YIELD IMPROVEMENT THROUGH ENHANCED LADLE BOTTOM DESIGN (ELBY)[1]

L.J. Heaslip[2]
J.D. Dorricott[2]
J. Richaud[2]
J.P. Rogler[2]
W.A. Alves[3]

Abstract

When slag is detected leaving a ladle, a significant residual quantity of steel often remains behind when flow is stopped, and this results in a costly loss of yield. In order to minimize the average quantity of steel residual in the ladle, ladle bottom geometry should be optimized. To improve ladle yield, an understanding of the fluid flow phenomena (including vortexing and surface collapse) occurring during the final stages of draining is necessary. Both computational fluid dynamics (CFD) and physical (water) modeling have been used to gain this understanding. The influence of steel flow rate on the bath depth of vortexing and surface collapse was studied. It was found that as ladle draining proceeds, three phenomena typically occur: (1) early vortexing (low strength intermittent vortices), (2) full vortexing (a slag-entraining funnel), and (3) surface collapse (pressure in slag exceeds pressure in the steel and the slag flow overwhelms steel flow). With the aid of CFD, optimized ladle bottom geometries (ELBY) that reduce residual steel at the onset of slag flow have been generated. CFD modeling has been found to correspond well with physical modeling and it was concluded that CFD analysis can be used to predict ladle draining phenomena. Plant testing of an ELBY ladle bottom design has shown that significant yield savings can be achieved.

Key words: Ladle yield; Ladle draining; Draining vortex; Ladle vortex; Slag entrainment.

---

[1] *XXXVII Steelmaking Seminar – International, May 21th to 24th, 2006, Porto Alegre, RS, Brazil*

[2] *Advent Process Engineering, Inc. ,5035 North Service Rd., C-13, Burlington, ON, Canada, L7L-5V2.*

[3] *Vesuvius Brazil, Rua Mexico No. 39, 06415-160 Barueri, Sao Paulo, Brazil*

INTRODUCTION

A typical ladle used in a steel melt-shop is filled with a heat of liquid steel, which is tapped into the ladle from the steelmaking furnace. The ladle holds the liquid metal during metallurgical treatment. The ladle is slowly emptied of liquid metal into the tundish during the casting process. Ladle filling, metallurgical treatment, and emptying occur in sequence and upon completion of some simple maintenance procedures, including the dumping of residual steel and slag, another cycle of filling, treatment, and emptying begins. At the end of its campaign, the ladle is temporarily removed from service for a major repair and rebuild of its refractory lining.

Non-metallic materials are added and slag is carried over from the furnace during ladle filling. These non-metallic materials are less dense than the liquid metal and form a non-metallic layer of molten slag that floats upon and covers the top surface of the metal bath. The ladle bottom incorporates an outlet nozzle connected to a slide-gate valve, which when opened allows the controlled outflow of liquid metal during casting. To simplify the engineering layout of casting equipment, the outlet nozzle is typically offset from center and is generally located close to the periphery of the ladle bottom.

While the ladle is slowly drained of liquid metal during casting, it is desirable that the flow exiting the ladle be as free as possible of non-metallic material to reduce the potential of contamination of the cast metal product. However, as the level (i.e. depth) of the liquid metal bath reduces during casting, the floating non-metallic slag layer approaches ever more closely to the outlet nozzle in the ladle bottom. During the final stages of draining, rapidly increasing quantities of slag droplets and non-metallic particles can become entrained within the liquid metal flow exiting the ladle. The severity of this slag entrainment increases with vortex strength. The presence of a strong continuous vortex can funnel a stream of entrained slag that contaminates the out-flowing liquid metal. Finally when the bath depth in the ladle is sufficiently low, the top surface of the bath can collapse into the outlet nozzle and at this moment the metal flow is overwhelmed by the slag flow.

Ideally, the extent of entrained non-metallic material in the outlet flow would remain at acceptably low proportions (with the limit of acceptability depending on cast product quality demands) until virtually all of the liquid metal has exited from the ladle. The ideal moment to stop the flow is at the instant when the proportion of non-metallic material entrained within the flow, or when the cumulative amount of slag that has exited the ladle, exceeds acceptable limits. However, even when flow is stopped (by closing the slide-gate) at the ideal moment, a significant quantity of liquid steel can remain in the ladle unless the slag entrainment processes are somehow retarded until all of the steel has been emptied.

