Optical Emission Spectroscopy as an Online Analysis Method in Industrial Electric Arc Furnaces

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1. Introduction

Electricity-based steelmaking with electric arc furnaces (EAFs) has been increasing during the past decades, currently amounting to around a third of the global steel production.[1] Reasons for this, to name a few, are lower carbon dioxide emissions and better energy efficiency compared with the traditional ore-based steelmaking.[1,2] Furthermore, favoring the recycled metal as the raw material over the ore-based steelmaking has a key role in sustainable resource and energy use.[3] Due to these reasons, electricity-based steelmaking can be expected to increase even more in the future.

Recycled metal is one of the main raw materials for an EAF. One of the downsides of the recycled metal is its highly varying composition and particle size. Thus, the composition of the slag that accumulates on top of the molten steel is unique for every batch. The slag is quantitatively a major byproduct in the steelmaking but the varying composition causes problems for the final slag product.[4] A common way to determine the slag composition is to make an offline X-ray fluorescence (XRF) analysis, which requires careful sample preparation[5] causing a time delay between the slag sampling and obtaining the XRF results.[6] Therefore, the results of the XRF slag composition analysis have limited use during the melting process in practice. In contrast, online evaluation of the slag composition would allow the furnace operator to decide how much and which additive materials, such as lime or ferrosilicon, should be added before the end of the melt. Also, the timing of these additions could be adjusted to optimal instances. By getting the information of the slag composition in advance, the operator would be able to plan the use of additive materials from the resource use and efficiency point of view.

Due to the demand for sophisticated modeling of the EAF processes and experimental validation of the methods, the fundamental EAF research has increased over the years. Especially, the online measurements and modeling have gained a lot of attention from the steel industry because online data analysis would contribute to more efficient resource use, real-time modification of the steel composition, and anticipation of abnormal and even hazardous phenomena in the furnace. From the melting point of view, Logar et al.[7] developed a computational model that can be used online due to low computational demand to estimate the heat transfer coefficient in the EAF. Fathi et al.[8] presented a computational model to estimate the arc energy distribution to conductive, convective, and radiative heat transfer processes with low enough computation times for online applicability. Li et al.[9] have proposed a model that combines offline and online aspects of the EAF process to adjust the electrode regulation system to optimum practice. Khoshkho et al.[10] introduced a model for efficient power control of EAFs that uses...
an artificial neural network for the online estimation of inductance values. Martell et al.\textsuperscript{11} proposed an arc stability index for EAF that is based on the online analysis of the line to ground three-phase voltage. Experimentally, Aula et al. used optical emission spectroscopy (OES) as an online analysis tool to estimate the Cr$_2$O$_3$ content of the slag in a pilot-scale EAF\textsuperscript{12} and to analyze the melting process and slag surface conditions in an industrial EAF.\textsuperscript{13}

In this work, the applicability of the OES as an online analysis tool has been evaluated in an industrial EAF. Because the electric arc forms plasma, the qualities of the arc spectra can be analyzed with plasma diagnostics from the OES spectra. The benefit of the OES is that the electric arc radiates throughout the melting process, and the measurement equipment is capable of online data acquisition. The electric arc is mostly in contact with the slag surface above the molten metal, which means that the majority of the light from the electric arc originates from the slag components.\textsuperscript{14} Thus, the OES combined with plasma diagnostics is a potential tool for the online analysis of the slag composition. Furthermore, the time evolution of the spectrum intensities and estimates of the bath surface temperature for high alloyed and carbon steel grades have been compared with each other.

2. Experimental Section

Optical emission spectra were recorded from an industrial EAF at Deutsche Edelstahlwerke, Germany. The measurement equipment consisted of the industrial EAF with 120 and 140 t capacity for high alloyed and carbon steel grade, respectively, a spectrometer, a measurement head, an optical fiber, and a data storage computer. A Czerny–Turner spectrometer Avaspec-ULS2048 provided by Luxnet Oy was used in these measurements. The optical fiber was attached to the measurement head that was welded to the furnace roof. The spectrometer cabinet was located away from the furnace. Neither the measurement head nor the spectrometer required any maintenance during the measurement campaign. Pressurized airflow was used to cool the measurement head and to prevent slag splashes from reaching the measurement head. The view cone of the fiber was aligned to the assumed electric arc position of the nearest electrode. The OES measurement equipment and data analysis for an industrial EAF are schematically shown in Figure 1.

