

Final Scientific Report

Steel Foundry Refractory Lining Optimization

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1.0 Executive Summary

The steel foundry refractory lining optimization study has added to the current knowledge of refractory issues in steel foundries in four main areas.

- (1) Improved understanding of high temperature chemistry and slag/refractory interactions in acid and basic foundry steelmaking practices.
- (2) Determination of the degree of magnesia dissolution into basic slags at the high temperatures and quite variable slag chemistries utilized by steel foundries.
- (3) Knowledge of the potential impact of ladle insulation and pre-heat on tap temperatures and the corresponding impact on steel foundry energy efficiency.
- (4) Knowledge of the nature and origin of defects in steel castings that result in the extensive grinding that is normal to current castings.

In almost every instance, the suggested refractory/process modifications were proven to be both technically and economically feasible. The difficulty in implementation of the proposed changes relates to the "up front" expense and the learning curve associated with any process modification. These two issues were compounded by production slow downs that are too common in the current market. Such slow downs normally result in less energy efficient processing coupled with reductions in capital or "up front" expenditures. A return to historical norms should allow foundries to implement the suggested modifications and then evaluate the overall benefit.

Besides the modest energy savings that should result from widespread implementation of the program results, the corresponding economic gains should help to keep foundries competitive, preserving a number of manufacturing jobs. An overall improvement in the quality of steel castings produced should have two main benefits. The first relates to improved performance of the castings and a longer useful lifetime. The second benefit is that improved castings may allow steel foundries to penetrate markets that currently use other materials, further improving the viability of a small but important manufacturing sector.

2.0 Goals and Objectives

The overall objective of the steel foundry refractory lining optimization program was to review established refractory and steelmaking practices to identify opportunities for improvements that would yield substantial energy savings for steel foundries. Energy savings were expected to arise from improved efficiency of the electric arc furnaces and from reductions in the post-casting welding and grinding that are normally required. Ancillary energy savings related to a reduction in the amount of refractories currently produced to meet the needs of the steel foundry industry, and a shift from pre-fired materials (shaped refractories) to monolithic refractories that are heat treated "in situ" were anticipated.

A review of the complete program results indicates that techniques for achieving the overall goal were demonstrated. The main difference between the predicted and the actual achievements relates to the areas from which actual energy savings could be realized. Although reductions in furnace tap temperature would result in a reduction in the power required for melting, such reductions are realized through changes within the ladle transfer portion of the process, through modified ladle pre-heat and refractory insulation. Reductions in clean room energy usage proved very difficult to track, and some questions as to just how much impact refractory related inclusions have on the degree of welding and grinding required for completion of a casting, remain. Post-mortem analysis of casting defects did identify refractory derived inclusions but the greatest concentration of inclusions related to steel reoxidation issue.

3.0 Project Activities

The overall objective of the program was to optimize refractory materials and foundry processing used in casting steel. This objective was to be met by completing the following:

- (1) Surveying the steel foundries both through paper/electronic surveys sent to North American steel foundries as well as plant visits to participants. Information concerning refractory selection and performance as well as refractory and steelmaking practices provides a baseline for future comparison and to identify opportunities for substantial improvement in energy efficiency.
- (2) Conducting post-mortem analysis of materials from existing refractory/steelmaking practices to determine wear/failure mechanisms.
- (3) Identify areas for research on developing refractories for use in steel foundry furnaces, adjusting steelmaking practices to improve efficiency and modifying slag practices to improve refractory performance.

Upon completion of the first two research areas, the original intent was to use a small electric arc furnace located on the campus of the University of Missouri-Rolla to conduct laboratory experiments. Difficulties associated with accessing and re-commissioning the 350lb electric arc furnace (EAF) led to a decision to modify the research approach to utilize other equipment on campus to conduct the necessary laboratory experiments. This variance likely had a positive impact on the overall research program as resources were not devoted to attempting to adequately simulate the wide variety of steelmaking practices that are used by the steel foundry industry. Instead, much of the "proof testing" of promising process/material modifications had to be completed at participating steel foundries. The time spent in the foundries facilitated knowledge transfer in both directions which helped to focus the direction of the research to areas of true need and promise.

The initial survey data showed that the types of EAFs were as varied as the types of refractories selected to line the vessels. The data also indicated that furnace size played an important role in refractory performance so it is likely that adequately simulating the varied processes with a single, small EAF may have been quite difficult. A fairly even split between and basic steelmaking slag practices and extremely high furnace tap temperatures would have pushed the limits of a university-based EAF. Additional paper surveys were conducted throughout the program to provide additional information and clarification of the data and to help focus the research efforts.