LADLE DRAINING FLOW PHENOMENA

The quantity of liquid steel remaining in the ladle after gate closure is called the steel residual and it is highly desirable that this residual be as small as possible in order to maximize yield and reduce costs. Thus, it is highly advantageous to retard the entrainment of slag in the liquid metal flow exiting a ladle until all, or very nearly all, of the liquid metal has left the ladle.

A good understanding of the fluid flow phenomena occurring during the final stages of ladle draining is necessary in the development of ladle bottom design and draining practices that retard slag entrainment and thereby allow increased yield.

There are two principle phenomena that contribute to slag entrainment in the flow exiting a ladle. These phenomena are the formation of a draining vortex and the collapse of the liquid metal surface. Both computational fluid dynamic (CFD) analyses and physical (water) modeling are useful to gain understanding of these ladle draining phenomena.

Vortexing

A classical representation for the formation of a draining vortex is based solely upon the principle of the conservation of angular momentum. In applying this model, it is simplest to consider that the outlet nozzle is located in the bottom of a cylindrical tank on its central axis. The tank is drained by allowing flow out the nozzle. Fluid elements approaching the outlet nozzle conserve their angular momentum by following tightening spiral paths toward the central axis and the outlet nozzle with a progressive increase in angular velocity as their distance from the central axis decreases. However, a necessary initial condition of this simple model, if a vortex is to form, is that the fluid must be in motion before draining begins and this motion must have a non-zero angular momentum about the central axis of the tank. Furthermore to use this model without invoking complex numerical calculations to make predictions, such as critical bath depths of vortex dimple or funnel formation etc., also requires that the state of initial motion of the bath be highly organized in the form a simple rotational motion that is constant throughout the bath. Such a model, applied to ladle draining, has been presented by Sankaranarayanan and Guthrie[1].

In the steel ladle, factors influencing vortex formation are considerably more complex than are considered by any classical representation. The outlet nozzle is almost never located centrally on the ladle bottom. The initial state of motion of the liquid steel in the ladle when draining begins is poorly understood, as it is influenced by many factors, such as residual motion from the ladle stirring during metallurgical treatments and natural convective motions as the liquid metal cools. Any residual stirring motion may involve large and small scale eddies distributed throughout the bath, while natural convective motion may involve sinking flows at the ladle walls, rising flows toward the central axis of the ladle and the development of temperature strata. In any case, the initial state of fluid motion in a ladle is not at all well represented as a simple constant axial rotation. A more reasonable assumption might be that of randomly oriented eddies throughout the bath, with an initial turbulence intensity distribution having little or no net angular momentum with reference to the outlet nozzle vertical axis. Assuming an initial condition of this form implies that CFD analysis should be a useful, or even necessary, adjunct to water modeling of ladle draining. Davila et al[2] have recently applied both physical (water) and numerical (CFD) simulation methods in an exploration of ladle draining.

Surface Collapse

When the steel bath depth above the entrance to the outlet nozzle is sufficiently low, the collapse of top surface of the liquid metal into the outlet can occur and this collapse is accompanied by a large flush of slag into the tundish. This phenomenon can be explained with reference to Fig. 1, which shows a typical configuration of the ladle-to-tundish flow channel that is formed by the connection of the ladle bottom, outlet nozzle, ladle gate, and ladle shroud.

The outlet nozzle has an entrance bore diameter where it meets the ladle bottom of D_1. A theoretical hemispherical surface (of radius $D_1/2$) centered on the entrance to the outlet nozzle is indicated on Fig.1 by a curved dotted line. The actual flow exiting the ladle is the net inward flow crossing this theoretical surface as shown by the arrows and this flow is referred to as Q_{ACT}. A ladle slide-gate valve is connected to the outlet nozzle. The diameters of the upper and lower bores of a ladle gate are typically equal and are shown in Fig.1 as equal to D_2, where D_2 is typically less than D_1. The gate operates to control the liquid metal flow rate from ladle to tundish by offsetting (or sliding) the lower part of the flow channel from the fixed upper part along the slide-gate plane. This offset provides an orifice size (d_o) which may be varied from a minimum of zero when the gate is closed, to a maximum of D_2 when the gate is full open. Below the gate, a ladle shroud tube is often connected in order to fully enclose the liquid steel flow entering the tundish bath.