The steel grades consisted of both high alloyed and carbon steel. High-quality arc spectra were observed for the high alloyed steel grade. The spectra from the electric arc for the carbon steel grades were very infrequent and not uniform enough for reliable plasma analysis. Slag foaming is a common practice for carbon steel grades, which means that there is a high chance for the electric arc to be covered by the foam. Because the measurement head was welded on the furnace roof, the initial positioning and aiming of the measurement head affect the visibility of the arc. Furthermore, the arc movement is erratic on the slag surface, which means that the arc will not always be in the view cone of the measurement head. Therefore, the location and aiming of the measurement head were carefully considered before the installation. With proper installation, the visibility of the arc can be improved, but due to the erratic movement of the arc, it will probably not be in the view cone of the measurement head all the time.

An example of a high alloyed steel grade arc spectrum and thermal radiation spectrum from the industrial EAF is shown in Figure 2. The wavelength range of the spectra is 497–1000 nm, covering visible and near-infrared light. The wavelength ranges for the most intensive atomic slag component emission lines had been marked in the arc spectrum. The OES plasma analysis had been conducted for the high alloyed steel grade. This analysis involved 43 melts and the qualities of the spectra were high on 30 melts. It had been observed in previous studies that the light from the EAF plasma is governed by the emissions from the slag components.\textsuperscript{12,15} Similarly, the atomic slag components that were dissociated from the slag molecules were the main source of light directly from the arc in this study. In contrast, the thermal radiation spectrum originated from the molten bath surface and the atmosphere. The drops in the intensity around 715, 770, 880, and 940 nm were caused by self-absorption. Self-absorption is a phenomenon in which the emitted light is reabsorbed by another particle in the plasma or the atmosphere. This absorption weakened the received light at the spectrometer.\textsuperscript{16} The self-absorption around 770 nm was related to intensive atomic potassium doublet emission lines. The other self-absorbed regions were assumed to originate from molecular sources or spectrometer settings, but the analyses of these aspects were outside the scope of this study.

Figure 1. Schematic illustration of the measurement method and data analysis.
between the upper energy state \( m \) and the lower energy state \( n \), \( g_m \) is the degeneracy of the upper energy state, \( A_{mn} \) is the transition probability, \( k \) is the Boltzmann constant, \( T \) is the plasma temperature, \( E_m \) is the energy of the upper energy state, \( h \) is the Planck’s constant, \( c \) is the speed of light, \( N^2 \) is the number density, and \( U(T) \) is the partition function. The term in the far right of Equation (1) is constant at a fixed temperature and can, therefore, be neglected. \( \varepsilon^* \) is proportional to the intensity of the emission line assuming that the plasma is in local thermodynamic equilibrium (LTE) and the atmosphere is optically thin.\(^{[17]}\) By plotting the left-hand side of Equation (1) as a function of \( E_m \), the plasma temperature can be determined from the slope, \(-1/kT\), of the plot. The error of Equation (1) can be estimated with

\[
\frac{\Delta T}{T} = \frac{kT}{\sum_{i=1}^{q} E_i^2 - \frac{1}{q} (\sum_{i=1}^{q} E_i)^2} \left[ \frac{\Delta \varepsilon}{\varepsilon} + \frac{\Delta A}{A} \right]
\]

where \( q \) is the number of the emission lines, \( \Delta \varepsilon/\varepsilon \) is the general relative error of the line intensity, and \( \Delta A/A \) is the general relative error of the transition probability.\(^{[18]}\) \( \Delta \varepsilon/\varepsilon \) and \( \Delta A/A \) were estimated to be 10% and 20%, respectively.

The electron density of the plasma, i.e., the number of free electrons, can be used to evaluate the conductivity of the arc and the fulfillment of the LTE condition. The electron density of the plasma follows the Saha–Boltzmann equation\(^{[17]}\)

\[
N_e = C \sqrt{\frac{T}{e}} \exp \left( \frac{E_m - E_{\text{ion}} - E_{i+1}}{kT} \right)
\]

in which \( C = 2(2\pi m_e k)^{3/2}/h^3 \), \( E_{i+1} \) is the intensity of emission line from the transition between the upper energy state \( i \) and the lower energy state \( j \), and \( E_{\text{ion}} \) is the ionization energy of the ground state.