Although quite helpful, paper surveys are never as useful as plant visits and person-to-person exchanges. As such, a considerable expenditure of resources devoted to travel to participating foundries. A number of visits were initiated over the course of the program including:

- (1) Missouri-Kansas-Iowa-Illinois
- (2) Chicago-Northern Indiana
- (3) Indiana-Ohio
- (4) Chicago-Milwaukee
- (5) Pennsylvania
- (6) Missouri
- (7) Tennessee-Alabama

These visits were spread out over the initial two years of the program and a number of plants were visited on numerous occasions. Most of the visits were 2-4 hours in duration providing ample time to tour the facility, review the materials and practices utilized and discuss critical aspects related to the program. In most cases, refractory samples were either acquired, or at least specified, for use in the post-mortem activity. Paper surveys were also completed for foundries that had not yet participated in that activity.

In almost every instance, tap temperatures were found to be extremely high, especially in the case of foundries using an acid slag practice. Often the survey data did not accurately relay the degree of superheat that was actually used in practice. Such discrepancies were not likely intentional but instead represent the nature of steel foundries, and quite possibly foundries in general, where the casting shop dictates the furnace practice. Foundries are required, by necessity, to guarantee that the last casting can be completed. As such the furnace tap temperature is raised to a level where there is sufficient heat in the liquid metal to fill not only the first casting but also the last. For foundries casting small parts where a large number of castings are poured from the same heat of steel, those that have infrastructural issues that cause considerable time to elapse during transfer of the molten metal from the furnace to the castings, those that have infrastructural issues that cause considerable time to elapse during transfer of the molten metal from the furnace to the casting floor, and those that pour into ladles and then re-ladle into smaller ladles prior to casting, the superheat required can be extremely large. In the worst scenarios, tap temperatures in excess of 3300°F (1850°C) were common.

High tap temperatures are of greatest concern in foundries using an acid slag practice therefore requiring the use of acid refractories. Acid refers to practices based upon largely silica slags while basic practices are based on slags containing added lime (CaO). Refractories that are resistant to silica are not normally able to withstand the extreme tap temperatures that are used in many foundries. At times the melting temperatures of acid refractories are actually below the typical tap temperature. More refractory, silica resistant materials had to be developed for these applications. Tap temperatures in foundries using a basic slag practice, although substantially lower than the acid based foundries, were still considerably higher than would initially be assumed necessary. On average basic refractory materials have considerably high melting temperatures than acid materials; however the elevated temperatures will still result in greatly accelerated refractory wear.

In both cases, the tap temperatures were a major concern, so extensive post-mortem analysis was conducted to establish with reasonable certainty, the prevailing wear mechanism(s) involved. Samples from any foundry were accepted but those representing the range of practices, furnace size and tap temperatures were actively pursued. Upon arrival at UMR, samples were logged and photographed, and sectioned into manageable sizes and geometry. The samples were then encased in plastic, ground and polished in preparation for post-mortem analysis using reflected light and cathodoluminescence light microscopy. The orientations of the samples were preserved in order to provide a continuous record of the microtexture of the refractory samples from the hot face in contact with the slag and molten metal to the cold face.

The cathodoluminescence technique is especially suited for this type of analysis. The color images that result are invaluable for understanding the wear of refractory materials. As expected

from the survey and plant visit data, post-mortem analysis indicated that the extreme tap temperatures caused much of the wear encountered in acid practices. One example of this was observed in samples provided by an acid practice foundry using zircon ($ZrO_2 \bullet SiO_2$) refractories. Zircon is quite refractory but will undergo decomposition into zirconia and silica above a temperature of about $1650^\circ C$ ($3000^\circ F$). The post-mortem analysis of the hot face indicated that no zircon particles were present; particles that originally constituted nearly 100% of the refractory lining. Instead the hot face contained a number of recrystallized zirconia crystals in a matrix of iron silicate glass. The recrystallized zirconia indicates that not only had the zircon decomposed, the resulting zirconia had been completely dissolved into the high silica, glassy phase. Although quite viscous, the glassy phase would have been fairly quickly incorporated into the slag by the normal stirring that occurs in the furnace during the steelmaking process.

