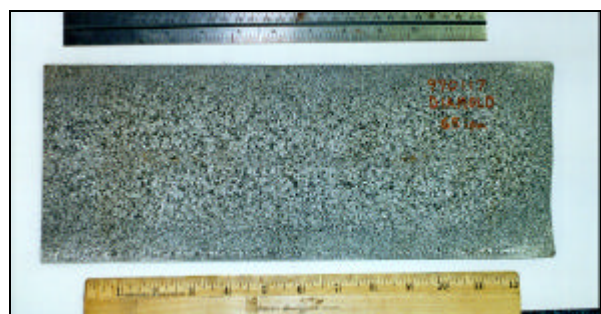


Figure 10: Slab Macroetch near narrowface for 409 stainless cast with the DIAFACE® mold; Transverse section through slab thickness.

DIAFACE® Mold

Standard Mold

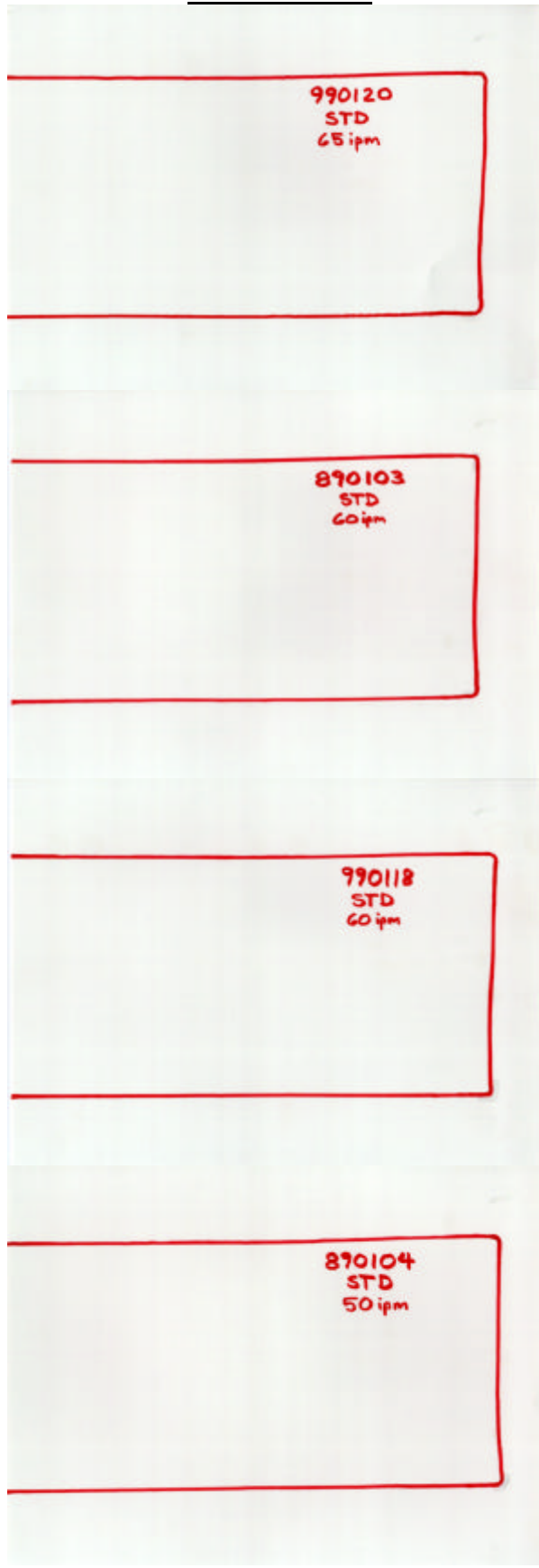
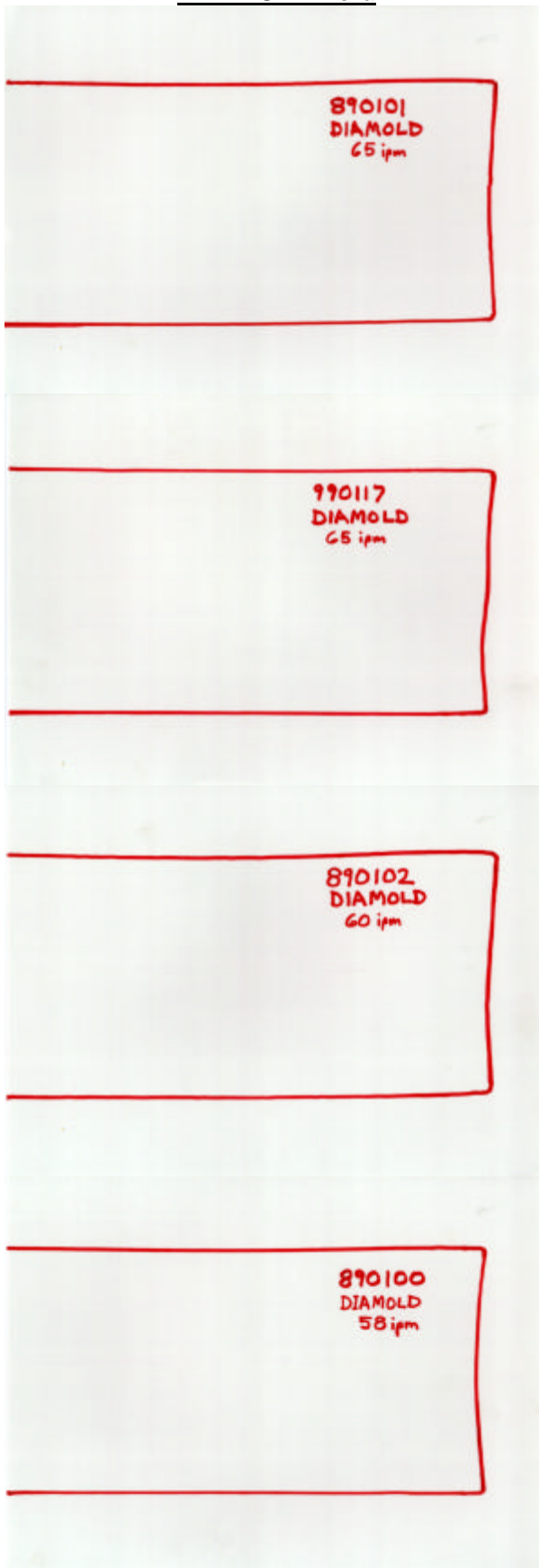