In real plasmas, the deviations from the total thermodynamic equilibrium occur, e.g., due to radiative energy transfer from the plasma. If the temperature is locally uniform within the plasma, it is said to be in LTE. An LTE criterion according to McWhirter\(^{[17,19]}\) states that the collisional processes have to be at least ten times the rate of radiative processes. This criterion is fulfilled when

\[
N_e \geq 1.6 \times 10^{12} \sqrt{T(\Delta E)^3} \text{ cm}^{-3}
\]

where \( \Delta E \) is the energy difference between the energy states in electron volts. The arc gains energy from the applied electric field and this energy is transferred mainly to the free electrons in the plasma.\(^{[20]}\) Thus, exceeding the McWhirter electron density criterion ensures that the collisional processes distribute the energy uniformly into the arc plasma. The constants, apart from the natural constants, in Equation (1)--(4) have been acquired from the NIST Atomic Spectra Database.\(^{[21]}\)

The thermal radiation profile of the OES spectra can be used to estimate the temperature of the object that the spectrometer observes. In the case of EAF, when the arc is not in the view cone of the measurement head, the heat radiation mainly originates from the molten bath and the atmosphere. Thus, the measured temperature is not exactly the molten bath surface temperature, but it is affected by the atmosphere. These temperatures can,
however, be used to monitor temperature differences and how the estimated temperature evolves during the heat. In this study, the temperature has been estimated with Wien’s law by approximating that the temperatures are less than 5000 K. This approximation holds, when the measurement head observes the molten bath and the atmosphere, but not directly the arc. The estimated temperature is

$$T_{\text{estimate}} = \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \frac{hc}{k \ln \left( \frac{I_1}{I_2} \lambda_1 \lambda_2 \right)}$$

(5)

where $T_{\text{estimate}}$ is the estimated temperature, $\lambda$ is the wavelength, $h$ is the Planck’s constant, $c$ is the speed of light, $k$ is the Boltzmann’s constant, and $I$ is the intensity. The subscripts 1 and 2 refer to the selected upper and lower wavelengths, respectively. $\lambda_1$ and $\lambda_2$ were chosen to be 600 and 800 nm, respectively, because neither of these wavelengths overlaps with strong alkaline or slag component emission lines. Consequently, $I_1$ and $I_2$ correspond to the intensity of the 600 and 800 nm in the spectra, respectively.

4. Results and Discussion

4.1. Time Evolution of the Spectra for High Alloed and Carbon Steel Grades

The time evolution of the spectra for high alloed and carbon steel grade melts was studied in more detail to determine the difference between the radiative properties of different steel grades. The spectra were divided into nine wavelength ranges to which Gaussian functions were fitted. These wavelength ranges were centered at 570, 650, 700, 750, 800, 850, 910, 970, and 1000 nm. The full widths at half maximum varied between 20 and 60 nm depending on the shape of the spectrum. With this division, the whole intensity profile of the spectra, such as the spectrum in Figure 2b, was covered and the different wavelength ranges together with their time evolution could be compared with each other.

The time evolution of 570, 750, and 910 nm centered fits together with estimated temperature for high alloed and carbon steel grades, as shown in Figure 3a,b, respectively. The data shown in Figure 3 have been averaged over five spectra. As shown in
Figure 3, the light emissions from the two steel grades differ from one another substantially. On average, the intensities of the high alloyed steel grade are higher than in the carbon steel grade. The main reason for the lower intensity of the carbon steel grade is the foaming of slag, which presumably blocks the direct view to the arc. Two notable drops in the light intensity can be observed in the time evolution of carbon steel grade in Figure 3b between the time ranges 100–225 and 270–380. These periods can be attributed to foaming slag that at least partially covers the arc. The time evolution of the intensities can be used to monitor the melting of the solid charge material. As the charge melts, more and more thermal radiation and light from the arc reaches the measurement head. In Figure 3b, the 570 and 750 nm centered intensities increase until time 100, after which the foaming is initiated. The OES intensity data could be used, e.g., to optimize the timing of the foaming.

The temperatures were estimated with Equation (5) for the melts shown in Figure 3. For high alloyed steel grade, the temperatures are mainly between 1000 and 2000 K with the exceptions of over 2200 K toward the end of the melt. The temperatures over 2200 K correspond to the instances when the arc is in the view cone of the measurement head. For carbon steel grade, the temperatures do not exceed 2200 K and thus the arc is not visible. Generally, the temperatures are close to the molten metal surface temperatures. However, as the atmosphere affects the light emissions from the surface, these temperature values should be treated as estimates, not the absolute values.

As shown in Figure 3a,b, the estimated temperatures have different trends than the intensities. Even though the intensities drop between times 100 and 200 for the high alloyed steel grade, the temperature increases. The same can be observed for carbon steel grade between times 250 and 300, where the light intensity drops significantly but the observed temperatures stay relatively unchanged. In contrast, for the high alloyed steel grade between time range of 300–500 and carbon steel grade between time range of 100–200, the temperatures approximately follow the behavior of the intensities. This information could be used to evaluate the progression of the foaming, where the light intensity would be an indicator of the radiative heat transfer and the temperature would provide an estimation of the molten bath or foam surface temperature. For example, if the spectra would indicate that the intensities and the temperature increase even though the slag foaming has been started, actions could be made to optimize the foaming conditions.