Post-mortem of samples from basic slag practice foundries revealed a different wear issue. Although the hot face of the refractory lining looked fairly "normal" showing only limited signs of slag penetration or corrosion, the slag attached to the refractory was saturated with magnesia. This is a common feature of slags obtained from wrought steel producers (integrated and "mini" mills) where the slags are intentionally saturated with magnesia to reduce refractory wear by reducing the concentration gradient that would normally exist between the refractory and the slag. However, none of the steel foundries pre-saturate slags with magnesia so all of the magnesia present in the slag had to have been dissolved from the refractory lining. Another interesting observation from post-mortem analysis of refractories from basic practices related to the basicity of the slags. Chemical analysis of the slags indicated that they contained considerably more silica than would be expected. Normal CaO to SiO₂ ratios for basic practice would be near 2.5, but some of the foundries were much nearer to 1.0. Such slags would be extremely corrosive to basic refractories, greatly accelerating wear. In fact the magnesia saturation limit for these slag chemistries would be expected to be very high.

Upon completion of the "baseline" evaluations, three main research areas were identified.

- (1) Development of refractories for use in extreme temperature, acid practice steelmaking.
- (2) Modification of basic slag practices to reduce magnesia dissolution.
- (3) Steelmaking practice modifications to substantially reduce tap temperatures.

Additional side issues relating to use of monolithic materials to replace brick linings and improved refractory selection were also initiated in an attempt to increase refractory lining campaigns. Although minor issues, compared to the main three, these two had the potential to substantially reduce refractory costs while resulting in at least minor reductions in energy consumption. Of the three main issues, reductions in tap temperatures would have the greatest potential to yield energy savings at the furnace end of the foundry process. All of the rest would result in reduced energy consumption, mainly in the opposite end of the process (in the grinding room) or outside the foundry through reduced refractory material production and improved properties associated with the resultant castings.

Development of the acid refractory began with identification of "acid" chemical systems that would withstand the extreme temperatures but that could be made economical for steel foundries. A number of systems were considered but the $ZrO_2 \bullet Al_2O_3 \bullet SiO_2$ system was the only one that

would result in a refractory melting temperature in excess of the prevailing tap temperatures. Candidate formulations from this system were fabricated into crucibles that were then filled with a representative slag and heat treated at temperatures in excess of 1750°C (3200°F). Formulations high in zirconia and alumina resulted in the greatest resistance to the temperature and corrosive slag. However the addition of zirconia to a refractory formulation would likely result in a lining cost that would not be favored by the acid practice foundries. A number of less costly zirconia containing aggregates were considered for substitution in the refractory formulation, the most promising being a fused alumina-zirconia-silica (AZS) aggregate that is mainly used in the glass industry. The AZS aggregate was combined with high alumina clay and other additives that would facilitate placement of the lining within the furnace. The resulting refractory material had the desired chemistry and corresponding melting temperature, while still remaining economical to the steel foundries. Industrial trials were initiated and initial results were promising despite initial difficulties associated with placement of the material onto the existing refractory lining. Production slow-downs related to the current national/global economy delayed completion additional iterations. As production levels return to historical norms, trials can be resumed.

Magnesia dissolution in basic slags has been studied for a number of years, mainly by the "big" steel companies. Those studies evaluated slags consistent with the wrought steel process. Studies on slag chemistries more consistent with steel foundries had not previously been completed and those studies related to wrought production were mainly limited to temperatures below 1600C. As such a magnesia dissolution study was initiated to provide the required data so that foundries could pre-saturate slags to reduce refractory wear. The study, which evolved into a master's thesis, was a design of experiments that resulted in a formula for determining magnesia saturation based upon knowledge of the calcia, silica, iron oxide contents and the tap temperature.

Attempts to reduce tap temperatures focused on issues not directly related to the EAF. Instead the impact of ladle pre-heat and insulation was considered. Plant visits had resulted in a concern that a considerable amount of heat was being "wasted" in the ladle, causing the need for greatly elevated tap temperatures. Temperature measurements were obtained from selected foundries and a simple heat loss model was developed using existing software. The results indicated that much of the superheat was actually being used to heat ladle refractory. Although improved pre-heating of the ladle would improve the situation, the amount of heat required would be the same in either case. It should be noted that the pre-heat energy would be derived from gas burners instead of from electricity so some overall energy savings would be realized. The major improvement in energy efficiency would result from the simple practice modification of utilizing ladle lids. The amount of energy lost from the surface of the molten metal was far greater than that lost through the ladle refractory lining. Although more insulating refractories could be used in the ladles, the resulting energy savings would be relatively small in comparison to use of a good ladle lid. The suggestion of a ladle lid, although seemingly obvious and simple to implement, can present production difficulties for foundries if the lid has to be removed and replaced during the casting procedure. Crane capacity may also be an issue in some foundries. Foundries that have implemented the suggestions should realize at least modest energy savings, with additional savings expected as the foundries become accustomed to any practice adjustments that are required.

