Evaluation of sound-, current- and vibration measurements in the Electric Arc Furnace

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Syftet med detta arbete var att undersöka nya metoder för att mäta tillståndet på skrotet in en ljusbågsugn. Detta genom att utvärdera tre olika metoder teoretiskt och välja två för test i ljusbågsugnen i Avesta. På grund av tids och utrustningsbrist användes bara Total Harmonic Distortion (THD) för tester i Avesta. Resultaten visar att THD når låga värden under raffineringen, detta tyder på att allt skrot är smält och att ljusbågarna är stabila.

Abstract
The aim of this report was to investigate new methods for measuring the condition of the scrap in the electric arc furnace. This was done by evaluating three different methods theoretically and chooses two of them for test in the electric arc furnace in Avesta. Due to lack of time and equipment only Total harmonic distortion (THD) measurements was used. The results show that THD reaches low values during refining. This suggests that all the scrap is melted and the arcs are stable.
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1. Introduction

The Electric arc furnace (EAF) is the most common process in scrap based steelmaking. The EAF can be described as a chemical reactor that utilizes electricity to transform scrap to molten steel. The trend in EAF development is to get a higher productivity by increased arc voltage and higher currents for melting scrap faster and more efficiently. However the higher voltage and current can cause tremendous damage to the furnace refractory if the arcs are not covered with slag. Common way to control the meltdown today is to control the transformer tap based on the energy input. This means that no on-line information is used to control the process and the operators manually adjust the set point with the information from the operational diagrams. When the productivity increase the operator need to make faster decisions. State of the art is to use automated process control to assist the operator. The automated process control is based on several real time measurements for example temperature on the cooling system, sound of the furnace, harmonic distortion on the current, vibration of the furnace vessel and off gas analysis. The use of automated process control can lead to reduction of power on time, optimization of injected carbon, arc stabilization and reduction of power off time.

The purpose of this project is to evaluate sound-, current- and vibration measurements and select two of them for trials in the production in Outokumpu stainless steel plant in Avesta. The aim is to find parameters that confirm that the scrap is entirely melted.

The trials will be carried out on one standard steel grade. Two of the evaluated methods will be used in the trials.
2. **Background**

1.1 **Stainless steel making**

This project is performed at Outokumpu stainless AB, Avesta works. The production in this plant is scrap based and the production process follows a few main steps described below and illustrated in figure 1.

1. Scrap is melted in an Electric Arc Furnace and tapped into a ladle.
2. The ladle is transported and tapped in the AOD-converter. In the AOD-converter carbon is reduced from the melt.
3. The ladle is now transported to the Ladle Furnace and the liquid steel is deoxidized and alloying elements are added.
4. The steel is then continuously cast into solid slabs. 

![Fig. 1- Schematic illustration of scrap based steel production](image)

1.2 **Electric Arc Furnace process**

In the production of scrap based steel the electric arc furnace (EAF) is widely used. An EAF melt raw material by transferring electrical energy to thermal energy in form of an electric arc. The arc is established between an electrode and the scrap. 36% of the steel production today uses an electric arc furnace and in year 2030 it is expected that 50% is produced by an electric ac furnace. A typical furnace has three electrodes. The scrap is heated both from the current passing through the scrap and by the radiant energy evolved by the arc. A regulation system controls the movement of the electrodes to adjust the voltage and current. Water panels are place at the furnace outer wall to prevent wear of the refractory material.
Typical stages in the EAF process is illustrated in figure 2 and consist of:

- Charging of scrap, slag formers and reduction agents.
- Arc ignition
- Boring of the electrodes
- Melting
- Refining
- Tapping

The electrodes are initially lowered to a point above the scrap and the current is initiated. The electrodes bore through the scrap and a bath of liquid steel is formed. The arc is in these steps are long and the voltage is high. The scrap helps to protect the lining. When nearly all scrap is melted, the arc is shortened to reduce radiation heat losses and to avoid refractory wear. When all scrap is melted the steel is refined. This is usually done by injecting oxygen to oxidize the carbon in the steel. In stainless steel production the refining step consist of injecting oxygen, carbon and silicon to create chemical energy and to reduce the chromium in the slag. Oxygen and carbon can create foaming slag which helps minimize the heat loss and increase the arc stability².

Fig. 2 – Typical steelmaking cycle
Figure 3 shows an energy diagram of the electric arc furnace. 70% of the total energy input is electrical. The remaining 30% is chemical energy from the oxidation of elements such as carbon and silicon and from the gas burners. 53% of the energy input is transferred into the steel, 47% is lost to cooling, waste gas and slag.

Approximately 440 kWh is needed to produce a ton of steel in the electric arc furnace, the theoretical minimum amount of energy required to melt a tone of scrap is 300kWh.

![Figure 3: Energy Diagram of the Electric Arc Furnace](image)

Fig.4- Energy diagram of an EAF

2. Literature survey

2.1 Total Harmonic Distortion

Random movement of the melting metal has the effect that no two cycles of the arc voltage and current waveforms are identical. These highly varying loads have a direct impact on the power quality of the interconnected power system. The varying current flow provides a source of harmonic currents and causes significant disturbance to the impedance circuits. This means that voltage and current deviates considerably from the symmetrical sinusoidal pattern and is illustrated in figure 5.
The harmonic disturbances are worst during early meltdown and occur in multiple frequencies of the fundamental frequency. This means that if the frequency of fundamental waveform is 60Hz, the harmonic components of \(2^{th}\), \(3^{th}\) and \(4^{th}\) order will be at 120Hz, 180Hz and 240Hz. The harmonic distortion is the degree to which the waveform with the distortions deviates from a pure waveform. The summation of all harmonics components of the voltage or current wave compared against the fundamental wave of current or voltage is the total harmonic distortion. The formula shows the calculation for the THD. The result is a percentage compared the harmonic component to the fundamental component of a signal.\(^3\)

\[
THD = \sqrt{\left(\frac{V_2'^2 + V_3'^2 + V_4'^2 + \cdots + V_n'^2}{V_1^2}\right)} \times 100\% 
\]