To better understand the radiative differences between the high alloyed and carbon steel grades, two melts from each grade have been studied in more detail. The intensity distributions of the high alloyed and carbon steel grades, both grades including two melts, are shown in Figure 4. As shown in Figure 4, the distribution of intensities in the wavelength ranges centered at 570, 650, 700, and 750 nm are close to one another. These wavelength ranges cover the visible light in the spectrum of light.

In contrast, the wavelength ranges centered at 800, 850, 910, 970, and 1000 nm cover the near-infrared region and display a notable difference between the two steel grades. The carbon steel grade spectra have lower intensities at these wavelengths, whereas the high alloyed steel grade has more high-intensity spectra. Because the near-infrared region covers the part of the heat radiation from the melt and the arc, the radiative heat transfer is higher for the high alloyed steel grade. One reason for this is that the foaming slag, which is typical practice for carbon steel grade, covers the arc and thus substantially lowers the heat losses via radiative heat transfer.[15,22,23]

4.2. High Alloyed Steel Grade Plasma Analysis

The plasma temperatures for high alloyed steel grade arc spectra have been determined with 5 Cr I, 7 Fe I, and 4 Ca I emission lines. These emission lines are shown in Table 1. The Roman numbers I and II correspond to neutral and singly ionized species, respectively. The emission lines have been selected so that the coefficient of determination, $R^2$, for the plot of Equation (1) is higher than 0.85. The median errors were determined with Equation (2) for chromium, iron, and calcium plasma temperatures resulting in 7.6%, 4.6%, and 35.4%, respectively. Calcium temperatures have a very high error because the upper state energies of the Ca I emission lines are close to one another. Furthermore, only 4 Ca I emission lines could be used reliably in the plasma temperature analysis.

The electron density $N_e$ has been determined using Equation (3) with chromium plasma temperature together with Ca I #1 and Ca II #1 emission lines in Table 1. The LTE criterion density $N_{LTE}$, which is the right-hand side of Equation (4), has been obtained using the chromium temperature and the energy difference between Ca I energy states. No matter what emission lines were used, the $N_e$ was always higher than the $N_{LTE}$. This indicates that the plasma is in LTE. However, the plasma temperatures from chromium, iron, and calcium had large differences occasionally, which is an indicator of a deviation from the thermodynamic equilibrium.[17] The differences in the plasma temperatures may also hold information about how the elements are distributed in the plasma because the plasma temperature is higher in the center of the plasma than in the edges of the plasma.

An example graph with the plasma temperatures, the electron density, and the LTE criterion density is shown in Figure 5. As shown in Figure 5, spectra from the arc can be observed 5–20 min before the end of the melt. The high-quality spectra were typically seen for all the melts within the last 30 min before the end of the melt. In Figure 5, the plasma temperatures from the chromium and iron emission lines are more uniform than the plasma temperature from calcium. However, the calcium temperature converges with chromium and iron temperature toward the end of the melt, which indicates a better LTE condition in the plasma. In contrast, the iron and calcium temperatures are very scarce just after 09:29:30, which means that the quality of the spectra has decreased.

The electron density of the plasma in the melt of Figure 5 varies from around $10^{16}$ to $10^{18}$ cm$^{-3}$ during the whole visibility of the arc. In contrast, $N_{LTE}$ is around $1 \times 10^{15}$ and $2 \times 10^{15}$ cm$^{-3}$. For the most part, the calcium temperature is over 1000 K below the chromium and iron temperatures or cannot be determined reliably if the electron density is below $5 \times 10^{16}$ cm$^{-3}$. When this happens, the number of reliable iron temperatures also drops significantly. The lack of reliable temperatures could indicate that only the edge of the plasma, where the plasma temperature and electron density are lower than closer to the center of the plasma, is in the view cone of the spectrometer. Another explanation could be
an increase in the optical thickness of the furnace atmosphere due to a higher evaporation rate from the slag surface. Toward the end of the melt, the number of calcium temperatures has dropped but the temperature values are closer to chromium and iron temperatures than before. The electron density drops below $10^{17}$ cm$^{-3}$ within 10 min before the end of the melt.