Refractory selection modifications and a shift to monolithic linings were initiated at selected foundries. The result was a considerable cost savings that resulted from more than a 3-fold increase in lining campaign duration. An expected benefit in the cleaning room that might be anticipated from reduced macro-inclusions in the casting was not realized. Precise records as to the amount of time spend grinding a specific set of castings is not available so only dramatic reductions would be noticeable. More subtle reductions are difficult to identify, even though they can result in considerable energy reductions, given the large number of castings impacted.

In the third year of the program, the scope was expanded to include survey and post-mortem efforts related to steel foundries using induction furnaces. As with the EAF effort, a number of foundries were surveyed on paper and visits to ~15 were initiated. Samples were acquired and post-mortem analysis was completed using the same procedure as with EAFs. Results from the effort indicated that unlike the EAFs, the refractory selection for induction furnaces was considerably more uniform. In general, the reported failure mechanism was metal penetration to the induction coil, at times complicated by extensive thinning of the refractory lining. Post-mortem analysis indicated that so long as the refractory was of the high quality (low level of impurities) spinel forming dry vibratable class of materials, the campaign duration was quite good. In instances where lower quality aggregate (brown fused as opposed to white fused) was used, the campaign duration was compromised. In rare instances, signs of extensive overheating of the lining resulted in melting of the lining.

Throughout the program technology transfer in the form of presentations and publications, including a CD on the post mortem efforts, were completed. The following is a comprehensive list of the transfers including dates and locations. A copy of each is included as an appendix in this report.

June 17, 1998: "Basic Refractories for Steelmaking – Cleaner Steel," Heavy Section Product Group Meeting of the Steel Founders' Society of America, Cleveland, OH.

November 6, 1998: "Steel Foundry Electric Arc Furnace Refractory Lining Survey," 52nd Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

July 28, 1999: "Foundry EAF Refractory Lining Optimization," Heavy Section Product Group Meeting of the Steel Founders' Society of America, Mobile, AL.

November 3, 1999: "Evaluation of Refractory Practices in Steel Foundries," Steel Founders' Society of America, Technical and Operating Conference, Member Workshop, Chicago, IL.

November 4, 1999: "Post Mortem Analysis of Foundry EAF Refractories," 53rd Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

November 4, 1999: "Update on High Alumina Castable Lining in Acid Arc Steel Melting Practice," 53rd Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

December 1, 1999: "Refractories for Electric Arc Furnaces in Steel Foundries," 14th Annual Metal Casting Technology Center Symposium - Refractories for the Foundry, Tuscaloosa, AL.

February 18, 2000: "Steel Foundry EAF Refractories," North Central Division Meeting of the Steel Founders' Society of America, Milwaukee, WI.

July 11, 2000: "Steel Foundry EAF Refractories," Steel Founders' Society of America Research Review Meeting, Chicago IL.

November 3, 2000: "Magnesia Dissolution in Steelmaking Slags," 54th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

November 3, 2000: "Effect of Ladle Practice on Tap Temperature," 54th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

July 24, 2001: "Steel Foundry EAF Refractories," Steel Founders' Society of America Research Review Meeting, Chicago IL.

November 4, 2001: "Development of Acid Gunning Materials," 55th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

November 4, 2001: "Refractory Challenges in Induction Furnaces," 55th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

November 4, 2001: "Magnesia Dissolution in Steelmaking Slags," 55th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.

July 23, 2002: "Steel Foundry EAF Refractories," Steel Founders' Society of America Research Review Meeting, Chicago, IL.

September 19, 2002: "Steel Foundry Refractory Lining Optimization Post Mortem Final Report," CD provided to SFSA (not included as portions are included throughout the documents in this list).

November 8, 2002: "Evaluation of Refractory Performance in Induction Melting Foundries," 56th Technical and Operating Conference, Steel Founders' Society of America, Chicago, IL.