Optimization of Refractory Ladle Sand

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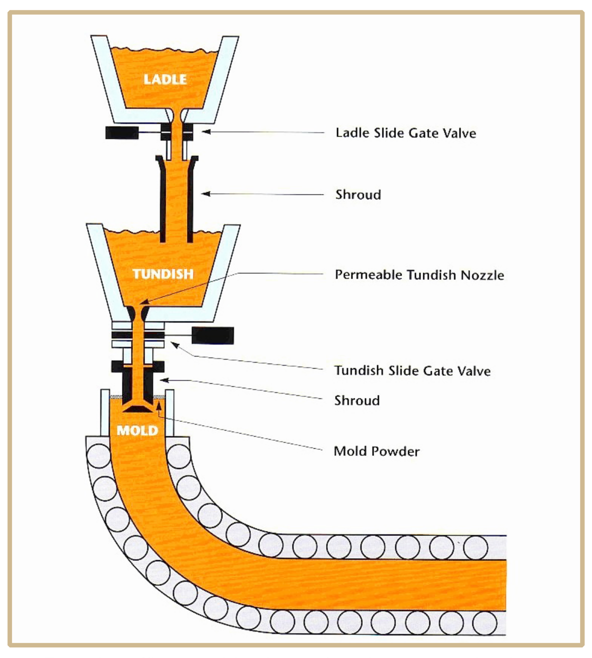
The senior design team was tasked with simulating the behavior of sand blend under varying conditions to determine the reasons why Nucor needs two blends and if we can determine a single blend that will work with both conditions.

This work is sponsored by Nucor Corporation and AJF Incorporated.

Project Background

Nucor uses two different blends of refractory ladle sands, produced by AJF Refractories, to protect the bottom of their steel ladles while the molten steel is held for varying residence times. A certain steel composition and residence time requires one type of sand, while another blend is more appropriate for other circumstances. The sand needs to insulate the gate at the bottom of the ladle, but also freely flow through once the gate opens. However, Nucor has experienced instances of the sand creating blockages in the drainage pipe which are dangerous and timely to fix. Switching between the two different sand blends also takes time, taking away from Nucor's bottom hourly production and causing potential safety risks. A single sand blend capable of performing at all residence times would be ideal.



From http://intocasthitech.com/continuous-casting.htm

The result of a clogged ladle gate. Steel appears to have seeped down the channel where the sand is held, hardening prematurely and forming an interface with the sand. This led to the molten steel in the ladle unable to flow through the channel once the gate was opened.
Image provided by Nucor Steel.

Experimental Procedure

We conducted several different experiments to model and analyze the interaction of the steel and sand:

Holding Molten Steel on Sand

We placed both blends of sand into a crucible and preheated it using a graphite block in an induction furnace to avoid the crucible cracking due to thermal stresses when in contact with molten steel. A stack of 8-10 coin shaped steel samples was placed on top of the sand, and power in the furnace was increased high enough to melt the steel. This power level depended on the initial crucible temperature. Once it began to melt, we held it at temperature for a desired residence time. Afterwards, we let the crucible cool off in a cooling sand pit overnight. Once safely cooled, we used a hammer to gently chip open the crucible, revealing the steel, sand, and interface between them. We repeated this experiment for residence times ranging from 20 minutes, 1 hour, and 3 hours.

Sand Flow Observations

500 ml of glycol was poured directly onto a sand bed and allowed to sit for one minute to allow penetration. The sand was then allowed to flow out of the tube leave an intact "crust" and free flowing unaffected sand. this was repeated for each type of sand as well as pouring on the side of the sand and directly on the sand. The thickness of the crust was observed as well as the size of displacement in the sands surface caused by the initial pouring.

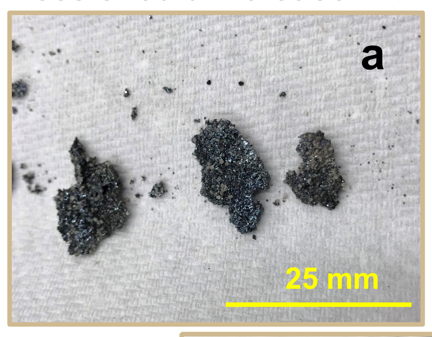
Sessile Drop Test Simulation

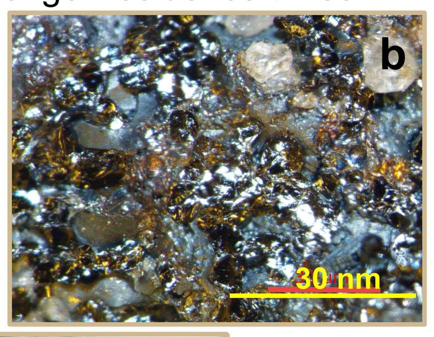
We placed the sand onto a transparent sample holder to create a relatively flat sand bed. We then dropped a small amount of glycol on top of the sand bed while having a slow-motion camera running in the background to capture the interaction in real-time. The video was analyzed frame by frame to capture the contact angle between the sand and the glycol right before the liquid dissipates through the sand bed. The experiment is done on both types of sand.