Even though the electron density of the plasma fulfills the McWhirter criterion for the LTE, the plasma temperatures, especially the calcium temperature, may deviate from the plasma temperatures that are derived from other elements. This can clearly be seen in Figure 5 before 09:25:00 when the calcium temperature is over 1000 K below chromium and iron temperatures. In the melt of Figure 5, the most reliable spectra are acquired between 09:23:45 and 09:29:00, during which the electron density is higher and the plasma temperatures closer to one another. This would yield 98 s of data while considering the gap between 09:24:15 and 09:27:10, during which the arc is outside of the view cone of the measurement head. Altogether, this evaluation would produce the most reliable data 7 min 59 s before the end of the melt.

A more uniform melt is shown in Figure 6, for which the plasma temperatures are closer to one another more often than in Figure 5. The best agreement between the temperatures is between $5 \times 10^{16}$ and $5 \times 10^{17}$ cm$^{-3}$ toward the end of the melt. The plasma temperatures deviate from each other significantly between 19:19:15 and 19:21:25, after which the temperatures are closer to each other except for a drop in calcium temperature between 09:26:30 and 09:27:45. Usually, calcium plasma temperature has the highest standard deviation of the temperatures, and only the spectra with the best agreement between the plasma temperatures should be taken into the analysis. The melt in Figure 6 would have 62 s of data, and the most reliable data would be acquired 6 min 30 s before the end of the melt.

Due to the changing environment in the furnace, gas emissions from the melt, and the possibility of the arc wandering on the slag surface, occasions with nonuniform plasma parameters can be expected for some melts. Figure 7 shows an example melt during which the plasma profile deviates substantially from Figure 5 and 6. In the beginning, the plasma temperatures are scarce and calcium temperature fluctuates significantly. Then, after a long gap with the arc outside of the view cone of the measurement head, calcium temperature is observed only occasionally and there is a 1000 K difference between chromium and iron temperatures.
The melt shown in Figure 7 was the only one to show such extreme differences in the plasma parameters. Comparing with other melts, the chromium temperature is close to the values of other melts (around 6500 K and above) between 13:48:00 and 13:49:10, whereas the iron temperature is lower than in the other melts. Lower plasma temperature has been linked to a higher amount of metal vapors in the plasma,[24] which could mean that there has been a high evaporation rate from the slag or steel between 13:41:30 and 13:42:55. In contrast, the lack of calcium temperatures and the high difference in chromium and iron temperatures between 13:47:40 and 13:49:10 is a sign that the optical emissions are affected by the changes in the furnace atmosphere or self-absorption. Several ways to correct the effects of self-absorption have been discussed by Aragón and Aguilera,[17] and one promising method studies the intensity ratios from the emissions that originate from the same multiplet of an energy state.[25]

By including plasma diagnostics as a validation tool for the spectra, the changes in the furnace atmosphere, electric arc behavior, and even evaporation rates from the molten bath surface can be evaluated and accounted for in the analysis. In the melt of Figure 7, 78 s of data would be acquired 14 min 33 s before the end of the melt between 13:41:30 and 13:42:55, or 129 s of data 7 min 30 s before the end of the melt between 13:47:40 and 13:49:10. Based on the aforementioned discussion, more reliable data are observed between 13:41:30 and 13:42:55, for which the lower average plasma temperature could be explained by the higher amount of metal vapor in the plasma. Metal vapors in the plasma also increase the radiative heat transfer, emissivity, and conductivity of the plasma column.[24,26]

The OES plasma analysis results for 30 high alloyed steel grade melts are shown in Table 2. The total number of high alloyed melts during the measurement campaign was 43. Thus, 70% of all the high alloyed steel grade melts had high-quality spectra. At the very beginning of the melt, the arc is covered by the charge material and the gases from the scrap charge. The very harsh atmosphere before the flat bath phase is probably the main cause of poor arc visibility.

The fact that the arc is visible toward the end of a melt is promising for slag composition analysis because at that point the charged material will have melted, and the molten bath has had time to mix. Furthermore, the slag composition at the end of the melt is closer to the final composition at tapping, which would make the slag composition evaluation more reliable.