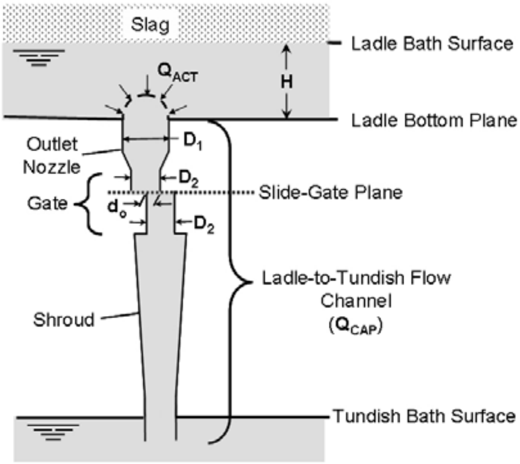

Fig. 1: A typical ladle-to-tundish flow channel

The ladle-to-tundish flow channel has a liquid steel flow capacity = Q_{CAP}. For a given geometry of the ladle-to-tundish flow channel, Q_{CAP} is a function only of the gate orifice size, d_o, and the depth of the liquid steel bath in the ladle, H. Q_{CAP} decreases with decreasing H, while Q_{CAP} increases with increasing d_o. Thus during the majority of the draining time, as H is slowly decreasing, d_o is slowly increased to maintain the liquid steel flow from the ladle that is required to keep the tundish full during casting and during this time $Q_{ACT} = Q_{CAP}$. When H approaches zero (i.e. at relatively low ladle bath depths), d_o must approach its maximum value (i.e. as $H \rightarrow 0$, $d_o \rightarrow D_2$) in order to support the casting flow and keep the tundish full. As long as the outlet nozzle remains full of liquid steel, the flow capacity of the ladle-to-tundish flow channel remains significantly greater than zero (i.e. even when H=0, $Q_{CAP} >> 0$). However as $H \rightarrow 0$, the flow exiting the ladle Q_{ACT} can not be maintain equivalence to Q_{CAP}. Surface collapse occurs when the actual steel flow exiting the ladle Q_{ACT} becomes less than Q_{CAP}. This may also be considered as the moment when the pressure in the slag exceeds the pressure in the steel flow above the outlet nozzle, at which point the liquid steel top surface will collapse and slag flow through the outlet will suddenly overwhelm the steel flow through the outlet; this is the moment of surface collapse.

WATER MODELING

The authors have carried out water modeling experiments in a ladle model with an offset outlet nozzle and typical configuration of the ladle-to-tundish flow channel (such as illustrated in Fig. 1). The ladle model was a cylindrical flat-bottomed tank 1700 mm in diameter. The center of the outlet nozzle was at a radial position of 760 mm from the vertical centerline. The ladle model was considered to have a 0.6 geometric scale as compared to a prototypical ladle. Considering Froude No. similitude as discussed by Heaslip et al[3], it can be shown that the ladle model employed in these experiments can simulate liquid steel draining rates between 1.9 and 7.3 ton/min using water flow rates of ~75 to ~290 litres per minute.

Typically, experiments were carried out with a floating layer of low-density polypropylene beads to imitate the presence of a slag layer. Experiments were also conducted with no simulated slag layer and other experiments with liquid slag analogues. The ladle model was filled slowly (~10 to 12 min.) using a large diameter (102 mm dia.) vertical source pipe located on the ladle bottom centerline in order to minimize the kinetic energy introduced to the bath during filling. After the model ladle was filled, several procedures were used to vary the state of initial motion of the water. One procedure was to wait a fixed time (30 min) after filling to allow residual motion to dissipate to before start of draining. Another procedure was to agitate the water in a way that produced random motions in the bath at start of draining.

