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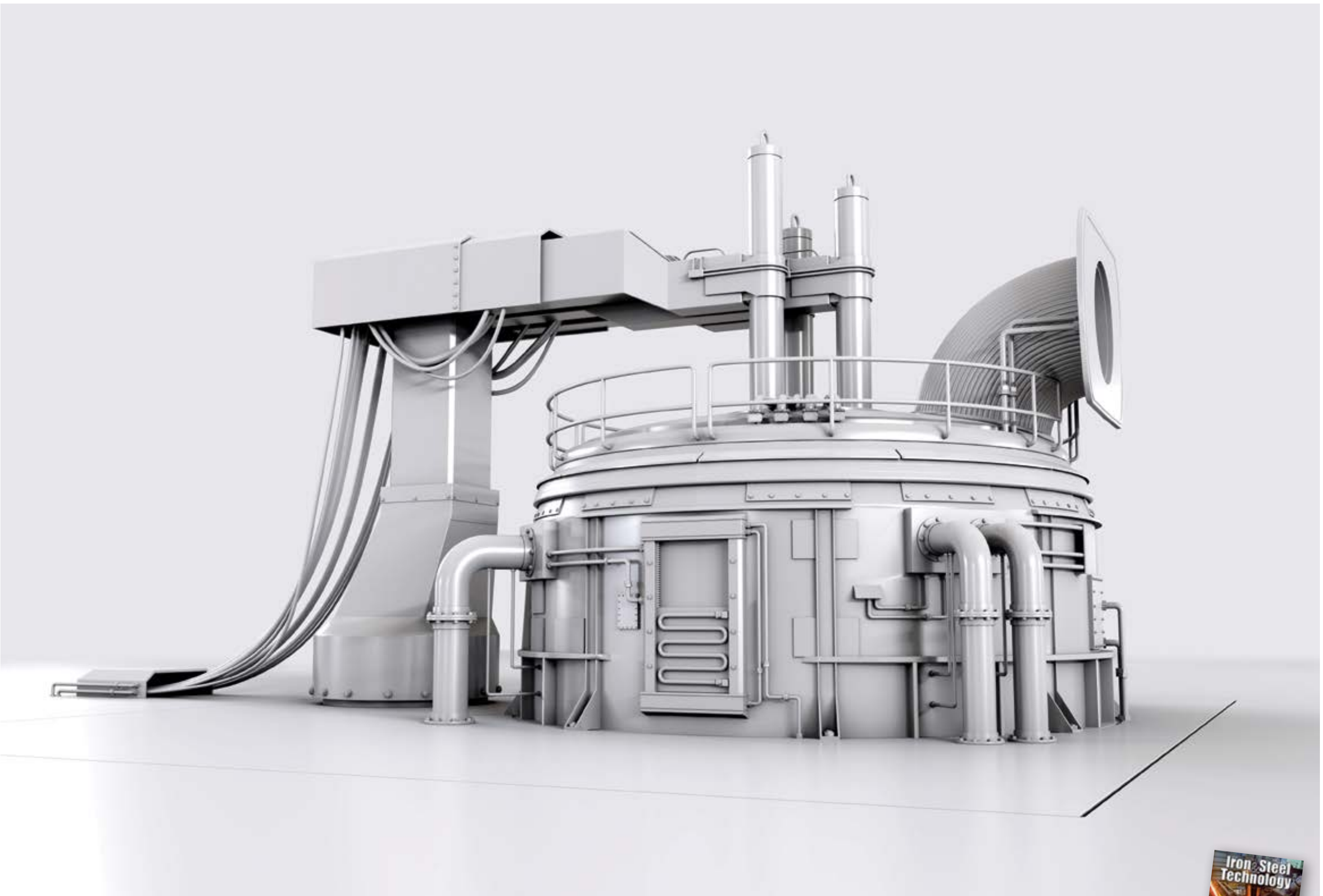

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Technical Article

Application of a Man-Less, On-Demand Immersion Optical Temparature Measurement Device at the EAF

AIST ASSOCIATION FOR IRON & STEEL TECHNOLOGY

Electro-Nite

Application of a Man-Less, On-Demand Immersion Optical Temperature Measurement Device at the EAF

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Reliable temperature control is critical in the operation of any electric arc furnace (EAF). Typically, temperature measurements are made with disposable thermocouples immersed using an automatic manipulator system. Recently, Heraeus Electro-Nite Co. LLC has paired with Steel Dynamics Inc. – Flat Roll Group Butler Division to commission a new, on-demand, immersion optical temperature measurement system. The system allows semi-continuous temperature measurements with endpoint temperature prediction to reduce the potential for excessive heating of the molten metal. This new method for measuring temperature has shown potential benefits to the EAF operation, such as increased safety through reduced operator exposure to molten metal, reduced variation of ladle metallurgy furnace (LMF) arrival temperatures and increased frequency of on-target LMF arrival temperatures.

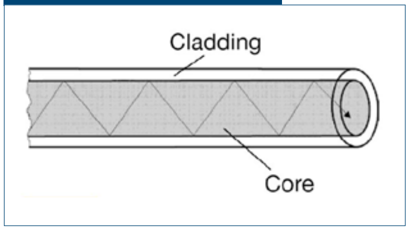
In late 2017, Heraeus Electro-Nite Co. LLC paired with Steel Dynamics Inc. (SDI) – Flat Roll Group in Butler, Ind., USA, to commission the first North American installation of a man-less, on-demand, immersion optical temperature measurement system, CoreTemp. The optical temperature measurement (OTM) system offers a new approach to measuring molten steel temperature in an electric arc furnace (EAF) by utilizing optical cored wire to perform the temperature measurement of the molten metal bath. At the end of 2017 and over the course of 2018, two systems were installed at SDI Butler on furnace Battery 2, one on EAF No. 3 and the other on EAF No. 4. SDI Butler operates two batteries of twin-shell Fuchs furnaces (four total furnaces), which have since been revamped by Superior Machine Co. Each individual furnace is capable of melting 150 metric tons and has a shell diameter of 7.3 m.[1] Each EAF battery shares a single 120-MVA transformer with a tap-to-tap time of approximately 40 minutes and a total melting capacity of 2.9 million metric tons per year across all four furnaces.[1] SDI Butler also charges 14 metric tons of hot metal per heat into its EAFs from the Iron Dynamics facility on-site, in addition to the scrap charge.