| Table 1. Emission lines used in the plasma temperature and electron density analysis. Wavelengths are in nm, transition probabilities in s\(^{-1}\), and energies in eV. \(g\) is dimensionless. |
|---|---|---|---|---|---|
| Line No. | \(\lambda\) | \(A_{mn}\) | \(E_n\) | \(E_m\) | \(g_m\) |
| Cr I 1 | 530.075 | 2.5 E + 5 | 0.98 | 3.32 | 7 |
| 2 | 531.288 | 9.3 E + 6 | 3.45 | 3.45 | 7 |
| 3 | 531.878 | 9.7 E + 6 | 3.44 | 5.77 | 5 |
| 4 | 666.926 | 5.9 E + 6 | 4.17 | 6.03 | 7 |
| 5 | 735.350 | 9.1 E + 6 | 2.89 | 4.57 | 7 |
| Fe I 1 | 522.553 | 1.3 E + 3 | 0.11 | 2.48 | 3 |
| 2 | 522.833 | 1.9 E + 6 | 4.22 | 6.59 | 7 |
| 3 | 528.362 | 1.0 E + 7 | 3.24 | 5.59 | 7 |
| 4 | 533.993 | 6.4 E + 6 | 3.27 | 5.59 | 7 |
| 5 | 550.678 | 5.0 E + 4 | 0.99 | 3.24 | 7 |
| 6 | 556.962 | 2.3 E + 7 | 3.42 | 5.64 | 3 |
| 7 | 557.609 | 2.5 E + 7 | 3.43 | 5.65 | 1 |
| Ca I 1 | 518.885 | 4.0 E + 7 | 2.93 | 5.32 | 5 |
| 2 | 526.171 | 1.5 E + 7 | 2.52 | 4.88 | 3 |
| 3 | 527.027 | 5.0 E + 4 | 2.53 | 4.88 | 5 |
| 4 | 551.298 | 1.1 E + 8 | 2.93 | 5.18 | 1 |
| Ca II 1 | 854.209 | 9.9 E + 6 | 1.70 | 3.15 | 4 |

Figure 5. Plasma temperatures for chromium, iron, and calcium together with electron density and LTE criterion density. The end of the melt is at 09:37:40.
Online measurement applicability, according to this study, suggests that estimation of the slag composition could be acquired within 30 min before the tapping for high alloyed steel grades. The most reliable data are usually acquired from the spectra between 5 and 20 min before the end of the melt. In contrast, for carbon steel grades, a different approach is needed due to the foaming slag practice. For example, increasing the arc length momentarily could allow better visibility of the arc and provide reliable arc spectra for slag composition analysis. The OES results that have been presented in this article are shown in Table 3.

Slag composition analysis with OES has already been tested in a laboratory setup for several slag components\[15\] and a pilot-scale EAF for Cr$_2$O$_3$ content with promising results.\[12\] In these studies, the emission spectra were recorded and analyzed to identify the most promising emission lines to be used in the slag composition analysis. The slag composition was also analyzed with XRF, which was then used as reference data for the OES slag composition analysis. The industrial application would follow a similar manner, i.e., measuring the intensities of the emission lines from the slag components and relating them to the

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**Figure 6.** Plasma temperatures for chromium, iron, and calcium together with electron density and LTE criterion density. The end of the melt is at 19:36:52.

**Figure 7.** Plasma temperatures for chromium, iron, and calcium together with electron density and LTE criterion density. The end of the melt is at 13:57:28.
reference data. The reference data could be, for example, the XRF composition analysis, which is widely used in the steel industry for offline slag composition analysis. Once the OES data have been compared with the reference data and calibrated accordingly, the slag composition analysis could be brought from offline to online.

Table 2. Plasma analysis results for the high alloyed steel grade melts with adequate arc spectra. The time to the end of the melt indicates how much time is left until the tapping after the observation of the last high-quality spectrum. The plasma temperatures and electron densities are median values.