Figure 11: Tracings of as-cast slab shape near narrowface for 409 stainless cast with standard and DIAFACE® molds; Transverse section through slab thickness.

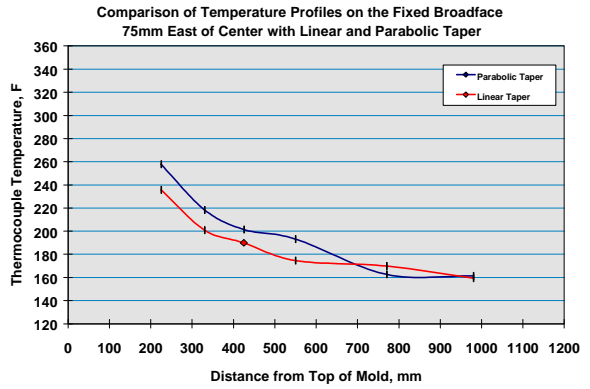
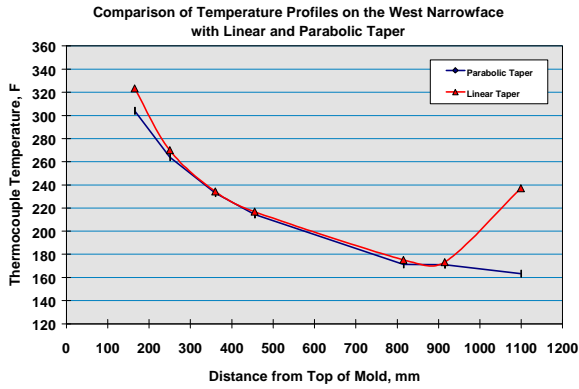
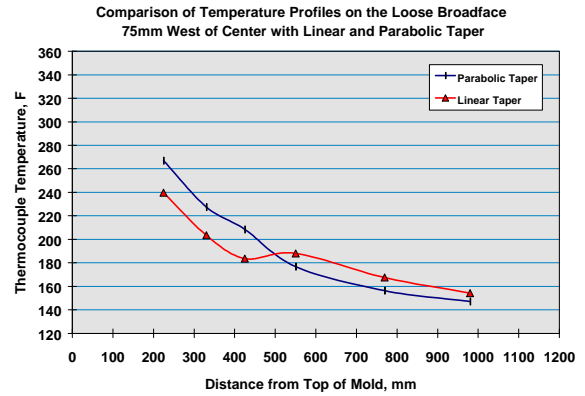
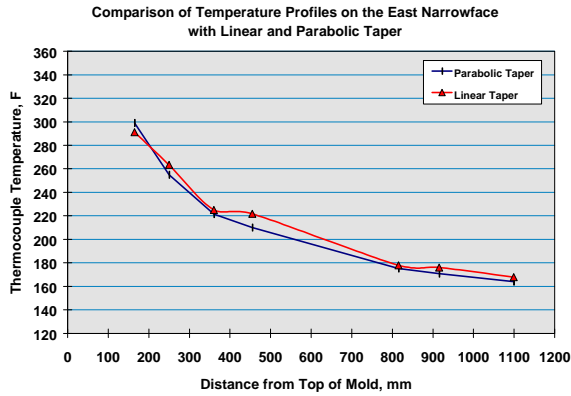