Theory of Operation

Unlike traditional temperature measurement techniques, such as thermocouples, which rely on the radiation of heat to a measuring element, CoreTemp is an OTM system. Temperature measurement is accomplished by the transport of infrared (IR) light to a measuring pyrometer that converts the measured light intensity to a temperature. The main components of the system that accomplish the optical temperature measurement are shown in Figs. 1–3. The optical fiber is used to transport light from one location to another.[2,3] In this case it is used to transport the IR light produced by a molten metal bath back to the measuring pyrometer. Optical fibers are typically made from two concentric glass materials, a core and the cladding.[2,3] A simple schematic of optical fiber construction and how light travels through optical fiber is shown in Fig. 1. The purpose of the metal jacket and filler material around the optical fiber is to add mechanical support so that the optical fiber can be reliably fed into a molten metal bath.

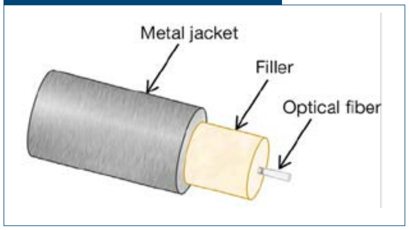
One of the requirements for a representative optical temperature measurement in liquid metal is that blackbody conditions are created when measuring. A blackbody is an

Figure 1



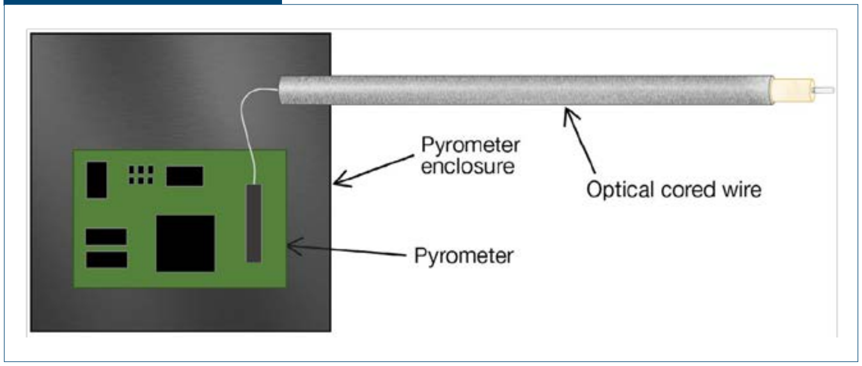
Simple schematic of optical fiber construction and how light travels through optical fiber.[2]

Figure 2



Cross-section of the optical cored wire construction.

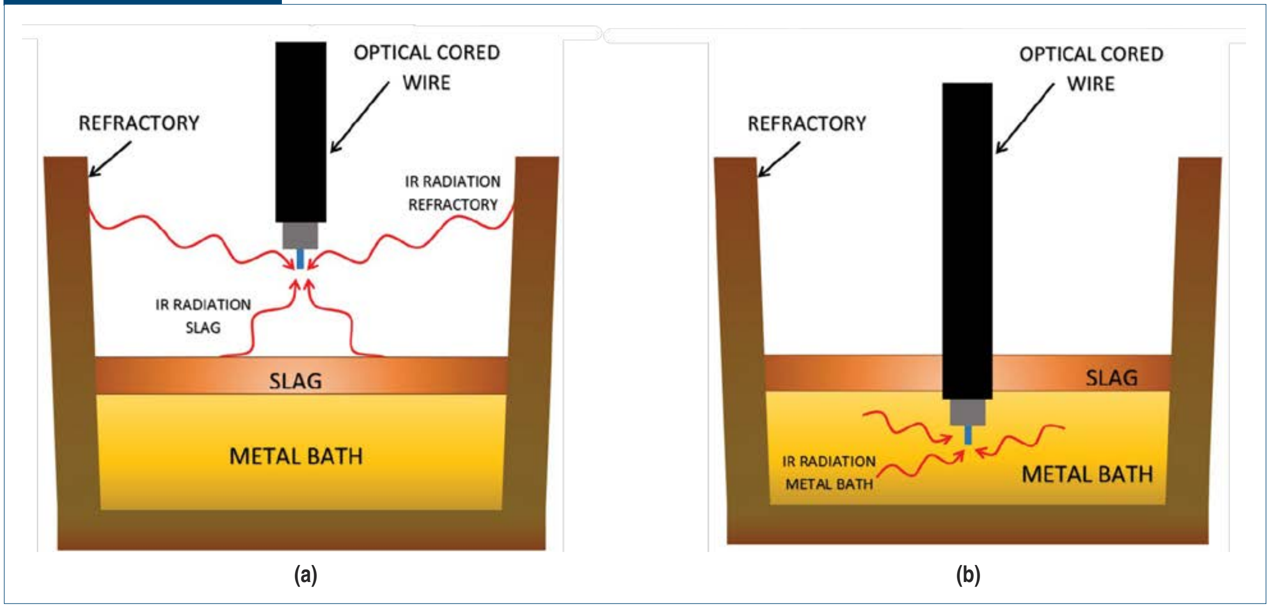
Figure 3



Simple schematic of the optical cored wire and measurement pyrometer.

ideal thermal radiator; as such, it absorbs all incident radiation and emits the maximum possible radiation energy.[4–6] The radiation energy, in this case IR light, can be transported to a measuring device, such as a pyrometer, by means of an optical fiber. When measuring the temperature of a liquid metal bath using the OTM system, the optical cored wire is immersed fully into the molten metal bath and creates a blackbody at the interface of the optical fiber in the cored wire and the molten metal bath. If blackbody conditions do not exist, such as in an instance where the optical cored wire is not fully immersed in liquid metal, the optical cored wire will transport IR light from multiple sources to the measuring pyrometer rather than from the blackbody (liquid metal, optical fiber interface). This will result in a non-representative temperature measurement. An example of this is shown in Fig. 4.

