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Leveraging optical emission spectroscopy (OES) for enhanced process control in Ladle Furnace (LF)

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The Ladle Furnace (LF) serves as a secondary metallurgical process unit for adjusting the composition and temperature of molten steel for casting. Changes and transformations in the steel industry—such as green steel and digitalization—emphasize the need for real-time process control and enabling measurement solutions. This work aimed to study how optical emission spectroscopy (OES) data can be used in process control of ladle furnaces. To this end, data from industrial ladle furnaces was employed to analyze and quantify changes of slag composition and temperature continuously and in real time.

The results show that OES can be used to provide real-time data about the chemical composition of slag and the temperature of slag-steel surface in ladle furnaces and thus allows timely process control. Finally, some special benefits of using OES in steelmaking are discussed. OES can yield information that is not possible or practical to acquire using traditional methods during the process. This cultivates several important use cases and helps operators make accurate decisions.

KEYWORDS: LADLE FURNACE; SLAG; OES; SECONDARY METALLURGY; STEELMAKING; TEMPERATURE.

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INTRODUCTION

Secondary steelmaking is where the final steel composition is adjusted. After primary steelmaking, the ladle furnace becomes the control center for refining molten steel, adjusting temperature, chemistry, and purity to meet demanding specifications. Successful secondary metallurgy depends on two critical components: slag and temperature. Both play an important role in the steelmaking process. Controlling these two helps melt shops achieve target steel grades and hit their quality targets.

Slag is far more than a byproduct; it is a critical process medium that forms a protective oxide layer over molten steel, shielding the metal from atmospheric contamination. Slag composition determines the efficiency of impurity absorption, the management of thermal conditions, and the control of refractory wear. In the ladle furnace, slag stabilizes temperature for precise alloying, protects steel from re-oxidation and nitrogen pickup, and serves as a sink for unwanted elements such as sulfur and SiO_2, enabling effective chemical refinement. In short: if you control slag, you control steel quality.

In the Ladle Furnace, accurate temperature control is critical to the success of secondary metallurgy. Optimal alloying requires that the molten metal temperature stays within limits. Certain chemical reactions will not happen in too low or too high temperatures. Moreover, too high temperatures may cause equipment wear and further issues in tapping and casting.

The challenge? Slag chemistry is dynamic and complex. Ratios of CaO, SiO_2, and Al_2O_3 continuously shift which calls for continuous monitoring to maintain process efficiency and product consistency. Without real-time insight into slag chemistry, variations can lead to costly inefficiencies and inconsistent steel quality and can impact refractory wear of the furnace lining. Similarly, continuous and real-time temperature measurement is essential for quality management and cost-effectiveness. Measurements enable timely adjustments, improved energy efficiency, reduced heat wear of equipment and thus extending the life of critical components.

MATERIALS AND METHODS

The ladle furnace environment is extremely harsh and limits the use of conventional in-situ sensors. As a result, slag composition and temperature measurement is traditionally assessed through probe sampling. This approach provides delayed and discontinuous process information. Real-time measurements are possible by using contactless and non-consumable technology, Luxmet OES. Technology for slag composition and temperature measurements was implemented in ladle furnaces operated by three European steel producers.

The electric arc in the furnace excites the electrons of the atoms in the slag. The release of this excitation energy generates electromagnetic emissions in the form of photons. These emissions can be observed with a spectrometer, and the measured spectrum can then be processed and analyzed [1].

OES system configuration

The system utilizes optical fibers to gather light from a ladle furnace. Measurement heads are placed on the furnace roof, and light is transmitted to a remotely placed spectrometer. In a ladle furnace, Luxmet OES system collects spectrum data, identifies and measures slag components, determines their proportions, and calculates indicator values (such as basicity). The system can measure both the evolution of major slag components and the temperature during the ladle furnace process. The real-time measurement of slag components allows the operator to make needed process control decisions, such as the use of additives, and supports in analyzing the process.

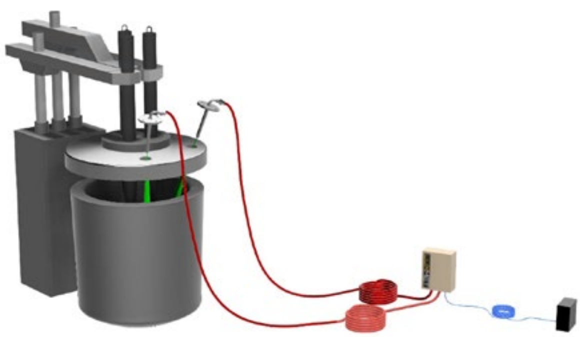

Fig.1 - OES system configuration.

Study focus

The system can measure the evolution of major slag components during the ladle furnace process. This study focuses on the main slag components CaO, MgO, Al_2O_3, and SiO_2. Each of the major slag components plays a key role in the process and may have multiple interrelated roles. Even though each slag components have their main purposes, the reality is dynamic. Ratios and relative quantities of each component affect chemistry continuously [2]. The second objective of this study is to evaluate whether the second measurement head can reliably capture the slag surface temperature in the ladle furnace and providing indicative information about the furnace atmosphere during ladle treatment.