Figure 12: Comparison of steady state temperature profiles on the east and west narrowfaces with linear taper and DIAFACE® taper.

Figure 14: Comparison of steady state temperature profiles on loose and fixed broadfaces with linear taper and DIAFACE® taper.

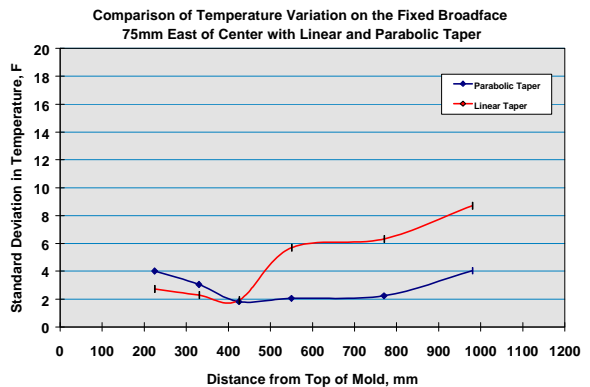
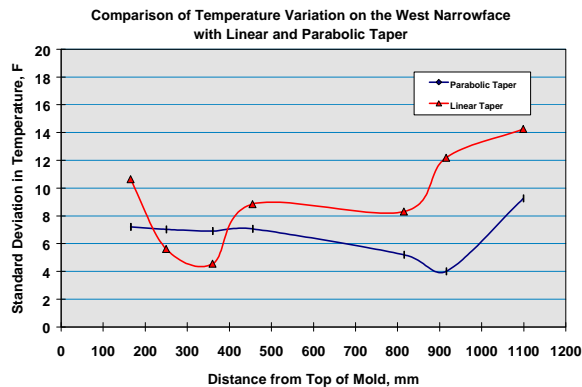
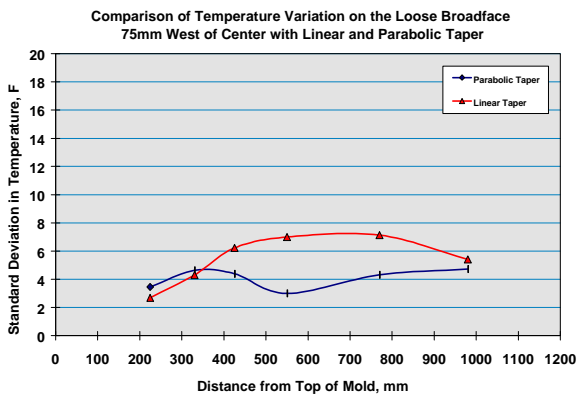
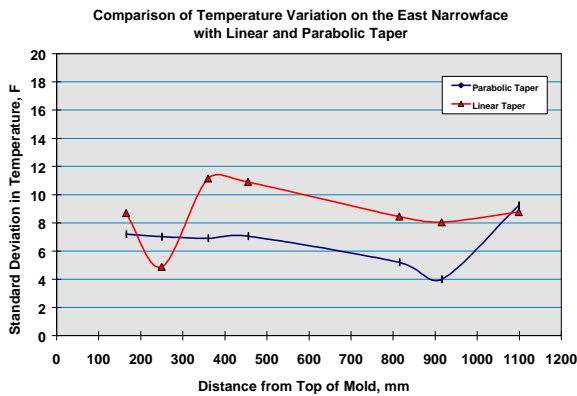


Figure 13: Comparison of temperature variability on the east and west narrowfaces with linear taper and DIAFACE® taper.