Figure 4



Optical cored wire transporting light from multiple sources when not fully immersed in the liquid metal (a) and optical cored wire fully immersed in the liquid metal, creating blackbody conditions and transporting light from only one source (b).

Looking at Fig. 4, it can be seen that when the optical cored wire is not fully immersed into the liquid metal, it will transport IR light arising from not just the metal bath, but also the IR light from the slag and the IR light from the hot refractory, thus contaminating the measurement. By bypassing the slag layer and completely submerging the optical cored wire into the metal bath, a blackbody is created at the tip of the submerged optical fiber and it transports only the IR light of the molten metal bath back to the measuring pyrometer. When measuring under blackbody conditions in a molten metal bath, the intensity of the light traveling through the optical fiber from the light source, which is the molten metal bath, to the measuring pyrometer can be converted to a temperature according to Planck's Law multiplied by emissivity.[5-7]

$$E_{b\lambda}(\lambda, T) = \frac{\in C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \quad \left(W / m^2 \cdot \mu m\right)$$

(Eq. 1)

where

$E_{b\lambda}$ = radiant intensity emitted from a body (W/m^2 · μm),
C_1 = 3.742 × 108 (W · μm^4/m^2),
C_2 = 1.439 × 104 (μm · K),
λ = wavelength (μm) and
∈ = emissivity (for a blackbody ∈ = 1).

The intensity and wavelength of the IR light in a molten metal bath directly correlates to the temperature of the molten metal bath. At lower temperatures, the intensity of the IR light produced from a molten metal bath is lower than when the molten metal bath is at higher temperatures. With regards to the wavelength of the measured light, a response can be seen at multiple wavelengths. For measuring the temperature of interest, the measured light must be filtered at the desired wavelength. This relationship is shown graphically in Fig. 5.

When measuring, typically the optical cored wire is fed into a molten metal bath starting from a location above the bath. The optical cored wire passes through the ambient air in the metal furnace or holding vessel first, then through the slag layer and last into the molten metal bath. Unlike traditional thermocouple temperature measurements, optical temperature measurements react almost instantaneously. This means that the measurement is sensitive to variations in the measurement region, such as:

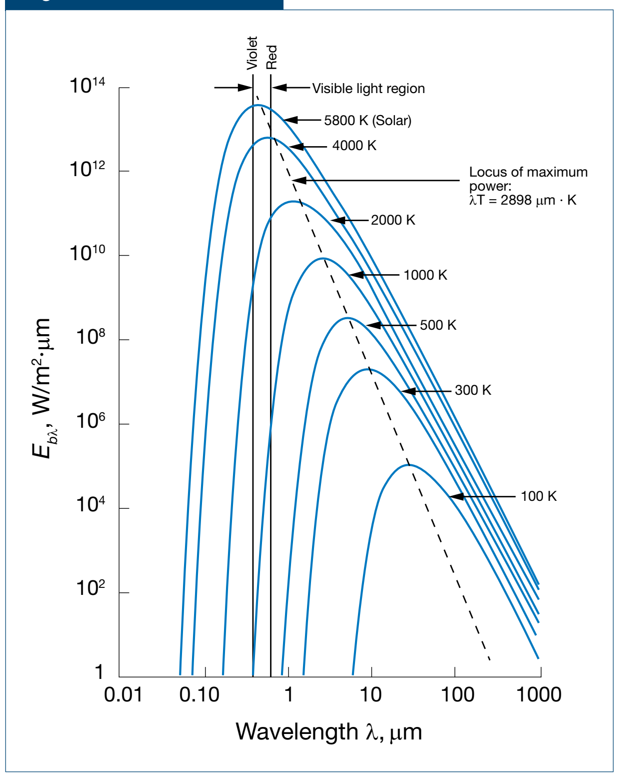
- Gas bubbles — Brief interruption of the blackbody conditions at the optical fiber and molten metal interface.
- Unmelted scrap — Decreases light intensity in the measurement region due to localized cooling of the molten metal bath.
- Fracturing and refreshing of the optical fiber as it is consumed in the metal bath during the measurement — Brief interruption in the transport of light through the optical fiber.

Due to the above sources of variation, optical temperature measurements, while just as representative as a traditional thermocouple measurement, are not as smooth in appearance, as shown in Fig. 6.

Laboratory Testing

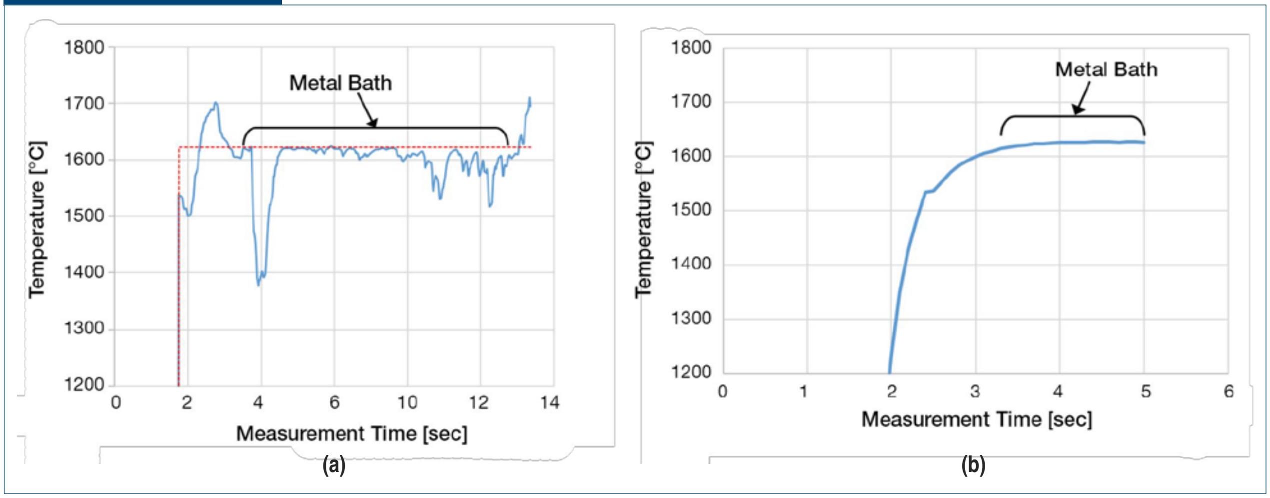
In order to establish the temperature measurement capability of the CoreTemp system as compared to conventional immersion thermocouples, the optical cored wire and system were tested in a series of controlled 250-kg induction furnace steel melts. For the first test, the steel temperature was heated to 1,580°C and held at that temperature. A reference thermocouple was taken, followed by a series of five optical measurements. This procedure was repeated until