| No. | Total time of high-quality spectra [s] | Time to the end of melt | Cr $T$ [K] | Fe $T$ [K] | Ca $T$ [K] | $N_e$ [$10^{16} \text{ cm}^{-3}$] |
|-----|--------------------------------------|-------------------------|------------|------------|------------|-----------------|
| 1   | 44                                   | 6 min 30 s              | 6590       | 5790       | 5690       | 10.36           |
| 2   | 25                                   | 6 min 45 s              | 5960       | 6160       | 5500       | 7.24            |
| 3   | 40                                   | 7 min 7 s               | 6730       | 6140       | 6350       | 18.08           |
| 4   | 41                                   | 6 min 31 s              | 6160       | 6100       | 5710       | 5.05            |
| 5   | 15                                   | 10 min 9 s              | 6910       | 6030       | 3540       | 4.20            |
| 6   | 40                                   | 8 min 1 s               | 6670       | 6180       | 5620       | 7.83            |
| 7   | 66                                   | 7 min 40 s              | 6840       | 5830       | 5400       | 7.13            |
| 8   | 29                                   | 11 min 59 s             | 6680       | 5860       | 5490       | 6.92            |
| 9   | 22                                   | 4 min 56 s              | 6350       | 6000       | 5600       | 3.59            |
| 10  | 98                                   | 7 min 59 s              | 6560       | 6310       | 5730       | 9.06            |
| 11  | 34                                   | 10 min 20 s             | 6490       | 6220       | 6070       | 8.63            |
| 12  | 38                                   | 13 min 57 s             | 6730       | 5690       | 5150       | 39.00           |
| 13  | 14                                   | 14 min 48 s             | 6950       | 5750       | 4200       | 15.49           |
| 14  | 8                                    | 8 min 50 s              | 6670       | 6120       | –          | 20.55           |
| 15  | 44                                   | 9 min 21 s              | 6540       | 6160       | 6500       | 21.07           |
| 16  | 53                                   | 22 min 18 s             | 6710       | 6170       | 5890       | 15.08           |
| 17  | 19                                   | 12 min 33 s             | 6660       | 5900       | 6040       | 16.65           |
| 18  | 26                                   | 10 min 44 s             | 6020       | 6070       | 5930       | 5.44            |
| 19  | 36                                   | 9 min 32 s              | 6720       | 6310       | 6370       | 8.23            |
| 20  | 62                                   | 6 min 31 s              | 6530       | 6170       | 5910       | 4.10            |
| 21  | 36                                   | 16 min 47 s             | 6510       | 6050       | 5790       | 4.61            |
| 22  | 28                                   | 13 min 12 s             | 6490       | 6140       | 5680       | 10.02           |
| 23  | 75                                   | 8 min 55 s              | 6440       | 6180       | 5860       | 12.18           |
| 24  | 55                                   | 10 min 48 s             | 6610       | 6290       | 5820       | 5.07            |
| 25  | 54                                   | 12 min 33 s             | 6380       | 6340       | 5400       | 3.90            |
| 26  | 140                                  | 9 min 13 s              | 6800       | 6480       | 5800       | 8.65            |
| 27  | 78                                   | 14 min 33 s             | 6090       | 6150       | 5120       | 5.66            |
| 28  | 106                                  | 6 min 36 s              | 6640       | 6370       | 5180       | 11.20           |
| 29  | 14                                   | 6 min 29 s              | 6820       | 6240       | 6040       | 16.76           |
| 30  | 33                                   | 3 min 25 s              | 6330       | 5770       | 4620       | 5.09            |

Table 3. Summary of the OES results for high alloyed and carbon steel grades.

| Steel grade | Time evolution of the optical intensities and temperature from the spectra | Electric arc spectra | Plasma diagnostics |
|-------------|--------------------------------------------------------------------------|----------------------|-------------------|
| High alloyed | Can be measured. High alloyed steel grade has more high-intensity spectra than carbon steel grade in the near-infrared region, and thus the heat radiation is higher. The temperature can be estimated from the spectra throughout the melting process. | Can be measured. High-quality spectra are typically observed within 30 min before tapping for 70% of the melts. | Can be determined. Plasma temperatures vary between 4000 and 7000 K and electron density between $3 \times 10^{16}$ and $4 \times 10^{17} \text{ cm}^{-3}$. |
| Carbon      | Can be measured. Carbon steel grade has less high-intensity spectra than high alloyed steel grade in the near-infrared region, and thus the heat radiation is lower. The temperature can be estimated from the spectra throughout the melting process. | Cannot be measured with the current setup. E.g., momentary increase in the arc length is required for the arc to be visible. | Cannot be determined due to the poor arc visibility. |
5. Conclusions

Optical emissions from an industrial EAF have been measured and analyzed for high alloyed and carbon steel grades. The time evolution of the spectrum intensities and estimated molten bath temperatures for these grades were compared with each other showing that the high alloyed steel grade has more high-intensity spectra in the near-infrared wavelength range. The near-infrared covers the part of the heat radiation wavelength band, which means that the radiative heat transfer is higher for the high alloyed steel grade. The temperatures that were estimated from the OES spectra were mainly between 1000 and 2000 K, with the exceptions of the electric arc spectra that have temperatures over 2200 K. Generally, the temperatures were observed to be within the range of molten bath surface temperatures. However, as the furnace atmosphere affects the OES spectra, the temperatures should be interpreted as estimates and not as absolute values.

The optical emissions from the arc could be observed only for the high alloyed steel grade and the results of the plasma analysis show that high-quality arc spectra can be observed within 30 min before tapping, when the slag composition already resembles its final composition. The electron density of the plasma fulfills the LTE criterion, but the plasma temperatures derived from the emission lines of individual elements (chromium, iron, and calcium) may fluctuate significantly.