In these experiments, it was observed that three phenomena typically occur, in sequence, during the final stages of ladle draining: (1) early vortexing (formation of low strength intermittent vortices or of a single weak vortex that generally appear as shallow dimples on the bath surface or as partial-depth funnels), (2) full vortex formation (a full vortex is strong and continuous in nature with a complete funnel reaching fully from the bath surface to the outlet), and (3) surface collapse. During early vortexing, multiple or even simultaneous weak vortices may be observed. Full vortexing occurs when an early vortex develops into a complete funnel. At surface collapse, it was observed that the spiral motion of liquid elements around the outlet disappeared and the proportion of slag analogue material and/or air in the outlet nozzle above the gate suddenly increased.

Figure 2 shows the simulated liquid steel height remaining in a ladle with a horizontal flat bottom, when early vortexing, full vortexing and surface collapse were observed to occur. It was found that increasing the draining throughput generally increased the bath depth at which the draining phenomena were observed. Little or no influence of the procedures used to induce different states of initial motion of the bath was found and Figure 2 reports the findings of all experiments regardless of these procedures. On the other hand, the presence or absence of a layer of beads (i.e. slag vs. no slag) was found to influence the depth of early vortexing. The presence of the floating beads suppressed early vortexing as compared to without this material. This effect was more pronounced at low draining throughputs. However, no influence of the presence of the simulated slag layer was found as regards the depths of full vortexing or surface collapse. In these experiments, full vortexing was found to precede surface collapse by only a relatively small difference in bath depth (6 mm to 24 mm).

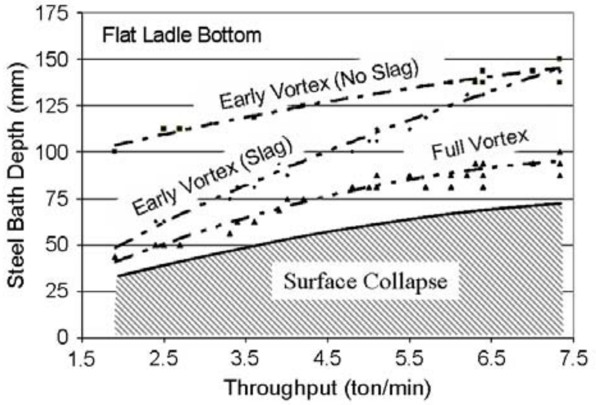

Fig. 2: Predicted influence of throughput on bath depths of final stage ladle draining phenomena in ladle with flat horizontal bottom

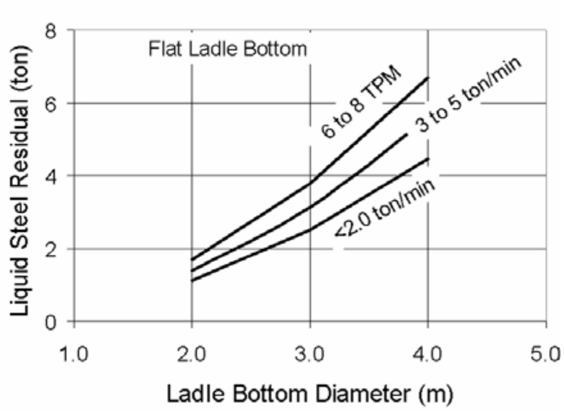

Fig. 3: Predicted range of liquid steel residuals in a ladle with flat horizontal bottom

In water modeling experiments using various water-insoluble oils as liquid slag analogues, early vortexing was observed to cause minor amounts of slag entrainment. This observation was also valid for other organic liquids such as kerosene, as well as to those experiments performed with the floating plastic beads. However with the formation of a full vortex, significant entrainment of any of the slag analogue materials tested was clearly observed, although this entrainment was still much less than that associated with surface collapse. It was estimated by photographic analysis that the volumetric proportion of slag analogue material entrained in the outflow from the ladle increased from less than 10% (with a full vortex) to more than 50% (upon surface collapse) in a matter of only several seconds.