Figure 5



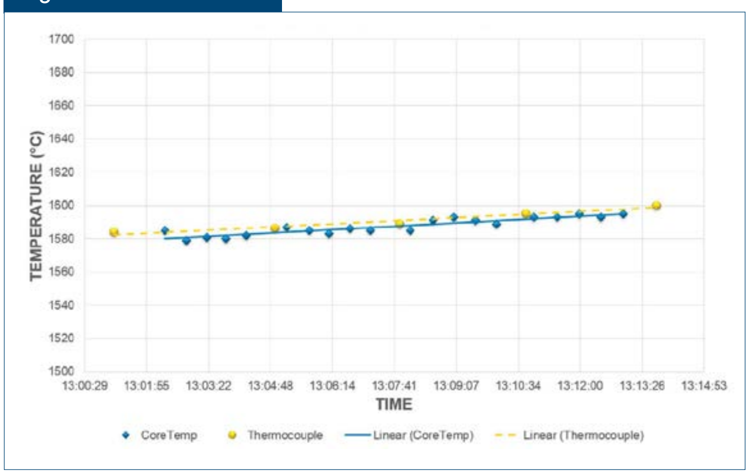
Blackbody spectral emissive power vs. wavelength for various temperatures.[5]

Figure 6



Optical temperature trace example (a) and thermocouple measurement trace example (b).

Figure 7



Optical temperature measurement stability at 1,580°C.

a total of 20 optical measurements were taken. The results of this test are shown in Fig. 7, with results summarized in Table 1.

In order to assess the performance of the system and cored wire across a range of steelmaking temperatures, another test was performed where the steel bath was heated to 1,700°C and the heat source was removed, allowing the steel to cool naturally. A reference thermocouple was taken, followed by a series of five optical temperature measurements. This sequence was repeated until the steel bath cooled to 1,560°C. The results of one of these test series are given in Fig. 8. Both Figs. 7 and 8 show that the optical temperature measurements were consistent with immersion thermocouple measurements at steelmaking temperatures.

Table 1

Summary Data for the Optical Temperature Measurement Stability Study

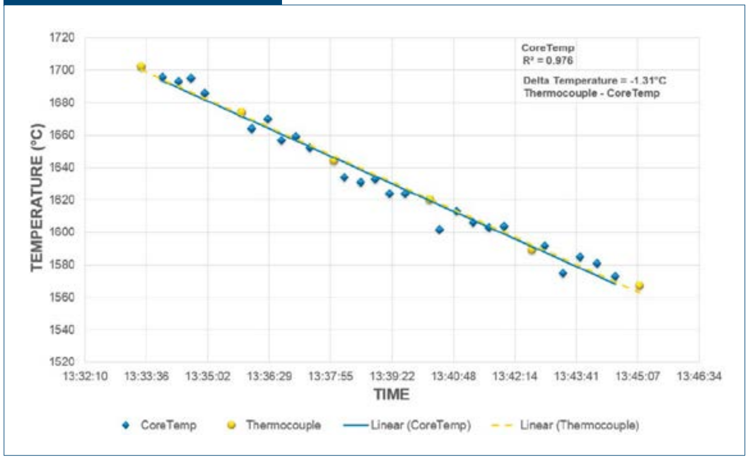
N	Delta temperature (°C)	Temperature StDev (°C)
20	–3.17	2.12

Industrial Results

The CoreTemp system shown in Fig. 9 is an on-demand OTM system consisting of a programmable logic controller (PLC) unit, a wire feeder, cored wire coil, wire guides, an entry port into the furnace and a human machine interface (HMI). The cored wire is the consumable portion of the system that transports light from the molten metal bath to a pyrometer, the measuring instrument. The length of optical cored wire contained in a coil is 1 km, which lasts for approximately 500 to 1,000 measurements, depending on application, before needing to be replaced. It is fed by the wire feeder into the furnace through a series of wire guides and an air-purged entry port. The wire feeder and cored wire are connected to and controlled by the PLC unit. The HMI in the operator pulpit or control room displays a unique user interface to operate the system and display the temperature measurements.

In October 2017, a system was installed on the slag door side of EAF No. 3 at SDI Butler. A schematic of

Figure 8



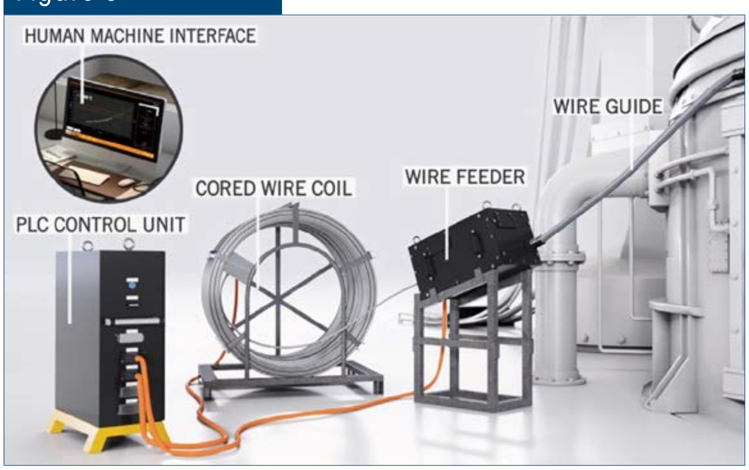
Temperature range capability study of the CoreTemp system and optical cored wire.

the initial application is shown in Fig. 10. The wire feeder, cored wire coil and control unit were all located on the slag door side of the furnace. The wire feeder was mounted on the tilt platform and moved with the furnace. The rigid wire guides were mounted around the furnace shell and connected the feeder on the slag door side to the furnace entry port on the sump (eccentric bottom tapping). The cored wire coil was located approximately 6 m behind the wire feeder. The cored wire was open to free air between the packaged coil and the feeder, and acted as the flexible joint when the furnace tilted to tap or slag-off.

