Casting Technologies Supporting the Development of Direct Hot Charged Carbon and Stainless Steel Production at Armco's Mansfield Operations

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ABSTRACT

Casting technologies that have contributed to the successful production quality flat rolled carbon and stainless steel at Mansfield will be reviewed, along with some recently implemented tools used to assist casting practice development. Future plans for the production of additional specialty steel grades at Mansfield will also be presented.

1. INTRODUCTION

In the two and one half years since the startup of the new thin slab caster at Armco's Mansfield operations, the practices necessary to produce high quality flat rolled carbon steels, 409 stainless steels and, most recently, 430 stainless steels have been successfully developed and implemented using a direct charge process routing without slab conditioning. Today, more than 50% of the 409 stainless supplied by Armco is produced at the new Mansfield facility, and 430 stainless produced at Mansfield is being successfully applied to demanding bright anneal applications.

2. CASTING TECHNOLOGIES

The successful production of quality carbon and stainless steels at Mansfield was achieved, in part, through the implementation of several key casting technologies and technical development projects aimed at producing high quality as-cast slabs suitable for direct hot charging. Supporting these key projects during the commissioning phase of the project was a joint development agreement between Armco and VAI. The responsibility for implementing these key technologies at Mansfield was split between VAI's research group in Linz, Austria, and Armco's Technology Center in Middletown, OH. The areas selected for joint development included[1]:

1) tundish flow control design and optimization of tundish operating practices,
2) submerged entry nozzle (SEN) design and optimization of SEN operating practices,
3) optimization of secondary cooling design and development of cooling practices for each grade, and
4) the development of mold oscillation strategies, testing the performance of the servohydraulic oscillator system, and the selection of mold powders.

2.1 Tundish Design

The Mansfield caster is equipped with a 30 ton capacity tundish with a 1 meter operating depth and automatic tundish level control to maximize steel cleanliness. Steel cleanliness is also enhanced through the use of synthetic tundish fluxes, complete shrouding of the steel during transfer, and an optimized tundish flow control configuration.

The work to optimize flow control in the Mansfield tundish was conducted at Armco's Technology Center in Middletown using a full scale water model. This work was conducted to select an optimum configuration for flow redirection to enhance steel cleanliness and to optimize tundish yield by minimizing vortexing during tundish drainage.

The flow control optimization development work explored various flow control design configurations incorporating baffles, weirs, dams, and redirecting impact pads. Residence time distributions were recorded under steady state conditions at 160 TPH, 120 TPH, and 80 TPH for each configuration by injecting pulse additions of a saline tracer at the tundish inlet and monitoring the conductivity of the water at the exit of the tundish. The flow redirection in the tundish was also recorded for each trial condition by mixing a visible dye with the saline tracer and videotaping the flow patterns after pulse injection of the tracer.

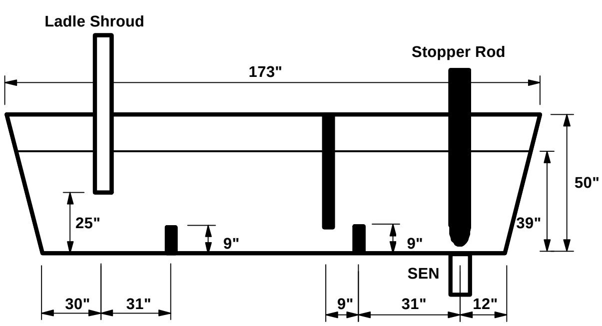

Fig. 1. Tundish flow control configuration for the Mansfield caster.

The flow control configuration that was adopted for Mansfield is shown in **Fig. 1**. This dam-weir-dam configuration proved to be very effective at redirecting flow in the tundish in a manner favorable for inclusion capture to the synthetic slag layer, while also minimizing short circuiting and dead volume in the 80 TPH to 160 TPH throughput range. The dam-weir-dam configuration was also found to be superior to equivalent dam-baffle configurations in resisting vortexing during tundish drainage. The flow patterns and RTD distributions obtained for the Mansfield tundish configuration are shown in **Figs. 2 and 3**.