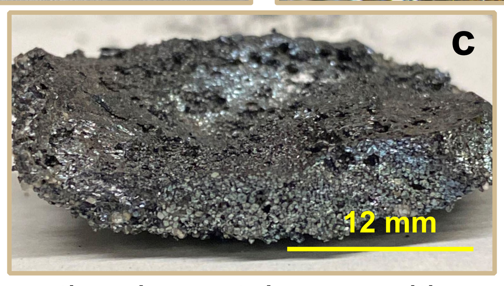
Results

Steel Residence Time Results:

The sand appeared to sinter, forming a solid layer at the interface with the steel. The layer (a) varied in thickness and averaged approximately 1.92 mm for the Cleanflow blend and 2.16 mm for the Zirflow blend at the initial 20 minute test. At the 1 hour residence time, a thicker piece of crust was retrieved from the crucible (c). Multiple thickness measurements were obtained for each blend's crust, with an average of 5.90 mm for Cleanflow and 7.42 mm for Zirflow. A crust was not retrieved for a 3 hour residence time due to premature crucible failure during the experiment. However, it was determined from this data that crust thickness should increase with longer residence times.



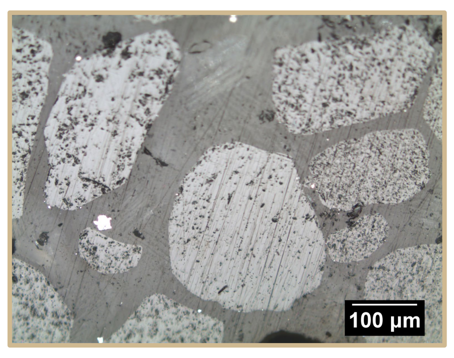




The table below shows the elemental composition of Zirflow sand before (left) and after (right) sintering in contact with the molten steel. The increase in oxygen is likely due to oxidation from the atmosphere. More importantly, there is no increase in iron content, suggesting that the steel does not penetrate into the sand or act as a liquid interface for sintering, like we initially thought may be possible.

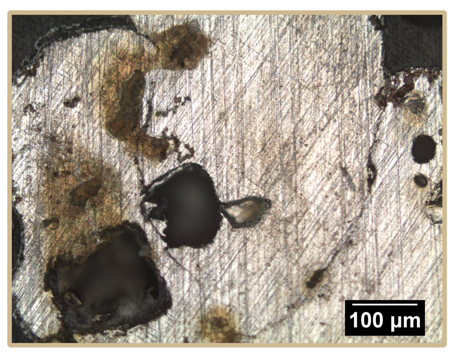
Element	Weight Concentration (%)	Element	Weight Concentration (%)
Oxygen	33.7	Oxygen	53.84
Chromium	23	Silicon	20.67
Carbon	18.6	Strontium	9.9
Iron	12.8	Iron	4.7
Bromine	9.4	Bromine	6.08
Magnesium	2.5	Magnesium	2.08

Optical Microscopy Results



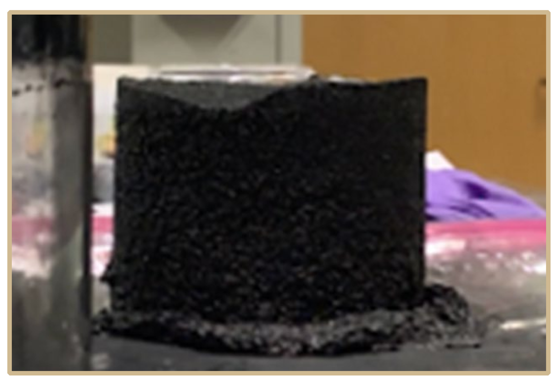
◀Optical analysis of the crust surface of 1020 steel + Cleanflow sand at 1 hour residence time shows sand particles (circular shape) suspends in a matrix rather than being attached to each other.