Figure 15: Comparison of temperature variability on the loose and fixed broadfaces with linear taper and DIAFACE® taper.

The additional shell support that is provided by the higher local narrowface taper high in the mold with parabolic taper appears to force the entire upper shell perimeter into better contact with the mold, counteracting the shell's tendency to shrink from the mold wall. This results in higher heat removal (**Figure 16**) high in the mold without an increase in thermal variability high in the mold (**Figure 15**). In addition, the reduced narrowface taper low in the mold provided by the parabolic taper profile appears to reduce the thermal variation low in the mold (**Figure 15**), suggesting that stability of the flux film is improved because of decreased friction in the lower part of the mold.

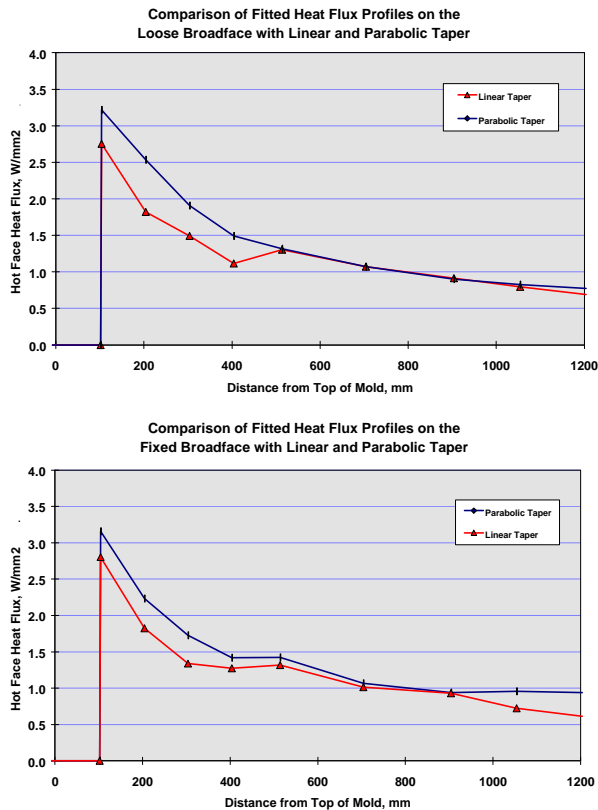


Figure 16: Comparison calculated heat flux curves for the loose and fixed broadfaces with linear taper and DIAFACE[®] taper.

The slight increase in concavity that is observed on the slab narrowface also indicates that the DIAFACE[®] mold remains in more intimate contact with the solidifying narrowface shell than with the standard linear taper mold. While this increase in concavity could suggest that the 1%/m equivalent taper employed in this trial may be too high, the small increase in concavity is inconsequential when weighed against the marked improvement in thermal stability observed with a 1%/m equivalent taper using the DIAFACE[®] mold. Additional trials will need to be performed to determine if the thermal stability improvements and reduced narrowface concavity are observed concurrently with lower equivalent operating narrowface tapers.

Previous studies at Mansfield with linear mold taper¹ have shown that the magnitude of the broadface temperature “rebound” observed in the mold is influenced by the grade of steel cast and the type of mold powder and mold oscillation practice employed. On low carbon, for example, no thermal rebound was observed on the mold broadfaces. On ferritic and martensitic stainless grades, however, varying amounts of thermal “rebound” were observed depending on the casting practice employed. The current investigation demonstrates that the shape of the narrowface taper profile can also influence thermal “rebound” in the mold. This recent finding provides additional supporting evidence that the “rebound” phenomenon in Mansfield’s mold is associated with the movement of the growing steel shell relative to the mold wall.