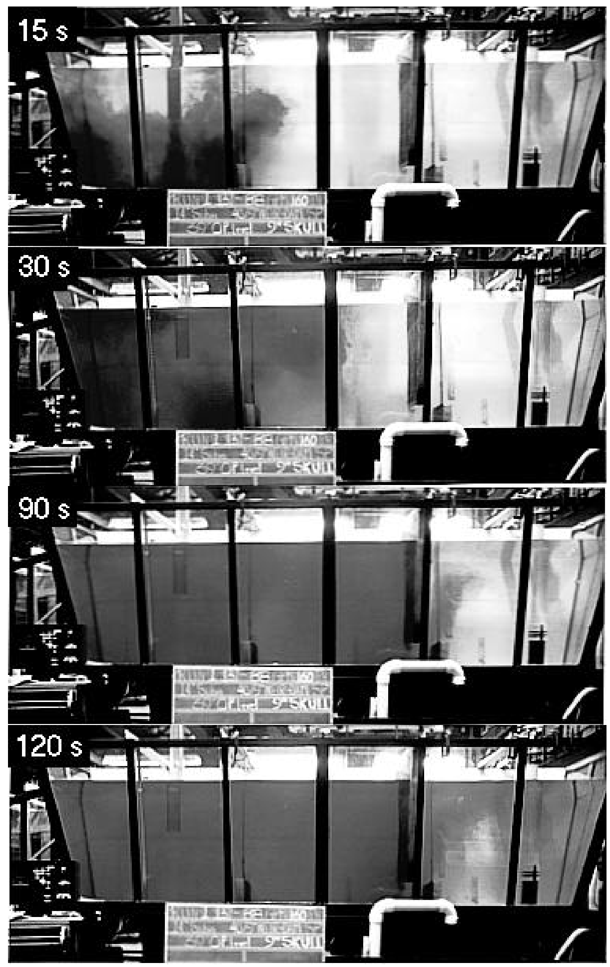

Fig. 2. Visible dye injection sequence in tundish water model at 160 TPH.

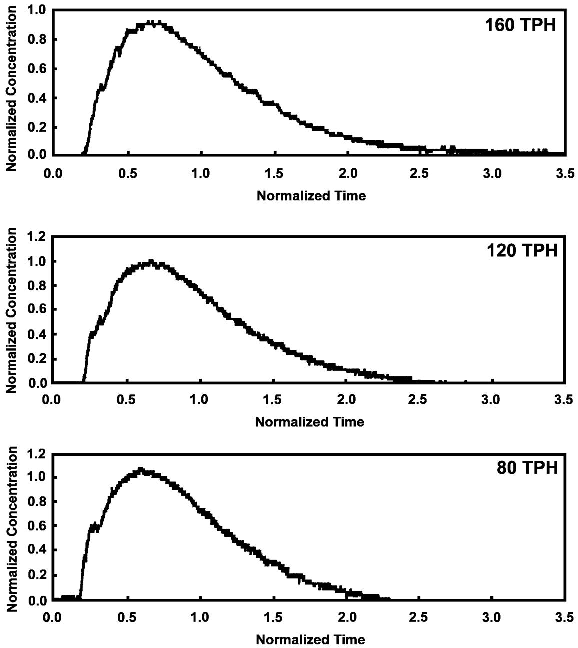

Fig. 3. Tundish residence time distribution plots at 160, 120, and 80 TPH throughputs.

2.2 SEN Design

Although it was recognized that the fluid flow conditions and turbulence in the mold must be carefully controlled to produce a quality direct hot charged product, Armco elected not to install an electromagnetic break (EMBR) on the Mansfield caster. Instead, provisions were made to ensure that an EMBR unit could be added in the future, if necessary. This decision was made based on initial work conducted by VAI on a multi-port SEN design that showed promise in controlling turbulence and wave activity in the Mansfield mold configuration. VAI conducted extensive water modeling work in their research facility in Linz to optimize the SEN design for a 100 mm cast slab thickness for the casting conditions expected at Mansfield.

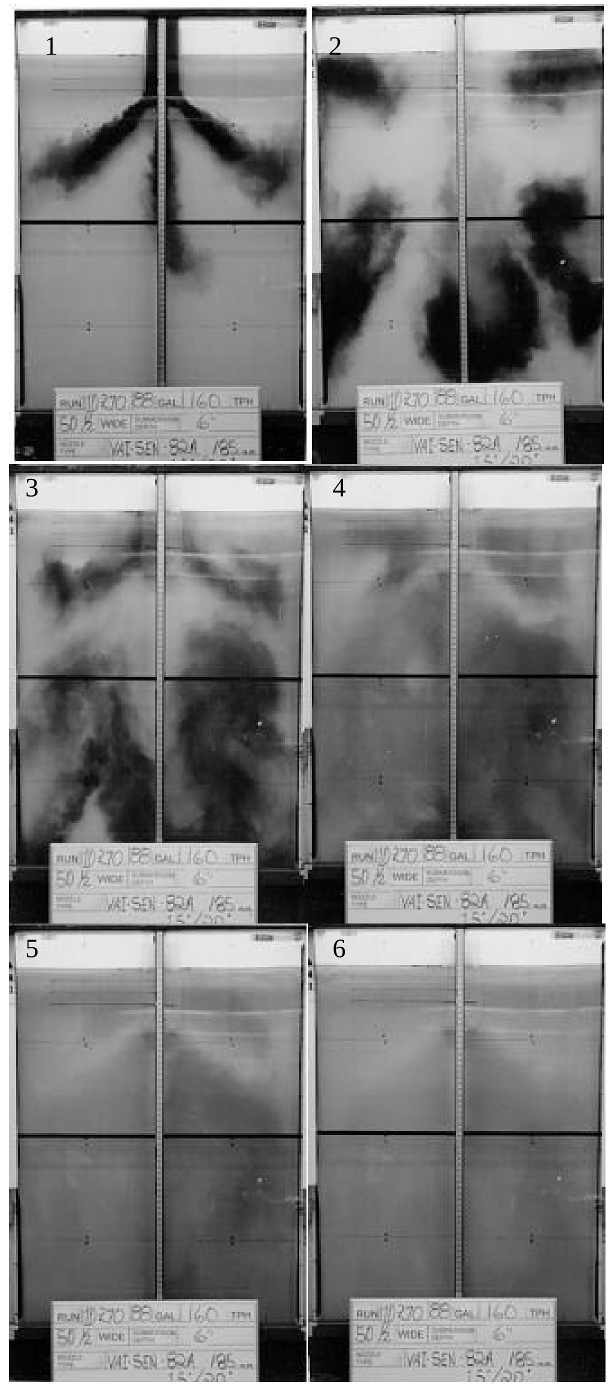

Fig. 4. Visible dye injection sequence in the mold water model at 160 TPH.