According to this study, OES could be used as a low-maintenance solution to evaluate the radiative heat transfer and temperature of the molten bath. Furthermore, because the optical emissions from the electric arc plasma are dominated by the slag components and the spectra can be measured online, the OES is a potential tool for online slag composition analysis. The OES analysis of the arc spectra suggest that estimation of the slag composition could be acquired within the last 30 min before tapping for high alloyed steel grades. In addition, the plasma diagnostics for the arc spectra can provide information on the furnace atmosphere, the amount of metal vapors in the arc, and conductivity of the arc.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

electric arc furnaces, online analysis, optical emission spectroscopy, plasma, process control

References

[1] H.-]. Odenthal, A. Kemminger, F. Krause, L. Sankowski, N. Uebbe, N. Vogl, Steel Res. Int. 2018, 89, 1700098.
[2] M. Kirsch, V. Risonarta, H. Pfeifer, Energy 2009, 34, 1065.
[3] A. G. Hernandez, L. Paoli, J. M. Cullen, Resour. Conserv. Recycl. 2018, 133, 132.
[4] I. Matino, V. Colla, S. Baragliola, Waste Biomass Valori. 2018, 9, 2481.
[5] V. Z. Serjün, B. Mirtič, A. Madenović, Mater. Technol. 2013, 47, 543.
[6] A. Harada, N. Maruoka, H. Shibata, S. Kitamura, ISIJ Int. 2013, 53, 2110.
[7] V. Logar, A. Fathi, ˇSrkrjanc, Steel. Res. Int. 2016, 87, 330.
[8] A. Fathi, Y. Sabooohi, ˇSrkrjanc, V. Logar, ISIJ Int. 2015, 55, 1353.
[9] Y. Li, Z.-Z. Mao, Y. Wang, P. Yuan, M.-X. Jia, J. Iron Steel Res. Int. 2011, 18, 20.
[10] H. Khoshkho, S. H. H. Sadeghi, R. Moini, H. A. Talebi, Comput. Math. Appl. 2011, 62, 4391.
[11] F. Martell, A. Deschamps, R. Mendoza, M. Meléndez, A. Llamas, O. Micheloud, ISIJ Int. 2011, 51, 1846.
[12] M. Aula, T. Demus, T. Echterhoff, M. Huttula, H. Pfeifer, T. Fabritius, ISIJ Int. 2017, 57, 478.
[13] M. Aula, A. Mäkinen, A. Leppänen, M. Huttula, T. Fabritius, ISIJ Int. 2015, 55, 1702.
[14] M. Aula, A. Leppänen, J. Roininen, E.-P. Heikkinen, K. Vallo, T. Fabritius, M. Huttula, Metall. Mater. Trans. B 2014, 45, 839.
[15] M. Aula, A. Mäkinen, T. Fabritius, Appl. Spectrosc. 2014, 68, 26.
[16] R. D. Cowan, G. H. Dieke, Rev. Mod. Phys. 1948, 26, 181.
[17] C. Aragón, J. A. Aguilera, Spectrochim. Acta Part B 2008, 63, 893.
[18] A. A. Ovsyannikov, M. F. Zhukov, in Plasma Diagnostics (Eds: A. A. Ovsyannikov, M. F. Zhukov), Cambridge International Science Publishers, Cambridge 2000, pp. 1–28.
[19] R. W. P. McWhirter, in Plasma Diagnostic Techniques (Eds: R. H. Huddleston, S. L. Leonard), Academic Press, New York 1965, pp. 201-264.
[20] G. Kühn, M. Kock, Phys. Rev. E 2007, 75, 016406.
[21] A. Kramida, Yu. Ralchenko, J. Reader, NIST ASD Team, NIST Atomic Spectra Database, https://doi.org/10.18434/T4W30F (accessed: January 2020).
[22] J. L. G. Sanchez, A. N. Conejo, M. A. Ramirez-Argaez, ISIJ Int. 2012, 52, 804.
[23] T. X. Zhu, K. S. Coley, G. A. Irons, Metall. Mater. Trans. B 2012, 43, 751.
[24] A. Gleizes, Y. Cressault, Plasma Chem. Plasma Process. 2017, 37, 581.
[25] E. Gudimenko, V. Milosavljević, S. Daniels, Opt. Express 2012, 20, 12699.
[26] A. B. Murphy, J. Phys. D: Appl. Phys. 2010, 43, 434001.
[27] H. Pauna, T. Willms, M. Aula, T. Echterhoff, M. Huttula, T. Fabritius, Plasma Res. Express 2019, 1, 035007.