Basicity

Proportions of slag components can be used to calculate estimations of the basicity of the slag, which is a crucial indicator in the ladle furnace process. Basicity is important for managing viscosity, refractory wear, and slag fluidity. Additionally, optimal basicity facilitates desired chemical reactions, such as desulfurization, and prevents undesired reactions, such as those that are damaging to the furnace lining.

For ladle furnace slag, the basicity is calculated as in Equation 1 [3]:

$$B_{LF} = \frac{\%CaO + 1.4 * \%MgO}{\%SiO_2 + 0.6 * \%Al_2O_3} \qquad (1)$$

Temperature

The temperature can be measured from the ladle furnace slag-steel surface. This allows for continuous measurement of temperature changes throughout the heat. Temperature affects how well ladle furnace slag performs. When the temperature is high enough, the slag can react efficiently with the molten steel. If the temperature is too low, the slag becomes less functional, and the refining reactions slow down [4].

A moderate superheat is required for optimal casting conditions. Too high superheat leads to slowing down the process and possible issues. Casting may be interrupted as the cast breaks out or freezes, or there can be surface defects in the cast product. With continuous temperature measurement, the delays and issues can be reduced by optimizing the temperature in ladle furnace [5].

RESULTS AND DISCUSSION

Components evolution

The evolution of major slag components has been measured using the Luxmet OES system in a ladle furnace. A ladle furnace treatment was measured, and the evolution of each major slag component during the treatment is shown in figure 2. The total sum of the slag components does not add up to 100%, as there are other slag components that were not analyzed. The concentration of MgO is rather stable at around 6%. The proportion of SiO_2 fluctuates slightly more, especially towards the end. Al_2O_3 and CaO have stable and fluctuating phases. Midway, aluminum is added to the bath, and the figure shows the change in the component proportions. The relative proportion of aluminum increased, while the proportion of calcium decreased correspondingly.

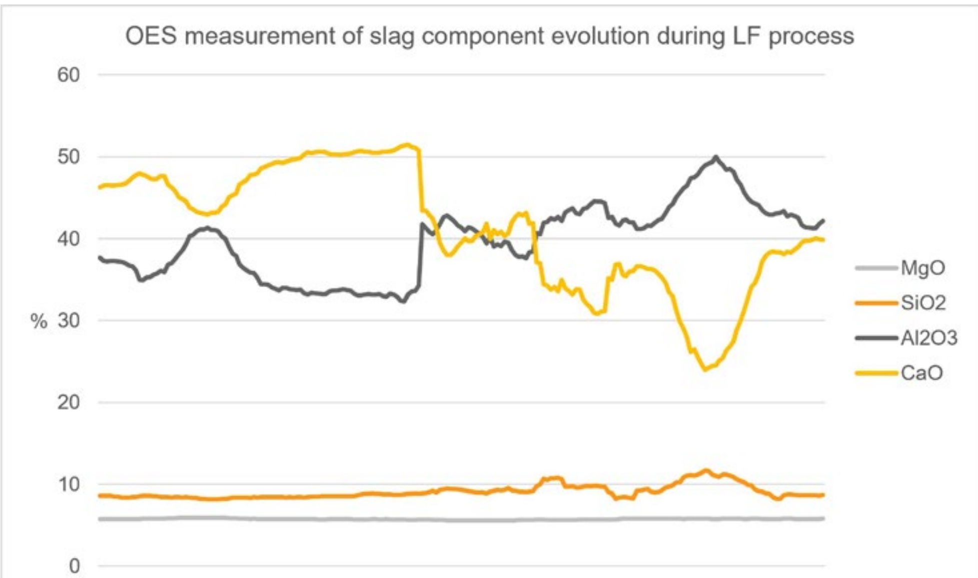

Fig.2 - Evolution of components in slag based on OES.

The presented figure of the evolution of components in slag indicates that OES is capable of capturing composition evolution. Changes in components relative proportions can be clearly identified with OES technology, providing reliable information for determining the evolution of these proportions and the effects of alloying on their relative concentrations. OES provides a stable and interpretable figure of the evolution throughout the ladle treatment, making it a suitable tool for monitoring the major slag components.

Basicity indicator

Figure 3 shows the basicity indicator calculated from the OES measurements as a function of time during the ladle furnace treatment. The continuous orange curve illustrates the evolution of the slag basicity value throughout the process. For comparison, a horizontal grey dashed reference line is included to show the basicity value that was calculated based on an XRF analysis of a sample collected at the end of the treatment. This allows for a direct comparison between the real-time OES based basicity trend and the XRF based basicity of the slag sample at the end.