Final refinements to the VAI SEN design proposals were made at Armco's Technology Center using a second full scale water model of the mold to adapt the VAI recommendations to accommodate a submerged SEN exchange system. Mansfield's SEN design and submergence practices were optimized for 100 mm and 132 mm cast slab thickness, 635 mm to 1283 mm slab widths, and 80 to 160 TPH throughputs. An example of the fluid flow and surface activity obtained in the water model with the SEN design is shown in **Fig. 4**.

The incorporation of a submerged SEN exchange system on the Mansfield caster proved to be extremely beneficial, eliminating SEN life as the primary limit to sequence length. Today, ten heat sequence of 409 stainless are commonplace at Mansfield, and the current limitation to sequence length is the life of the stopper rod tip.

2.3 Mold Oscillation

The Mansfield caster was equipped with VAI's first commercial servohydraulically driven mold oscillation system to support Armco's direct charge processing strategy for the production of specialty steel grades at Mansfield. To maximize the flexibility in mold oscillation practice, both oscillation stroke and frequency can be adjusted with casting speed during casting, and non-sinusoidal oscillation asymmetries of from 50% (sinusoidal) to 80% can be employed, as shown in **Fig. 5**.

The operating frequency range for the oscillator is 0 to 400 cpm and the oscillator stroke range is 0 to 12.7 mm. In practice, the oscillator may be operated within any of the above mentioned ranges that fall within a 0.5 G mold acceleration limit.

The mold oscillation practice on the Mansfield caster is specified for each grade by six oscillation parameters, C_1-C_6. The oscillator stroke and frequency can be controlled according to the following relationships,

$$s = C_1 + C_2 \times V_c \quad (1)$$

$$f = C_3 + C_4 \times V_c + C_5 \times (1000 \times V_c/(2 \times s)) \quad (2)$$

and the non-sinusoidal factor is specified as follows:

$$C_6 = \tau/100 \quad (3)$$

where s is oscillator stroke in mm, f is oscillator frequency in cpm, V_c is casting speed in m/min., and τ is the percentage of non-sinusoidal asymmetry.

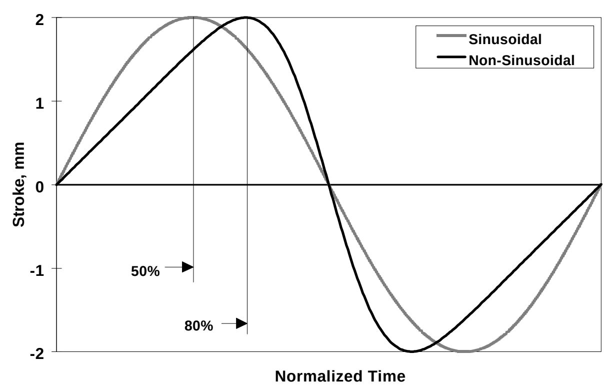

Fig. 5. Range of non-sinusoidal oscillation capabilities.

A unique oscillation practice that has been in use at Mansfield since startup is the so called inverse frequency control practice[2]. With this practice, shown in **Fig. 6**, the oscillator stroke is increased with casting speed and the oscillator frequency is decreased with casting speed.

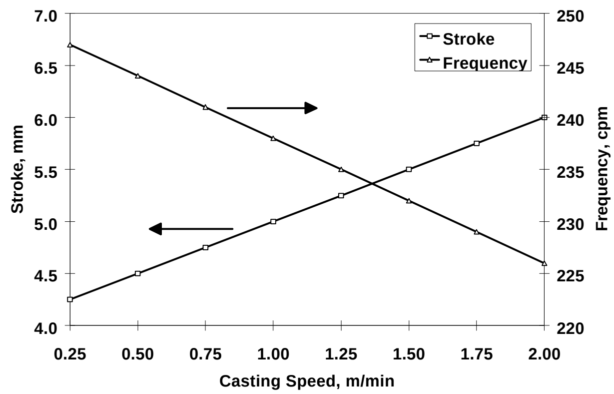

Fig. 6. Typical inverse frequency oscillation practice.

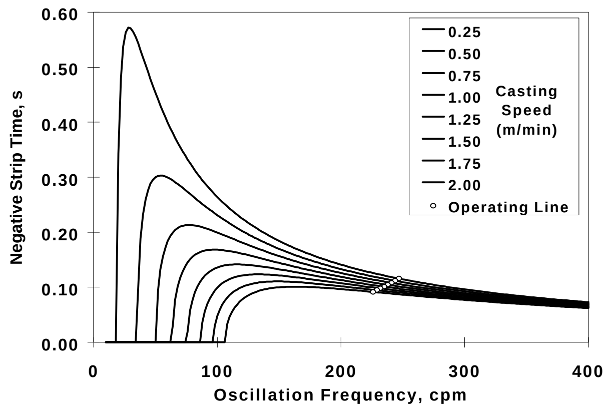

Fig. 7. Mold oscillation operating line with inverse frequency control.