In May 2018, a second system was installed on the sump of EAF No. 4 at SDI Butler. The wire feeder was placed on the sump platform due to space constraints on the slag door side of the furnace. It was also proposed to move the system on EAF No. 3 to the sump after the setup on EAF No. 4 made it through the trial phase. The system on EAF No. 3 was moved to the sump during October 2018. A schematic of the current system installations is shown in Fig. 11. A short run of wire guide pipes connected the outlet of the wire feeder to the entry port located in the gap between the vertical shell and horizontal sump panel of the EAF. The cored wire coil was located on the melt deck approximately 12 m behind the wire feeder. The wire was run through a series of roller guides to direct its path of movement to the feeder. The PLC control unit was placed on the mid-deck below the melt deck. The wire feeder was electrically connected to the PLC control unit on the mid-deck, via cables that were routed through the water-cooled shell on the EAF.

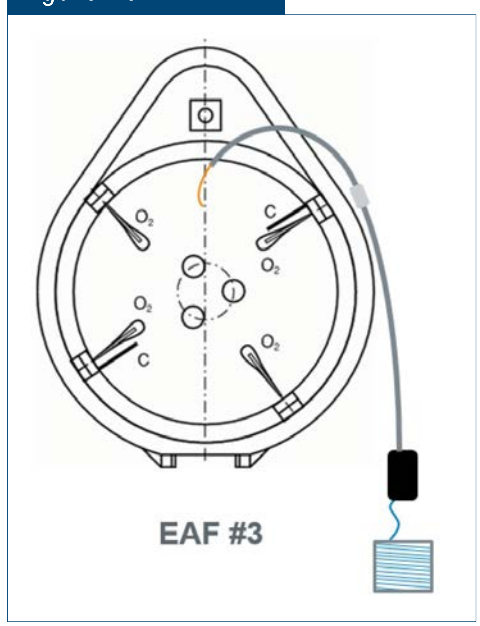
Fig. 12 shows the sump side of EAF No. 3. The cored wire coil was set well behind the furnace with the wire being fed through a series of roller guides up to the feeder on the sump platform. The cored wire was

Figure 9



CoreTemp components.

Figure 10



Simple schematic of the system installed on the slag door side of EAF No. 3.

routed in such a way as to not interfere with walkways or other working areas.

The wire feeder mounted on the sump platform was angled toward the sanding hole and connected to the OTM system entry port via two sections of rigid stainless 1 1/4-inch SCH 10 pipe to guide the wire into the furnace.

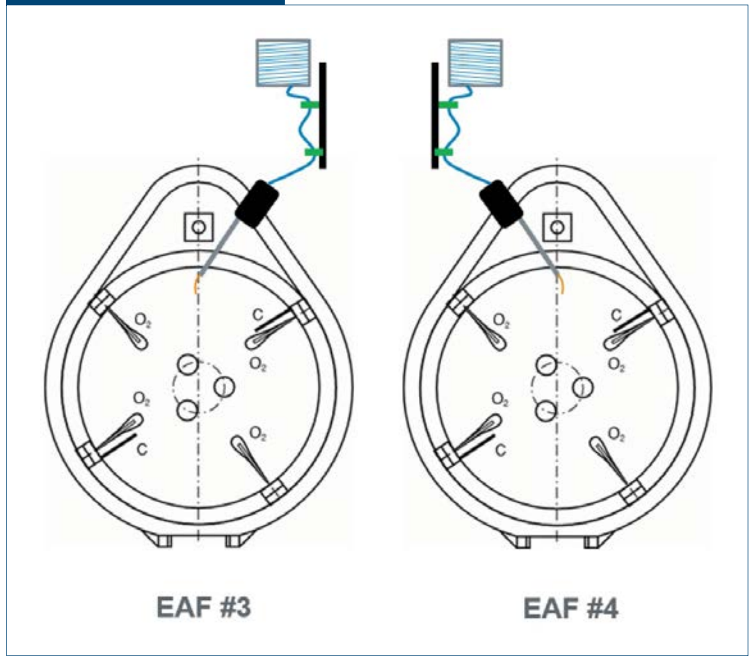
During EAF operation, the OTM system was used to determine the ideal time to measure the endpoint oxygen with a CELOX® sensor. The recommended practice when using CoreTemp is as follows:

- The first measurement is taken as a check to confirm the bath is completely molten in the sump.
- When the metal bath is confirmed molten in the sump, a measurement sequence is initiated. The measurement sequence consists of four measurements, one directly after the other, in 20-second intervals from the start of the first measurement.
- An endpoint CELOX measurement is taken to determine bath oxygen and carbon content.

Two different examples of heats where this practice was used are shown in Fig. 13. During the heat shown in Fig. 13a, the first four optical temperature measurements taken established a heating rate to give the operator a good idea of when to take an endpoint CELOX to determine the carbon content, as well as to confirm the temperature of the steel at the slag door. In this case, although the steel was at the desired temperature, the carbon content was high, resulting in continued oxygen refinement for the next 4 minutes, which further increased the bath temperature. The heat plot in Fig. 13b shows a heat in which the optical temperature measurements align with the CELOX and the carbon content was in the desired range so the heat was immediately tapped. Another interesting phenomenon that can be seen in Fig. 13b is a slight cooling of the bath when the power to the arc is reduced or turned off.