It is interesting to consider the practical implications of these results. Ladle gates are typically closed when slag is detected entering the tundish. Visual detection of the low quantities of entrained slag predicted with both early vortexing and full vortex formation seems very unlikely. Automated slag sensing systems may be incapable of reliable detection of the very low proportion of non-metallic material in the ladle exit flow during early vortexing. Visual detection is expected to be very ineffective at restricting the quantity of slag getting to the tundish because of the rapid detection and response that is required when surface collapse occurs. Even for automated slag sensing systems, it is easiest to detect slag exiting the ladle at surface collapse, and thus it is expected that this event triggers most ladle gate closure commands. However, it is clearly desirable to implement an automated slag sensing system that can trigger ladle gate closure just prior to full vortex formation to minimize slag contamination of the steel in the tundish. Recently, Uhlenbusch et al[4] reported on the advantages of such a system.

It can be seen from Figure 2 that the liquid steel bath depth in a ladle upon surface collapse increases from about 40mm at low throughputs (<2 t/min) to about 75 mm at very high throughputs (>6.5 t/min). Assuming that this relationship is independent of ladle diameter, Figure 3 converts this trend to a graphical form which provides insight into the typical potential magnitudes of the liquid steel residual in ladles depending on ladle size and casting throughput. Figure 3 indicates that the expected quantity of residual liquid steel in a ladle varies between 1 ton and 6 ton. A mini steel shop may produce 6000 to 8000 heats per year in smaller (~80 to 130 ton) ladles, while a large steel shop may produce twice this number of heats in larger ladles (150 to 250 ton), but regardless of this the potential yield loss is significant.

Assuming an average steel residual of 2 ton/ladle and a production of 10000 heats per year, the total steel production lost when the ladles are dumped is 20000 tons per year or ~0.8% to 1.5% of production.

MODEL VERIFICATION & APPLICATION

The results of a modeling study performed for a European steel maker are presented in Figure 4, which shows the relationship between steel bath depth over the outlet nozzle and the liquid steel residual weight remaining in the ladle in tons. The shape of this line reflects the fact that this ladle bottom is not flat and horizontal, but rather is tilted toward the outlet. The throughputs used at this plant are high and typically in the range of 7 to 10 ton/min. In this range of throughputs, it was found that the bath depths associated with the three final stages of ladle draining (early vortexing, full vortexing, and surface collapse) are reasonably independent of the throughput and thus the predicted bath depths of each draining stage for this case can also be shown on Figure 4. In this case, early vortexing is predicted to first occur at a bath depth of ~215mm, which corresponds to ~9.0 ton of steel remaining in the ladle. The full vortex is expected to start at a depth of ~170mm (~5.7 ton remaining), while surface collapse is predicted to occur at a bath depth of ~125mm at which point the residual steel would be ~2.7 ton.

Two types of automated slag detection systems were compared. The R.A.D.A.R.™ system uses a vibra-acoustic sensing technology that claims the ability to detect slag entrainment in the ladle outflow, as well as early vortexing, since distinguishable characteristic acoustic signals are generated in the ladle-to-tundish flow channel. The other system uses an electromagnetic (EM) sensing technology which claims to detect slag reaching the outlet nozzle. The plotted symbols on Fig. 4 indicate and compare the amount of residual steel in ladles at the first moment of slag detection. There are several interesting observations in this study. The first is that for both systems, slag detection occurred before reaching the predicted bath depth of surface collapse. It is surmised that at the high throughputs used at this plant, vortexing is strong enough that the automatic slag detection systems have no difficulty in achieving detection before surface collapse. Secondly, the EM slag detection system did not typically detect slag entrainment at bath depths in the predicted early vortex zone. Both the EM system and the RADAR system were set to high sensitivity and slag detection using the EM system mainly occurred in the predicted zone of full vortexing, while slag detection using the RADAR system mainly occurred in the predicted zone of early vortexing, as desired at high sensitivity using this system. Finally, the different response of the two slag detection systems provides confirmation of the validity and applicability of the ladle draining model.