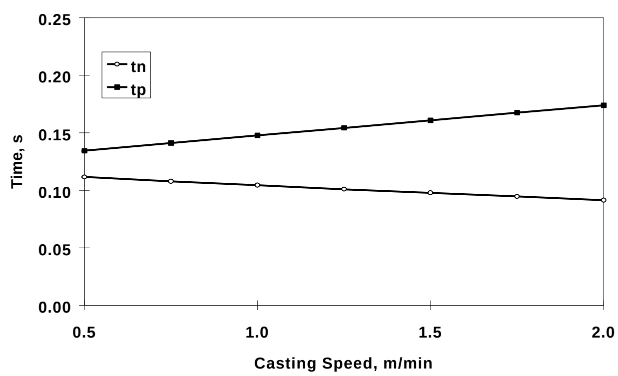

Fig. 8. Typical negative and positive strip times with inverse frequency oscillation.

As shown in **Figs. 7 and 8**, the inverse frequency control practice maintains a low and relatively constant negative strip time within a stable region of mold oscillation to control oscillation mark depth, while increasing positive strip time with increasing casting speed to promote enhanced mold powder consumption[3] where it is needed most. An example of the relationship between mold powder consumption and casting speed observed on the Mansfield caster for low carbon steel using the inverse frequency mold oscillation practice is shown in **Fig. 9**.

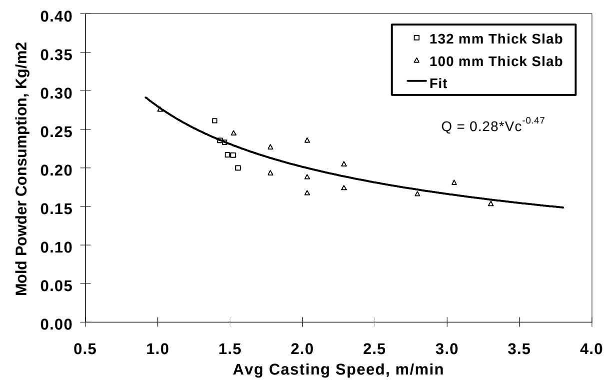

Fig. 9. Mold powder consumption observed on low carbon steels at 4” and 5.2” slab thickness with inverse frequency oscillation.

2.4 Secondary Cooling

The secondary cooling system on the Mansfield caster is another area that was given special attention by Armco. Air mist cooling with air pressure control was installed on the caster to ensure that the wide range of secondary cooling demands for the specialty grades to be produced in Mansfield could be met. VAI’s DYNACs dynamic spray control system was also installed to ensure that secondary cooling is appropriately controlled under both steady state and transient caster operating conditions.

The air mist nozzles and header layouts initially proposed by VAI were tested for spray density uniformity by Armco in the Technology Center in Middletown prior to startup[1]. Based on these measurements, refinements were made to the air mist nozzle design in several critical spray cooling zones to improve spray density uniformity. Modifications were also made to the DYNACs software to allow the models thermophysical properties to be more readily accessed and modified for future model tuning work.

3. RECENT DEVELOPMENTS

The success of the joint development project approach that was adopted for the commissioning of the Mansfield caster prompted Armco and VAI to continue the joint development efforts beyond commissioning and to initiate several new joint projects. Some of the more recent joint development projects include: (1) implementation of an instrumented mold to improve our understanding of the thermal behavior of Mansfield's 1.2 m long parallel plate mold and (2) development of a prototype mold friction monitoring system using pressure measurements from the servohydraulic oscillator to examine mold lubrication behavior.

Other joint projects that are still ongoing include: (3) verification and tuning work on the dynamic spray control system through the use of strain gauges for liquid core on detection and optical pyrometers and trace thermocouples for strand surface temperature measurement and (4) periodic audits of the quality of carbon steel produced in Mansfield.

Still other joint projects that are under consideration include: (5) evaluation of the VAI's new variable mold narrow face taper (DIANA) technology, and (6) evaluation of VAI's dynamic liquid core reduction (SMART) technology on the Mansfield caster.

3.1 Mold Thermal Monitoring

To better understand the thermal behavior of the Mansfield mold, an experimental mold was equipped with 106 stud welded copper constantan thermocouples, as shown in **Fig. 10**. The thermocouple temperatures were collected along with casting speed and mold level at 5 second intervals using a computerized data acquisition system. Some typical thermocouple data obtained from the instrumented mold are shown in **Fig. 11**.

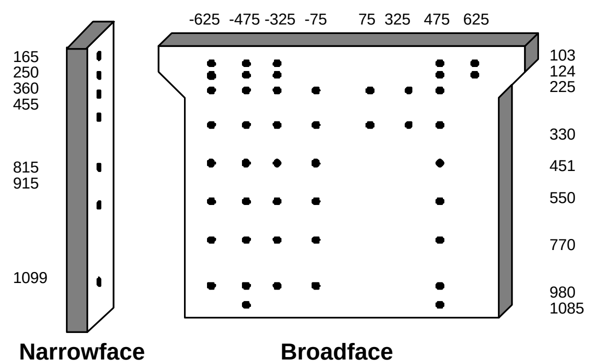

Fig. 10. Thermocouple layout employed on instrumented mold relative to mold top center position, in mm.