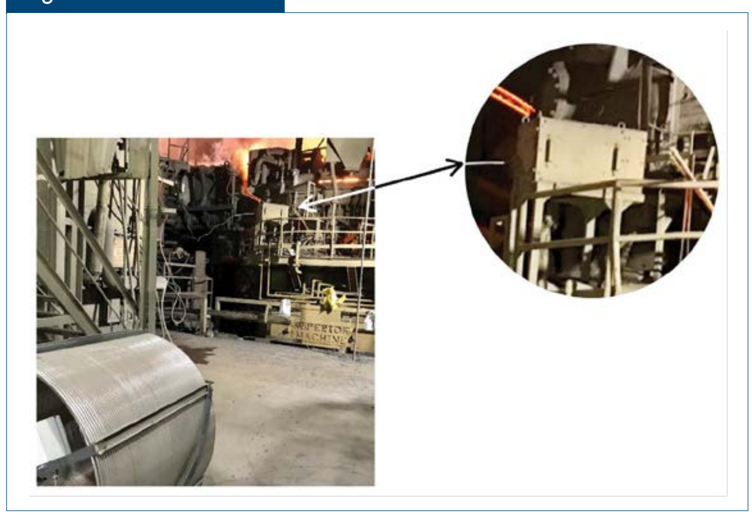
In addition to a temperature measurement, the HMI in the operator pulpit also displays the electrical power input, the tilt of the furnace, along with the temperature and active oxygen measured with a CELOX. The HMI is also used to initiate a single optical temperature measurement or a sequence of measurements with each result being plotted on the graph against the electrical power input, as shown in Figs. 14 and 15. In the sequence of measurements shown in Fig. 14, the first two measurements resulted in scrap impacts, shown as blue squares at the bottom of the y-axis on the graph. Although no temperature was measured, the result of an identified scrap impact is also valuable information because the sump area is not typically visible and knowing there is unmelted

Figure 11



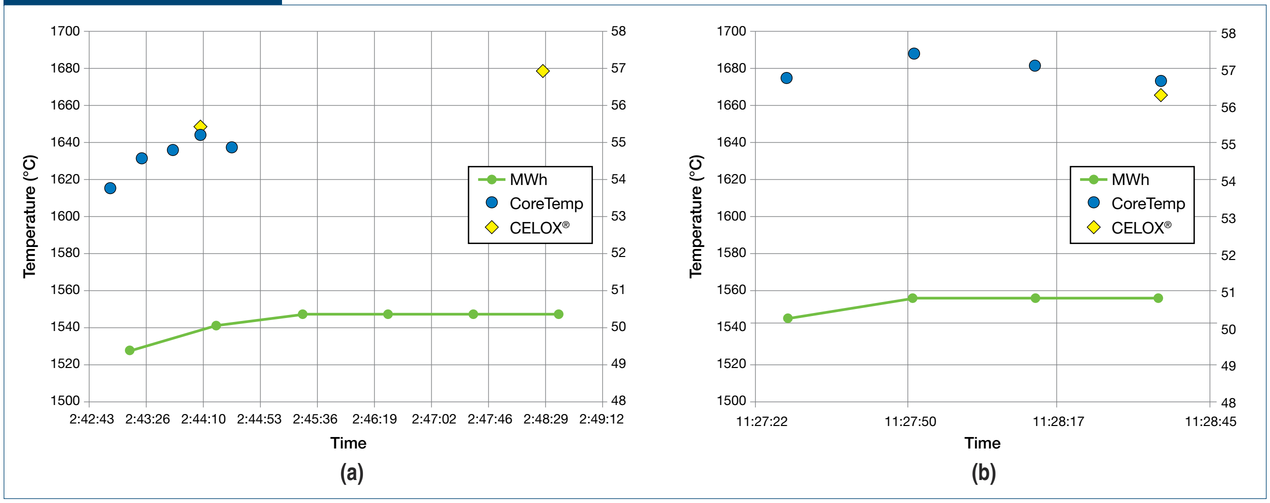
Current installation schematic of the optical temperature system on EAF No. 3 and EAF No. 4.

Figure 12



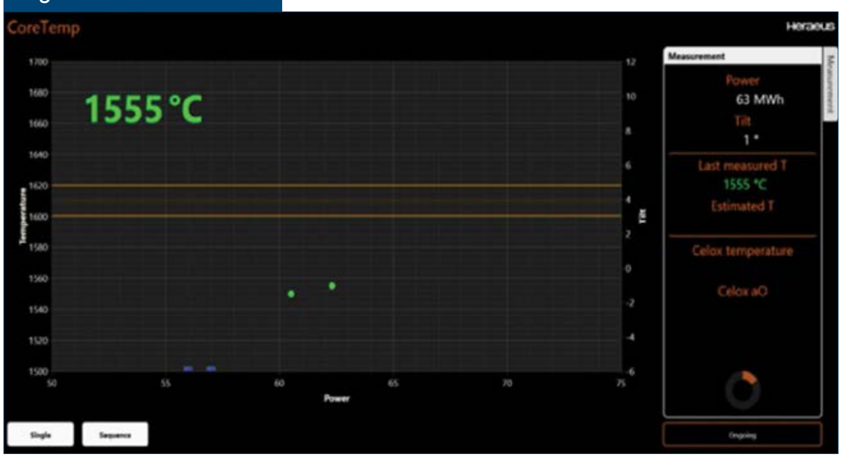
CoreTemp application install on the sump side of EAF No. 3.

Figure 13



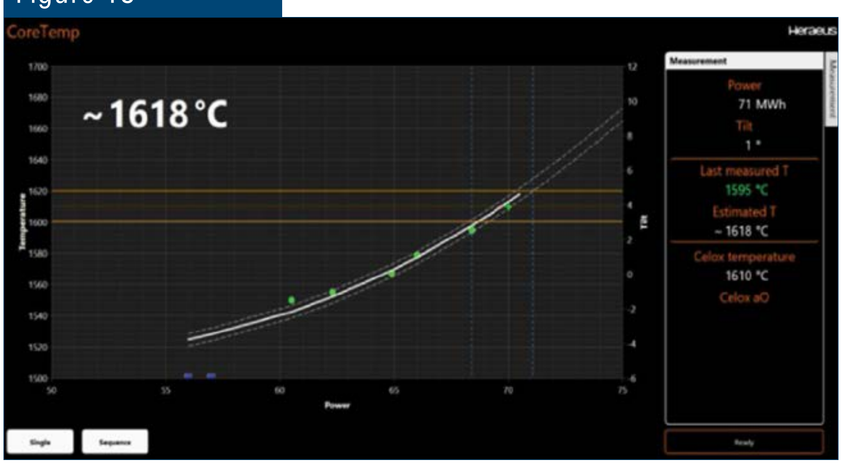
Heat plot from December 2018 on EAF No. 4 (a) and heat plot from January 2019 on EAF No. 4 (b).