The relationship between mold temperature fluctuations and surface quality has been well documented by many investigators.⁽⁵⁻¹⁰⁾ Nonetheless, the casting trials conducted on 409 stainless with the DIAFACE[®] mold has failed to reveal any significant impact on surface quality in this study, despite the well documented decrease in thermal variability documented with the parabolic mold. We suspect that this result is a direct consequence of the high temperature fracture resistance of 409 stainless compared to other grades and the high level of surface quality that has already been achieved on this grade at Mansfield.

SUMMARY

The use of parabolic narrowface taper on 409 stainless cast at Mansfield with the 1.2 meter long plane parallel mold was found to have a strong positive influence on the operating stability of the mold, but no measurable influence on 409 quality. The improvements in operating stability observed in trials with the DIAFACE[®] mold include:

1. a reduction in shell-mold contact on the narrowface in the lower portion of the mold,
2. a reduction in temperature variability on the narrowfaces,
3. a decrease in thermal “rebound” on the mold broadfaces,
4. an increase in heat removal high in the mold on the broadfaces with no corresponding increase in temperature variability, and
5. a reduction in temperature variability in the lower portion of the broadface.

We believe that these documented benefits will result in more quantifiable surface quality improvements on more crack sensitive stainless grades, and plan to run additional DIAFACE[®] mold trials on these grades in the future.

ACKNOWLEDGEMENTS

The authors would like to thank all of the individuals at VAI, AK Steel's Technology Center, VAST, and AK Steel's Mansfield Operations that contributed to this investigation.

REFERENCES

- 1 "Observations of Various Steady State and Dynamic Thermal Behaviors in a Continuous Casting Mold", R. J. O'Malley: *Proc., 82nd Steelmaking Conf.*, ISS, Chicago, IL, pp. 13-33, 21-24 March, 1999.
- 2 "Casting Technologies Supporting the Development of Direct Hot Charged Carbon and Stainless Steel Production at Armco's Mansfield Operations", R. J. O'Malley: *Proc., 39th Mechanical Working and Steel Processing Conf.*, ISS, Indianapolis, IN, pp. 849-860, 19-22 October, 1997.
- 3 "Measurement of Temperature, Solidification, and Microstructure in a Continuous Cast Thin Slab", B. G. Thomas, R. J. O'Malley, and D. Stone, *Proc. Modeling of Casting, Welding & Advanced Solidification Processes VIII*, San Diego, CA, pp. 1185-1199, June 7-12, 1998.
- 4 "Spread Sheet Model of Continuous Casting", B. Thomas and B. Ho, *Trans. ASME*, Vol. 118, pp.37-44, Feb., 1996.
- 5 "Mold Powder Technology for Continuous Casting of Low-Carbon Aluminum-Killed Steel", S. Ogibayashi, T. Mukai, Y. Mimura, Y. Nagano, K. Yamaguchi, T. Takahashi, K. Koyama, T. Nakano, *Nippon Steel Technical Report*, No. 34, pp. 1-10, July 1987.
- 6 "Improvement of Surface Quality of Continuously Cast Slab", Y. Miyashito, M. Suzuki, K. Taguchi, S. Uchida, H. Sato, M. Yamamura, *Nippon Kokan Tech. Rpt.*, Overseas No. 36, pp. 55-64, 1982.
- 7 "Development of Mold Powder for Kakogawa No. 4 Slab Caster", S. Saruhashi, J. Abu, K. Matsuo, and K. Ebato, *Proc., 4th Int. Conf. On Molten Slags and Fluxes*, ISIJ, Sendai, Japan, pp. 462-467, 1992.
- 8 "Prevention of Surface Crack Formation in Continuous Cast Slab", T. Saito, M. Kimura, H. Ueta, T. Kimura, K. Takemoto, and T. Mine, *Kobelco Technology Review*, No. 11, pp. 53-57, June, 1991.
- 9 "Effect of Thermal Properties of Mold Flux on Surface Quality of Continuously Cast Slab", H. Yasunaka, H. Matsuda, and K. Matsuo, *Proc., 4th Int. Conf. On Molten Slags and Fluxes*, ISIJ, Sendai, Japan, pp. 409-414, 1992.
- 10 "The Performance of Mold Powders and Their effect on Surface Quality", K. C. Mills, *ISS Steelmaking Conference Proc.*, Vol. 77, pp. 121-129, April, 1991.