Steady state temperature distributions in the Mansfield mold were examined by extracting the mean thermocouple temperatures and standard deviations of these temperatures under a wide range of steady state casting conditions. A typical steady state temperature profile for 409 stainless is shown in **Fig. 12**.

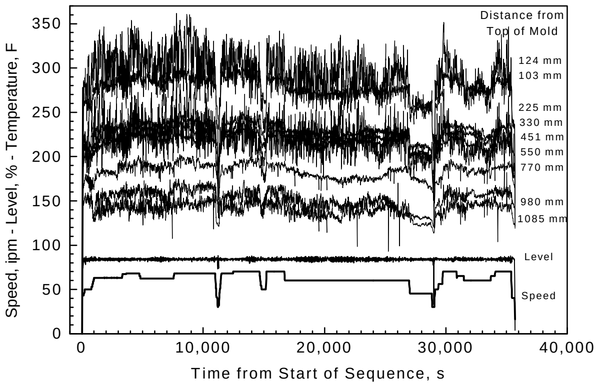

Fig. 11. Typical mold thermocouple temperatures from an 8 heat sequence of 409 stainless. Fixed broadface 475 mm east of mold centerline.

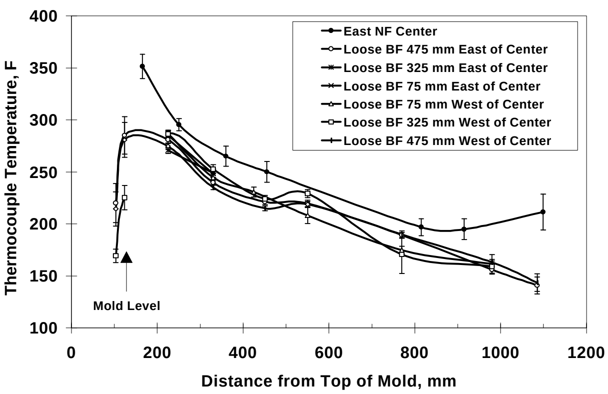

Fig. 12. Typical steady state temperature distribution on the loose broadface for 409 stainless cast at 70 ipm.

The steady state thermocouple temperatures were employed to calculate heat flux profiles for the mold hot face with the help of a two dimensional thermal model of the mold[4]. The heat flux profile was fitted to force agreement between the predicted and measured thermocouple temperatures and the total mold heat removal that was determined by separate measurements of the mold water temperature rise. A typical fitted hot face heat flux profile is shown in **Fig. 13**.

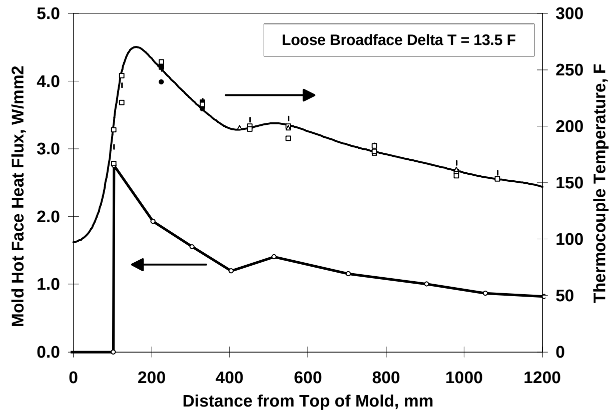

Fig. 13. Mold hot face heat flux profile for 409 at 60 ipm determined by fitting mold thermal model results to measured thermocouple temperatures and mold water heat extraction.

The temperature distributions in the mold, the time variability of these temperatures, the calculated hot face heat fluxes, and the calculated mold face temperatures obtained from studies with the instrumented mold have been important tools for the development of casting practices at Mansfield.

3.2 Mold Friction Monitoring Feasibility

The potential for extracting mold friction information from the servohydraulic oscillator was recognized early in the Mansfield project. Pressure transducers were incorporated into the initial oscillator cylinder design to allow the inlet and outlet pressures of each cylinder to be monitored, and a high speed data collection system was installed to examine the oscillator performance. The feasibility of using these existing systems for monitoring mold friction was examined in a recent Armco-VAI joint development project.

The net cylinder force, F, was determined for each of the two hydraulic cylinders used for mold oscillation using equation 4,

$$F = (P_{in} - P_{out}) \times A \tag{4}$$

where P_{in} is the cylinder inlet pressure, P_{out} is the cylinder outlet pressure, A is the cylinder cross sectional area. The net force due to mold friction, $F_{friction}$, was determined by subtracting the total cylinder force measured in an off-line test with no metal in the mold, $F_{offline}$, from the total cylinder force measured during casting, $F_{casting}$, at equal operating stroke, frequency and non-sinusoidal factor.

$$F_{friction} = F_{casting} - F_{offline} \tag{5}$$

Some examples of the cylinder force and position traces extracted from on-line and off-line cylinder pressure measurements from Mansfield's servohydraulic oscillator are shown in **Figs. 14 and 15**. A comparison of cyclic friction forces with the cyclic velocity of the oscillator and the velocity of the strand in **Fig. 16** shows that the calculated mold friction forces change sign during the negative stripping time, t_n, as expected, supporting the validity of the friction measurement.