Figure 14



HMI display showing the beginning of a measurement sequence.

Figure 15



HMI display showing the measurement sequence temperature evolution and prediction.

scrap present helps the operator make informed adjustments to the melting process.

As the sequence of optical temperature measurements continues, an algorithm is used in conjunction with the continued electrical power input to plot a temperature prediction curve that provides the operator an approximation of how much more power is required to reach a desired temperature, as shown in Fig. 15. Examining Fig. 15, the predicted temperature is displayed to be 1,618°C at 71 MWHr while a CELOX was taken at 70 MWHr and displayed a temperature of 1,610°C, thus the prediction correlated with the actual heating rate of the steel bath. Instances where a significant difference is observed between the optical temperature measurement trend and the CELOX measured temperature are indicative of a non-homogeneous bath, due to either unmelted scrap or incomplete mixing.

One of the key performance indicators (KPIs) that has been tracked at SDI Butler to gauge the impact of CoreTemp on the operation of the EAFs is the percentage of heats that have arrived at the LMF cold, hot or within temperature specification (OK). Fig. 16 shows the percentage of heats that arrived at the LMF hot, cold and within specification (OK) from September 2018 to end of December 2018 for EAF Battery 1 (no OTM) and EAF Battery 2 (has OTM). Fig. 16 shows a reduction in hot heats and an increase in heats arriving to the LMF within temperature specification for Battery 2 over the 4-month analysis period.

The next KPI examined was the standard deviation of the LMF arrival temperatures for all heats made between September 2018 and December 2018. The LMF arrival temperatures for Battery 2 had a standard deviation of 2°C lower than Battery 1 during the months of September, October and December and are shown in Fig. 17. Additionally, the distribution of LMF arrival temperatures for Battery 2 was typically 6°C tighter than Battery 1 during those months.

Another KPI that has been tracked is equipment uptime of the OTM system. Fig. 18 shows system uptime for the months of September 2018 through December of 2018. Percent uptime was calculated as follows:

$$\%Uptime = \frac{No.\ heats\ CoreTemp\ available\ for\ use}{Total\ No.\ of\ heats\ made} \quad \text{(Eq. 2)}$$

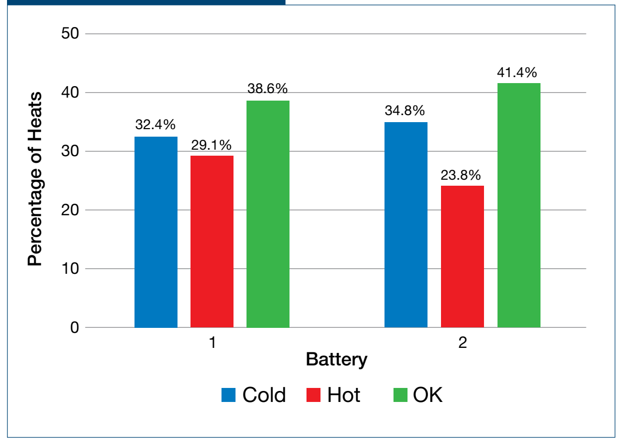
There were two instances that negatively affected the uptime of the OTM systems:

1. Incineration of the feeder electrical cables routed through the EAF shell on the EAF No. 3 system in November, causing the OTM system to be unusable until repairs and installation improvements could be made during the down day a week and a half later.
2. Failure of the welds on the cored wire entry port mounting flange on EAF No. 4 in December. The OTM system was unusable until the mounting flange could be rewelded in place during the next down day 2 weeks after the incident.

In addition to uptime of the OTM system, the actual usage of the system by the EAF operators was tracked as well and is shown in Fig. 19. The graphs of Fig. 19 show the usage of the OTM system by month per crew on each of the two furnaces at Battery 2. The impact of the equipment downtime shown in Fig. 18 can be seen in Fig. 19, specifically in November for EAF No. 3 and December for EAF No. 4.

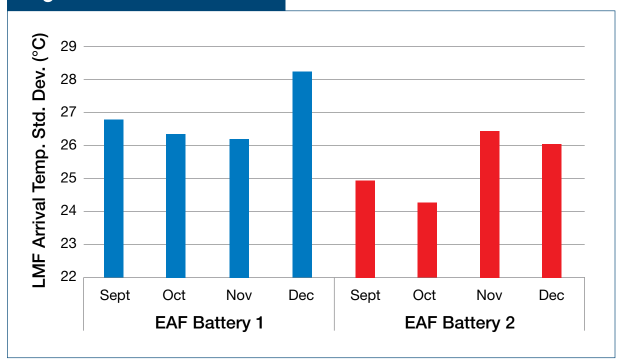
Data was also tracked on the usage of the consumable products at EAF Battery 2, specifically on the usage of oxygen probes. When using CoreTemp, a reduction in EAF probes was also observed and is shown in Fig. 20. An average reduction of one probe

Figure 16



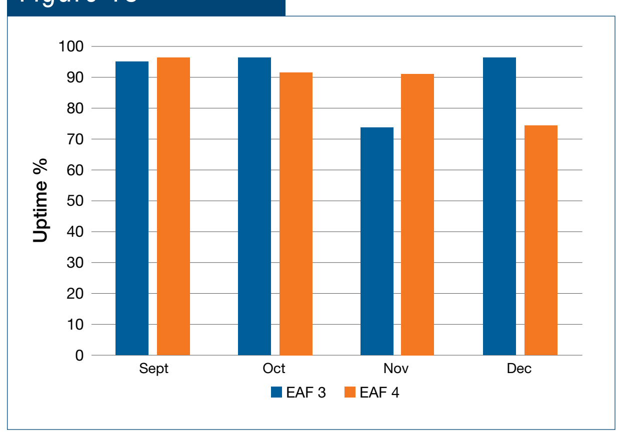
Percentage of heats that arrived at the LMF hot, cold or in specification for both EAF Battery 1 and Battery 2.