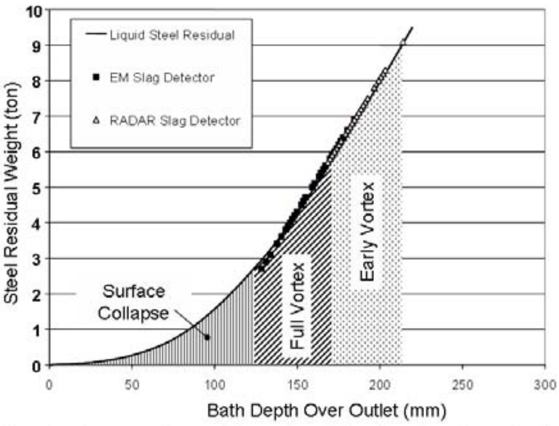

Fig. 4: Comparison of steel residuals of automated ladle closures with predicted draining stages

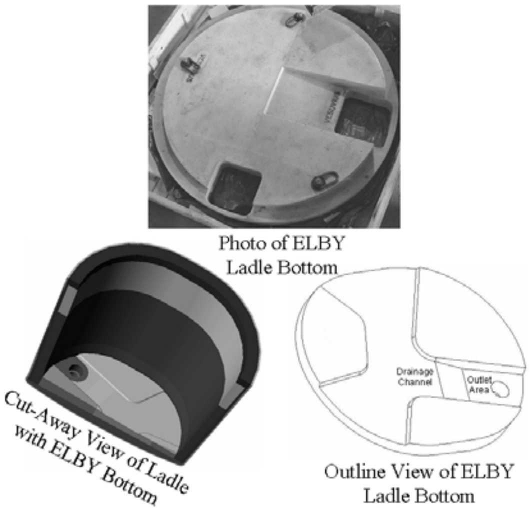

Fig. 5: Examples of ELBY ladle bottom designs

ELBY (ENHANCED LADLE BOTTOM YIELD)

With the goal of reducing residual steel remaining in the ladle at the time at which slag is entrained in the outlet flow due to either vortexing or surface collapse, criteria for novel ladle bottom designs have been developed. An ELBY (Enhanced Ladle Bottom Yield) ladle bottom beneficially alters the draining flow pattern during the final stages of ladle draining. An ELBY bottom controls the path of flow exiting the ladle so as to reduce the potential for vortex funnel formation as compared to conventional flat or tilted ladle bottoms, and thereby to retard the entrainment of slag in the liquid metal flow exiting a ladle until all, or very nearly all, of the liquid metal has left the ladle. Figure 5 shows some typical features of an ELBY ladle bottom design. The most important feature of the new ladle bottom is the incorporation of a drainage channel. When the bath depth in the ladle is low and approaching the critical depths for early vortexing and full vortex formation, the channel acts to force an increasing portion of the flow exiting the ladle to follow generally parallel paths as flow draws near to the outlet area. Modeling (both water and CFD) has shown that channel flow can significantly retard slag particle entrainment at equivalent steel residual as compared to a conventional bottom design.

By means of CFD analysis, a simple flat bottom ladle at 90 mm bath depth has been compared to an ELBY ladle bottom design at the equivalent residual volume of liquid steel. Figure 6 plots the computed results for the maximum size of slag particle entrained (≅ to the vortex funnel diameter) in the ladle outlet flow versus ladle throughput (draining rate). This figure shows that with an ELBY bottom at throughputs up to 6 ton/min, the max. diameter of entrained slag particles is less than 500 micron, whereas for the flat bottom ladle, the max. size of entrained slag particle is approx. 750 micron, even at a throughput as low as 3 ton/min. At throughputs greater than 5 ton/min, the CFD prediction for the flat bottom ladle indicates that entrained slag particle size increases dramatically, which is expected for surface collapse. Thus, CFD predictions for the flat bottom ladle are in good agreement with water modeling results (see Figure 2), while CFD predictions for the ELBY bottom ladle indicate the potential for significant yield improvement.