To examine the feasibility of on-line friction monitoring, a complimentary data collection system was installed as part of the joint project that allowed total cylinder work, W, to be calculated and observed on-line[5]. The work was calculated from the area bounded by the force-displacement cycles shown in **Fig. 15**,

$$W = \int^{1\ \text{cycle}} (P_{in} - P_{out}) \times A \times ds \tag{6}$$

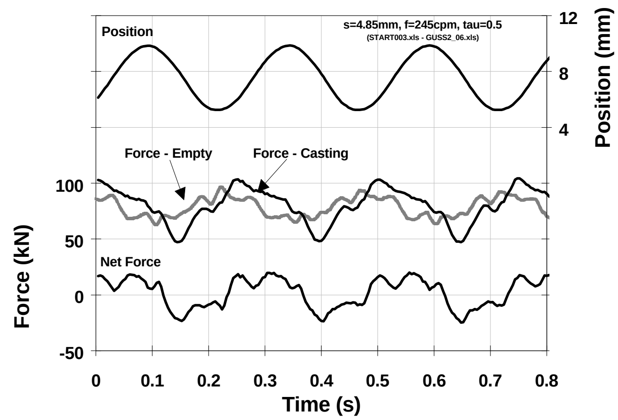

Fig. 14. Net friction force extracted from oscillator cylinder hydraulic pressure measurements.

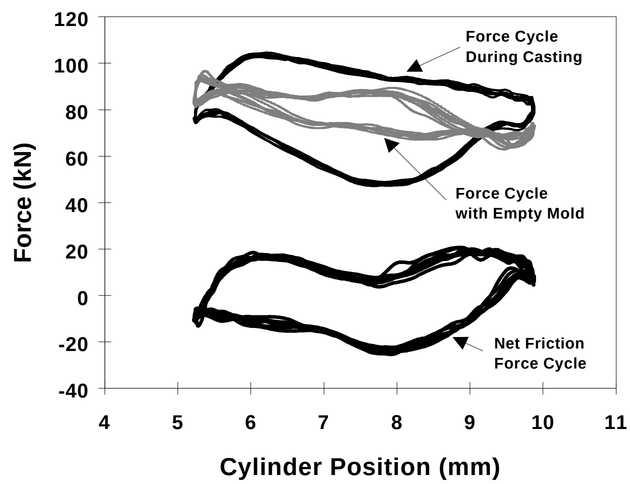

Fig. 15. Force vs. cylinder position for empty mold and during casting, and net friction force determined by difference.

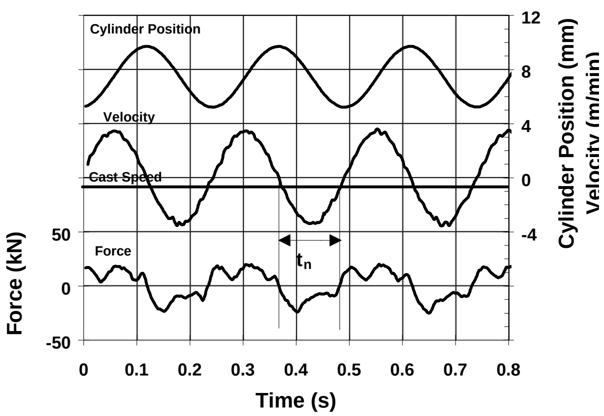

Fig. 16. Net strand friction force over several oscillation cycles.

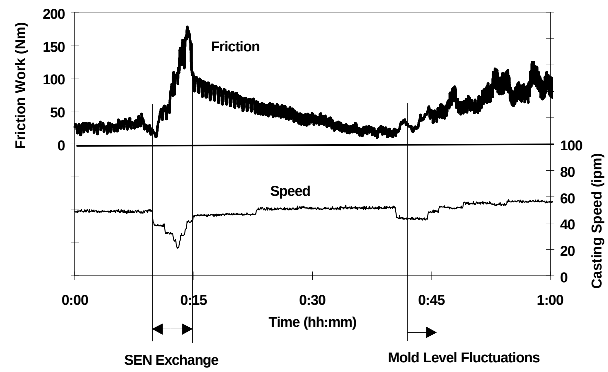

Fig. 17. Typical mold friction trend.

where A is the cylinder cross sectional area and ds is the differential cylinder position. The net work due to mold friction, $W_{friction}$, was determined by subtracting the total cylinder work measured during off-line oscillator operation, $W_{offline}$, from the total cylinder work measured during casting[5], $W_{casting}$.

$$W_{friction} = W_{casting} - W_{offline} \quad (7)$$

The work due to mold-strand friction was trended in real time by developing a parametric representation of $W_{offline}$ as a function of stroke, frequency, and non-sinusoidal factor from off-line oscillator tests and substituting the relationship into equation 7 to calculate $W_{friction}$ from $W_{casting}$ in real time.

An example of a typical friction trend plot determined from this prototype system is shown in **Fig. 17**. As shown this figure, the friction trends observed using the prototype system suggest that events such as SEN exchanges and mold level fluctuations can have a strong influence on mold friction, and that their effects can sometimes persist for 15 to 20 minutes after the event takes place.

Because of the promising results from the prototype system, Armco and VAI are currently examining options for installing a permanent mold friction monitoring system on the Mansfield caster.