The 1020 steel + Zirflow sand on the other hand has zero presence of sand in its surrounding. There is no sand particle stuck up between the matrix. ▶



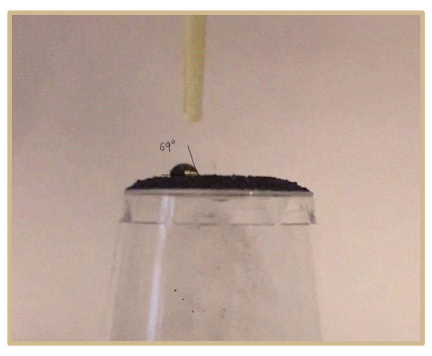
Experiment 2 results:

Based off the observations made during the sand flow experiments, it was determined that the glycol was able to penetrate the Zirflow sand (left) easier than the Cleanflow sand (right). This was determined based off the differences in composition and may be a contributing reason for why one sand performs better than the other sand. It was also determined in these experiments that there was a significant disturbance to the sand bed when poured directly on or near the bed compared to away from the sand bed. This was also found to be a potentially significant cause for the increased likelihood that the ladle will not properly drain when the gate is opened.



Experiment 3 results:

Simulation of sessile drop test using glycol yield contact angle of less than 90 degrees for both type of sand. The glycol wetted the sand but is not easily seen in the image due to it being captured right before the liquid diffused into the sand. The contact angle is measured using ImageJ angle tool.



Discussion

- Based of observations made during our experiments, we recommend future testing on the effect of the sands average grains size and grain distribution on the ability for steel to penetrate the sand as well as for the sand to form a crust when in contact with the steel. We believe that a slight increase to the Zirflow sand grain size would allow for an increase in the required time to sinter the sand. This could theoretically decrease the thickness of the sintered layer, allowing for the sand to protect the ladle gate while still allowing the crust to break once the gate is opened.
- Optical images revealed that the Zirflow sand turned into a glassy substance and did not maintain any of its original particulates. This was expected given the information that the Zirflow sand is known to go through a transition phase at 1173°C and turn "gummy" after sitting in the ladle for periods of 1 hour or less (the melting temperature of steel is ~1600°C). This transformation is thought to assist in the formation of a crust that is not fully hardened, but rather in a highly viscous state, which may lead to increased probability of the sand becoming clogged and failing to allow smooth flow of molten steel once the gate is opened.

$$\text{Monoclinic} \overset{1173^\circ C}{\Leftrightarrow} \text{Tetragonal} \overset{2370^\circ C}{\Leftrightarrow} \text{Cubic}$$

Ranges of stability for the crystallographic phases of zirconia. From https://www.azom.com/article.aspx?ArticleID=5780

- It was also noted that there was an increased chance of the sand failing to leave the ladle when the gate was opened; based off which furnace the steel came from, which is believed to be dependent on the proximity to the sand mound one furnace pours near compared to the other. Based on experiments, it is theorized that the sand mound is heavily disturbed when the furnace is used leading to increased penetration of the steel and higher failure percentage of the ladle gate evacuating the sand properly upon opening.
- The glycol that was used in the experiment has low surface energy in comparison to steel. Steel has a surface energy of approximately 2 J/m^2. This value is one to two orders of magnitude greater than the surface energies of room temperature liquid such as the glycol. The type of bonding in glycol is achieved by a weak, intermolecular reaction, hence it can wet the sand because the sand is coated with carbon, which is covalent near the surface. Wetting of steel on the other hand is only possible if the adhesion energy is close to the cohesion energy of the sand. In this scenario, we can conclude that wetting is not possible if steel was used instead of the glycol because the interfacial bond of the steel is metallic.

Wetting of different types of solids by non-reactive liquid metals at temperatures close to the metal melting point.

Type of substrate	Type of interaction	θ (degrees)
Solid metals	Strong (chemical)	θ << 90 °
Semiconductors		
Ceramics with a partially metallic character		
Carbon materials	Weak (physical)	θ >> 90 °
Ionocovalent ceramics		

Conclusion

- The main issue appears to be inconsistency in the steel pouring, which displaces the sand, causing blockages.
- Finding a sand blend that can withstand the effects of molten steel at all current residence times may not be possible with the current sand components available. This may also require a deeper chemical and thermodynamic analysis of the sand blend components and further experimentation at different residence times.

Recommendation/Possible Future Work

- It may be best to invest in different infrastructure to allow pouring without any degree of human error or inconsistency; if this is not possible, finding an ideal spot to pour the steel without disturbing the mounds of sand would be most beneficial.
- Further SEM/EDS analysis of polished sand crust retrieved from a melt experiment may provide more detailed data on sand particle and matrix composition.