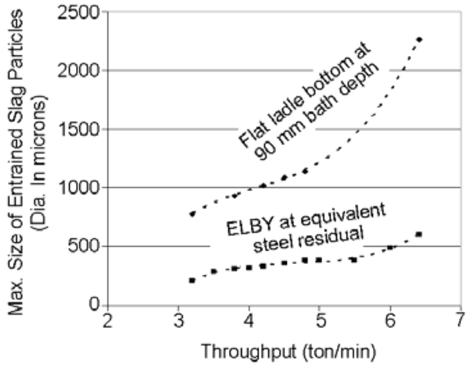

Fig. 6: CFD predictions of slag entrainment for flat ladle bottom as compared to ELBY bottom

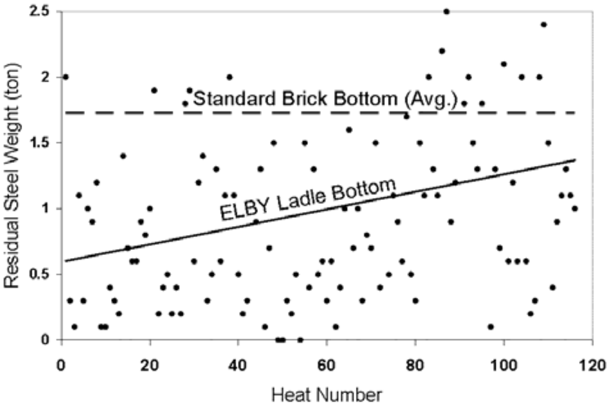

Fig. 7: Results of 116 Heat Campaign with ELBY ladle bottom as compared to average result with standard ladle bottoms.

Plant Trials of the ELBY

A pre-cast refractory ELBY ladle bottom was tested at a plant in South America. The bottom was installed in 1 hour as apposed to 3 to 4 hours for a standard brick bottom. The drying cycle for the ELBY ladle was increased to 48 hours as compared to 12 hours for a standard brick bottom ladle. After drying, no cracks or deformation of the pre-cast bottom was observed. A 116 heat ladle campaign with the ELBY ladle was then monitored, using ladle scale weights to determine the yield for each heat. Results of this campaign are presented in Fig. 7, which plots the averages of the steel residuals for each 10 heat segment of the campaign. It can be seen in this figure that the liquid steel residual tended to slowly increase as the ELBY ladle campaign progressed and this was attributed to the wear of the ladle bottom refractory, causing the ladle bottom shape to slowly lose its ideal contours with time of use. Early in the ELBY ladle campaign, the average steel residual was found to be on the order of 0.7 to 0.8 tons, but this slowly increased to 1.2 to 1.3 tons at the end of the campaign. Over the entire campaign, the average steel residual in the ELBY ladle was approx. 1 ton with standard deviation of 0.78 ton. This compares very favourably with the steel residual remaining in standard brick bottom ladles, which was determined as 1.73 ton with standard deviation of 1.26 ton. Thus, the ELBY provided an average yield improvement of (1.73 – 1.00 =) 0.73 ton per heat, for a total estimated yield savings of (116 * 0.73 =) 84.8 ton over the entire ELBY ladle campaign.

CONCLUSIONS

Increased ladle yield can result in substantial savings to the steelmaker. However, slag contamination of the liquid steel flow can occur while substantial steel still remains in the ladle. An understanding of vortexing and surface collapse during the final stages of ladle draining is necessary to increase yields while avoiding slag contamination. Automated slag detection systems that can reliable sense early vortexing as it develops toward full vortexing are highly desirable to minimize slag contamination of the steel in the tundish and maximize ladle yield.

With the aid of water modeling and computational fluid dynamic (CFD) analysis, optimized ladle bottom geometries (the ELBY bottom) that retard the entrainment of slag in the liquid metal flow exiting a ladle until nearly all of the liquid metal has left the ladle can be developed. Plant trials have clearly indicated the effectiveness of the ELBY design principles.

REFERENCES

1 R. Sankaranarayanan and R.I.L. Guthrie, Ironmaking and Steelmaking, Vol. 29, No. 2, 2002, pp. 147-153.
2 O. Davila et al., AISTech 2005 Proceedings, Vol. I, pp. 873-899.
3 L.J. Heaslip, A. McLean, and I.D. Sommerville, Continuous Casting, ISS-AIME, 1983, Vol. 1, pp 67-71.
4 J. Uhlenbusch et al., The Refractories Engineer, Institute of Refractories Engineers, May 2003, pp. 23-26.