3.3 Secondary Cooling Model Verification

Verification and tuning of the secondary cooling model for the various steel grades produced in Mansfield is an ongoing effort. While the VAI secondary cooling model has performed well to date at Mansfield, the underlying thermophysical properties and boundary conditions within the model must be verified and fine tuned to optimize the secondary cooling model's performance for each grade. This verification and optimization work is considered to be an especially important part of the practice development for new specialty grades at Mansfield, since the thermophysical properties of many of Armco's specialty grades are not as well documented as they are for carbon steels, and the strand temperature must be carefully controlled on many of these grades to avoid surface defects.

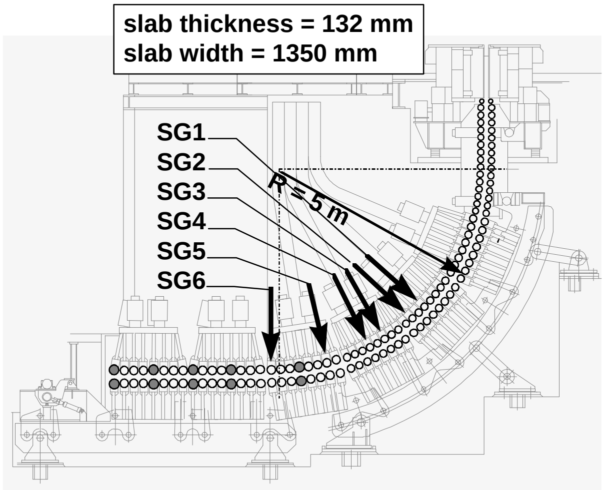

Fig. 18. Location of strain gauges in caster.

The ongoing work to verify the secondary cooling model is being performed by measuring strand surface temperatures using optical pyrometers and trace thermocouples, and by measuring the position of the liquid core through the use of strain gauges at various locations in the caster[6], as shown in **Fig. 18**.

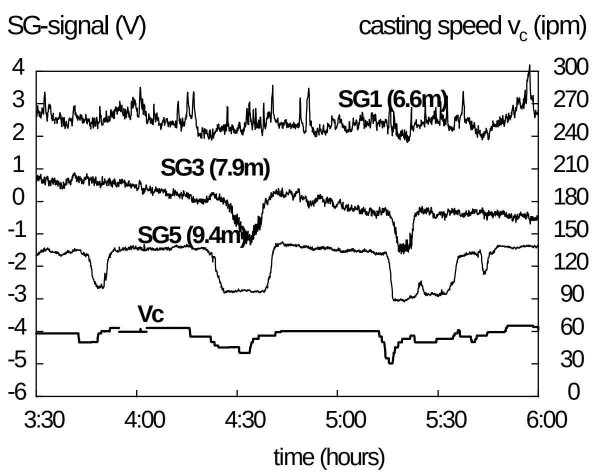

Fig. 19. Typical strain gauge signals.

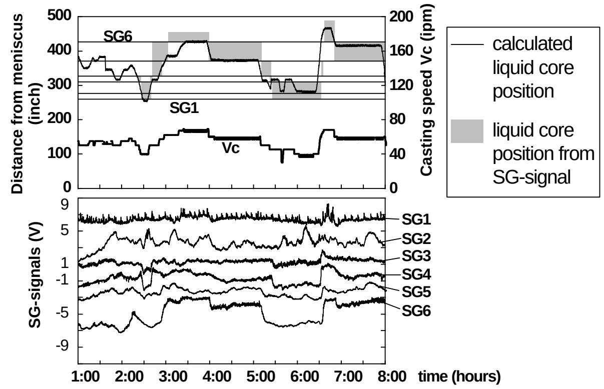

Fig. 20. Comparison of measured and predicted liquid core position for low carbon steel.

Liquid core position measurements are performed by attaching strain gauges to the support webs of various non-driven rolls on several segments, and measuring the small deflection of the support web that results when the liquid core passes under the roll is recorded during casting by the strain gauge. Some typical strain gauge signals are shown in **Fig. 19**.

The strand temperatures and liquid core predictions from VAI's dynamic spray control model are archived along with additional caster operating data to allow these predictions to be readily compared with strand surface temperature and liquid core verification measurements. An example of a comparison between predicted and measured liquid core positions for a low carbon steel grade is shown in **Fig. 20**.

4. CASTING PRACTICE DEVELOPMENTS

While the production of quality direct hot charged carbon steel proved to be relatively straightforward at Mansfield, the production of quality 409 stainless at Mansfield proved to be somewhat more difficult to accomplish. Despite some serious initial problems with scale streaks, short line defects, and ridging, these problems were all overcome and commercial production of 409 stainless was achieved within the first year of operation. An index of the successive improvements made to the surface quality of 409 during the first year of operation is shown in **Fig. 21**.

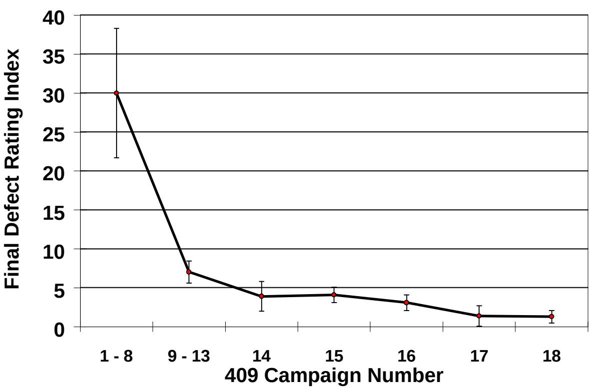

Fig. 21. Progression of hot band surface quality improvements on 409 stainless at Mansfield.