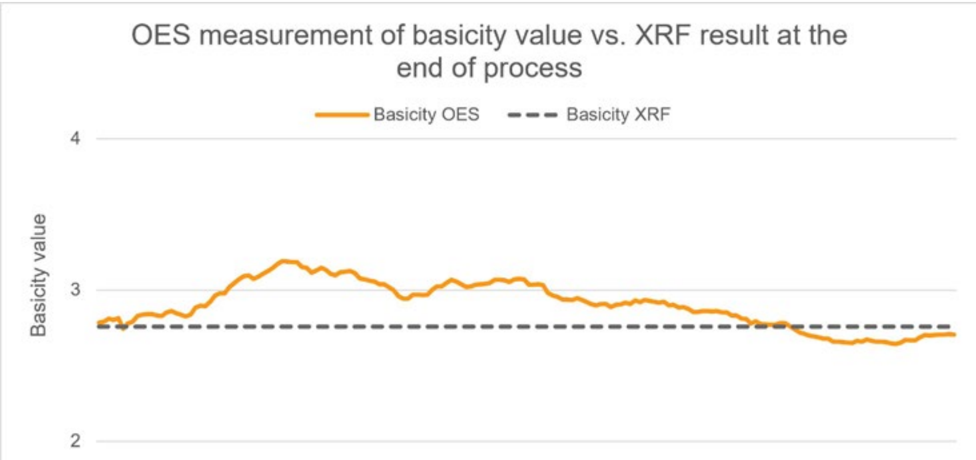

Fig.3 - Basicity values based on OES and the basicity value based on XRF.

The basicity indicator calculated from the OES measurements shows strong applicability for real-time monitoring of slag chemistry in the LF process. The trend follows the expected evolution of basicity and aligns well with the XRF reference value from the end of the treatment. Real-time basicity value information enables improved process control, as operators can adjust flux additions and process controlling actively rather than relying on delayed laboratory analyses. This enhances both the ability to modify the slag toward its target composition more efficiently and the controllability of the refining conditions.

Temperature

The evolution of temperature has been measured using the Luxmet OES system in a ladle furnace. A ladle furnace treatment was measured, and the evolution of the surface temperature during the treatment is shown in figure 4. The continuous orange curve illustrates the evolution of the temperature throughout the process. The grey intervals indicate periods which the arc is on in the ladle treatment. The figure shows that accurate temperature measurements have been obtained during periods when the arc is off.

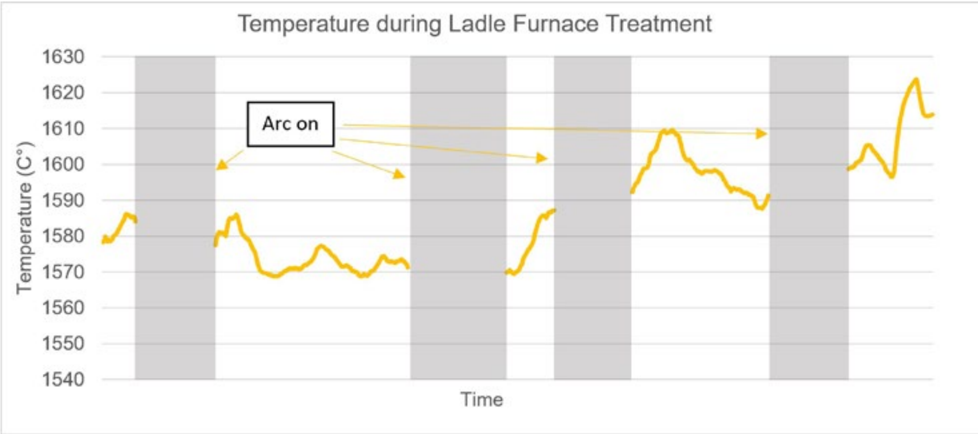

Fig.4 - Evolution of temperature during a Ladle Furnace Treatment.

The temperature measured from the ladle furnace using OES technology shows strong capability for real-time temperature monitoring. The trend follows the expected evolution of temperature, and the measurement is accurate when the arc is off. This improves the ability to obtain real-time insight into the furnace conditions during ladle treatment.

CONCLUSIONS

Ladle furnaces play a critical role in secondary metallurgy, refining molten steel before casting. While the furnaces offer precise control over temperature and composition, they also present several challenges that can impact steel quality, process efficiency, and equipment longevity. Luxmet OES technology is well-suited for real-time slag analysis and temperature measurement in the ladle furnace. The OES-based system can provide information on the evolution of slag composition in real time during the process and thus enable timely and precise process control. The evolution of the major components can be measured, and new components are being added to the list. Using a system configuration of two measurement heads, the surface temperature can be measured with the other measurement head when the arc is off, providing real-time insight into the thermal state of the furnace. Real-time, data-driven process monitoring enables dynamic process control. Contactless, continuous, and real-time slag analysis in the ladle furnace can lead to consistent product quality and steel grades, optimal alloying and the use of additives, and the prevention of excessive refractory lining damage.

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