Figure 17



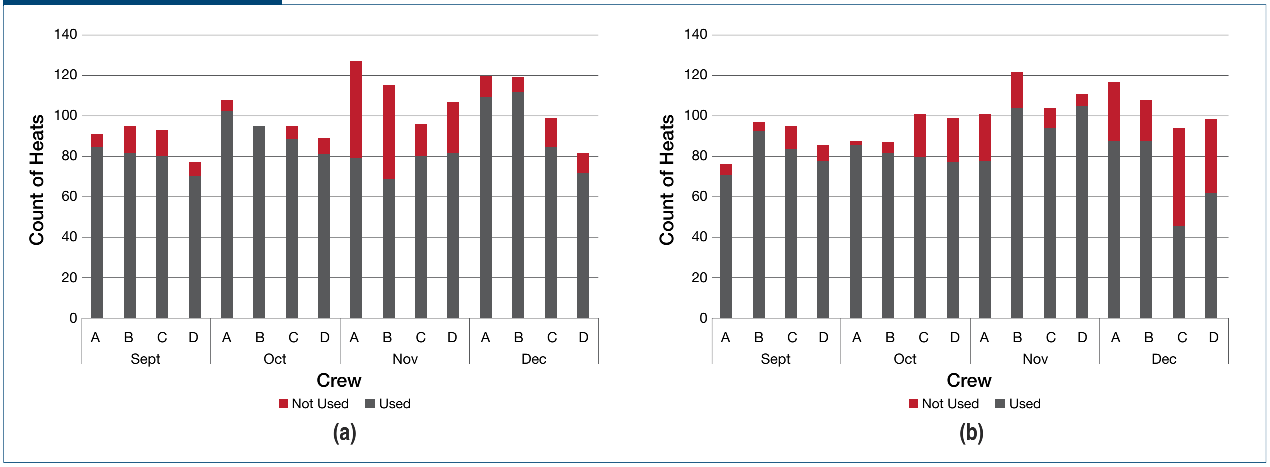
Standard deviation of LMF arrival temperatures for both EAF Battery 1 and Battery 2.

Figure 18



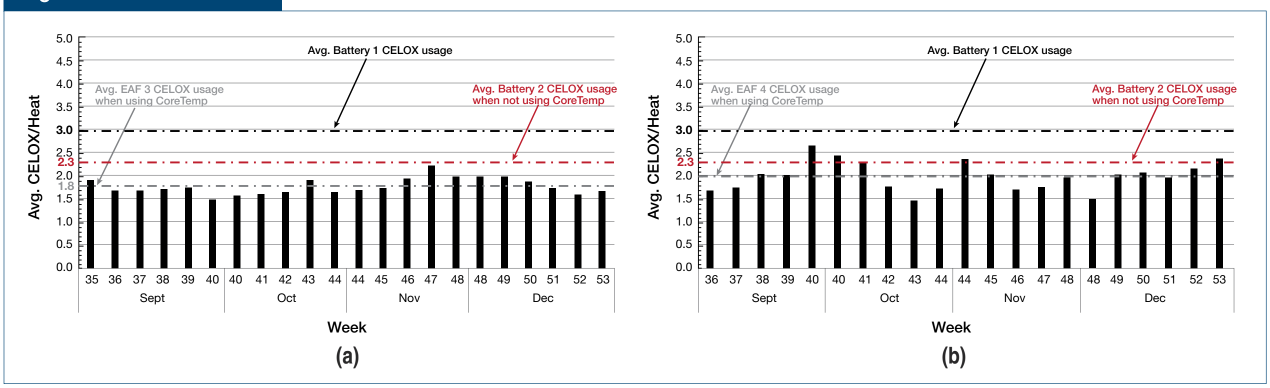
Uptime of the optical temperature equipment for each EAF by month.

Figure 19



EAF No. 3 OTM usage by crew and month (a) and EAF No. 4 OTM usage by crew and month (b).

Figure 20



EAF No. 3 average CELOX usage per heat when using the OTM system (a) and EAF No. 4 average CELOX usage per heat when using the OTM system (b).

for every two heats made was observed for EAF No. 3 and a reduction of one probe for every three heats made was observed for EAF No. 4. In comparison and shown in Fig. 20, the average CELOX usage for Battery 1 was three probes per heat.

Safety

The unique design of the CoreTemp system allows for significant improvements to plant practice that provide a safer workplace for all employees. The system was designed to reduce operator exposure to molten metal as a component of Industry 4.0 and has been achieved by housing all controls within the furnace operator pulpit, meaning the system can be run completely by one operator from the pulpit. The coil lifetime of approximately one week means that a coil exchange can be planned to align with a period of no production so the operators are not on the furnace floor when molten metal is present, such as after EAF tapping. The improved control of the furnace provided by the increased measurement resolution also reduces the risk of any temperature-related events within the furnace that may prove harmful to operators.

Conclusions

During 2018, the CoreTemp system was successfully implemented on EAF No. 3 and EAF No. 4 at SDI Butler. The measurement capability of the system was confirmed both in the laboratory as well as in a typical steelmaking production environment at SDI Butler. The benefits of using the system in the EAF melting process as observed by SDI Butler were:

- Safety — Ability to take temperature measurements in the EAF without having any operators on the operating floor.
- Increased percentage of heats arriving to the LMF within the proper temperature specification.
- Reduced temperature variation of heats arriving at the LMF.
- Ability to measure steel temperature in the EAF earlier in the heating cycle.
- Ability to measure steel temperature in the EAF without collapsing the foamy slag during arcing done by opening the slag door and removing the oxygen lance, as is done with immersion measurements using a manipulator.
- Increased control over the EAF steel temperature by being able to measure temperature in the sump with CoreTemp and through the slag door with CELOX.

The results obtained present the opportunity to move one step closer to a "no man on the floor" operation and increased control over the EAF melting process.

Acknowledgments

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