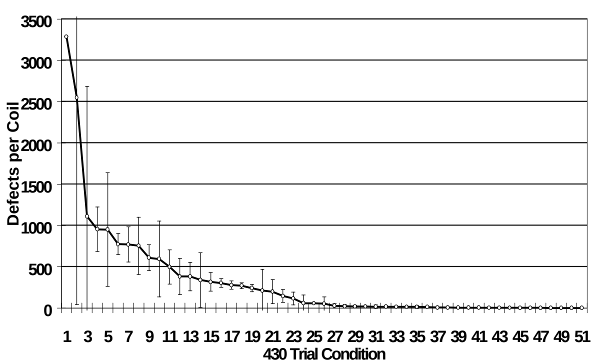

Fig. 22. Reduction in short line defects on 430 stainless at Mansfield by trial condition.

The development of the casting practices for producing direct charged 430 stainless at Mansfield proved to be more difficult than for 409. The principal caster defects that had to be overcome on 430 were short line defects and caster folds. The progress made in eliminating these defects over the past year in Mansfield is shown in **Figs. 22 and 23**. The 430 produced at Mansfield is now being successfully applied to demanding bright annealed applications.

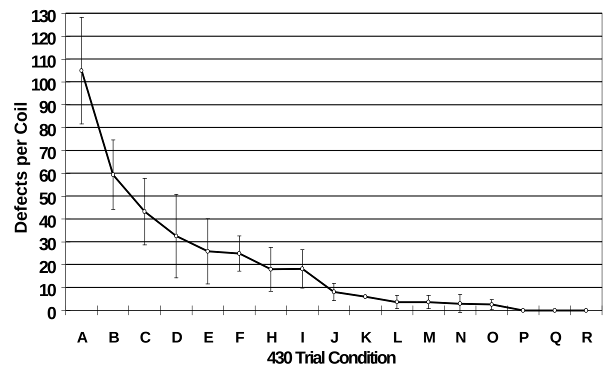

Fig. 23. Reduction of caster fold defects on 430 stainless at Mansfield by trial condition.

The success in achieving bright anneal quality on 430 stainless is a testament to the flexibility of the VAI caster, and to the casting technologies that have been employed to produce high surface quality direct charged specialty steels at Mansfield. Today, as shown in **Fig. 24**, stainless production at Mansfield is at about 20,000 TPM. With the recent successes in the development of the 430 casting practices the proportion of stainless production is expected to increase further in the near future.

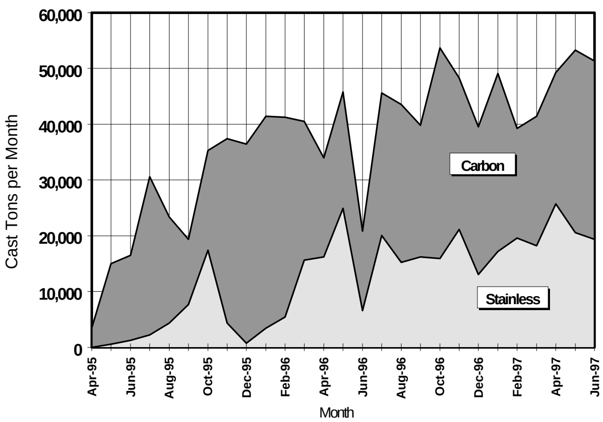

Fig. 24. Carbon and stainless production at Mansfield Operations.

5. FUTURE DEVELOPMENTS

With the development of practices for direct hot charge processing of 409 stainless and 430 stainless at Mansfield now successfully completed, Armco is now focusing its efforts on the development of practices for producing other new grades at Mansfield. Work is already underway to develop practices for other unstabalized high chrome grades, such as 434 and 436 for automotive trim applications. Efforts have also begun for producing martensitic stainless grades, such as 410, 420, and possibly 440 stainless, at Mansfield. In the longer term, Armco plans to continue expanding the production of specialty ferritic grades at Mansfield to take advantage to of the lower costs, higher yields, and shorter lead times inherent in Mansfield's direct hot charge process routing.

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REFERENCES

1. R. O'Malley, A. Flick, G. Hohenbichler, *Proc. VAI CCC'96*, Slab Session, Paper 16, pp. 1-17, Linz, Austria, May, 1996.
2. M. Wolf, *ISS Steelmaking Conference Proc.*, Vol. 74, pp. 51-71, April, 1991.
3. M. Suzuki, *et al.*, *ISIJ International*, Vol. 31, No. 3, pp. 254-261, 1991.
4. B. Thomas and B. Ho, *Trans. ASME*, Vol. 118, Feb., pp.37-44, 1996.
5. M. Ozgu, *Canadian Metetallugical Quarterly*, Vol. 25, No. 3, pp. 199-223, 1996.
6. K. Morwald, J. Watsinger, and R. O'Malley: *Conf.*, Instrumentation and Control Developments in Steelmaking and Casting, The Royal Society, London, UK., 25-26 March, 1997.