In steel production the harmonic distortion contribute to an increase in effective inductive reactance. This increase has been reported to be as high as 25% but is often in a rage of 10-15%. The current into the EAF is therefore less then expected from calculations based on symmetrical sinusoidal wave shapes and losses in frequency-sensitive equipment are higher than the sinusoidal wave shape would produce. The initial period of melting causes the most disturbances. As the temperature rises a liquid pool of metal forms and the disturbances decreases. When sufficient molten metal exist the arc is shortened by the electrode regulators. The current will rise because the resistant is reduced and the power will drop.\(^2\)

To make calculations on systems harmonic levels you need to know the systems harmonic source characteristics and representation. For analysis purposes harmonics sources can be represented as ideal current sources.

In previous work THD of current and voltage has been used to analyzed the foaming slag.
2.2 Sound Measurement

Basically there are two ways of quantifying sound, by magnitude of a sound field or the strength of a sound source. The sound can be analyzed by changes in density, particle velocity or particle displacement but the easiest way is to measure the change in pressure expressed in decibels relative to 20µPa. This is called the sound pressure level (SPL).

To measure the SPL a condenser microphone is one of the few instruments that lives up to the requirements. The condenser microphone consists of two electrically charged plates. Between the plates there is a variation in capacitance. One of the plates is a light membrane which moves in response to acoustic pressure changes and result in a change in capacitance that produces the output voltage\(^4\).

In the case of sound measurements in the steel industry the microphone is placed for aiming directly to the liquid bath through the door of the furnace, figure 6. The microphone is connected to a computer which filters and analyzes the sound. There is always some kind of background noise. This means that you need to analyze the frequencies spectrum to realize at which frequencies the sound to analyze appears in. For example the sound during slag foaming has a specific frequency that can be determined. Then the sound level can be measured in this frequency to analyze the amount of foaming slag. The operators experience is used to verify when the foaming slag appears.\(^5\)

![Fig.6- Placement of sonicmeter at an Electric Arc Furnace](image-url)
Fig. 7 - Sonicmeter signal as function of frequency

Fig. 8 - Assessment of slag foaming with a sonicmeter
2.3 Vibration measurement

Vibrations or structure-borne sound is a method that measures the vibrations generated by the electrode. The vibration is transmitted by the scrap to the furnace wall where a vibration sensor is placed. The main source of vibration is the electronic arcs beside the vibration from random movement of the scrap. The vibration via liquid steel bath can be neglected because of the high damping factor of the refractory lining. The initial vibration of the arcs has to be estimated since it is impossible to measure. To do this estimation another method has to be used to match the vibration. The amount of scrap that lies between the electrode and the furnace wall can therefore be measured by how much the vibration is damped. High amount of scrap will create a higher shielding factor. The sensors is placed in the opposite each electrode. This means that the parts with the most thermal stresses can be monitored and the wear can be controlled. This can also be used to control the foaming slag and discover when the scarp is melted. The magnitude of the vibrations can be used to estimate the height of the foaming slag. In this case a frequency analysis is needed to detect at which frequencies slag foaming occurs.\(^5\)

![Diagram of vibration measurement](image-url)

Fig.9- Principle for measuring and evaluation vibrations of furnace shell
3. Method

3.1 THD

THD data which is recorded every second is collected at the EAF digital regulator. This data is text based and needs to be converted. This is done with software called Monarch. The THD data has great variation and therefore need to be filtered. This is done with a moving average.

\[ X_{m1} = \frac{x_1 + x_2 + x_3 + x_4 + \ldots + x_{60}}{60} \]

\[ X_{m2} = \frac{x_2 + x_3 + x_4 + x_5 + \ldots + x_{61}}{60} \]

An appropriate filtration is a 20 seconds moving average but the variations in this case is too great, therefore a 60 seconds moving average is used.

![THD measurement without filtration](image.png)
Fig. 10- THD measurement with 60 seconds moving average filtration

3.2 Effect of injection on THD

To analyze which effect the injection of carbon, ferrosilicon, nitrogen and oxygen have on the THD values are collected from a database and plotted.

Fig. 11- Effect of injections on THD
4. Results

4.1 THD
Due to the change of tap positions that had a great effect at the THD values the analysis was focused on the last part of the second basket. The aim to find a point that implies when the scrap is completely melted was discovered to be hard to complete due to the tap changes. When the scrap melt there should be a large decrease of the THD value but this also happens when the tap position is changed. The THD-values can not be seen on-line which makes it hard to interpret if the variation of THD appeared due to melting or tap change.

In this project 43 heats have been analyzed. After the last change of tap 32 of the heats have a THD value of approximately 3%. An expert in this field interpreted that at 3% the arcs were covered with slag. This can also be detected by the sound of the furnace. When the arcs are covered with slag the sound level from the furnace decreases.
In some cases the THD does not decrease to 3% directly at the time of the tap change. This can be interpreted that the foaming slag did not cover the arcs until a few minutes into the refining step.

Fig. 13 - Low THD during refining

Fig. 14 - THD during refining
To control the refining step of the process two break values is needed. These values are decided after a statistical evaluation. The aim of the interval is to show when the disorder of the current is stable. The high breakpoint is set to show at which THD-value the tap position needs to be changed to decrease refractory wear. The low breakpoint is set to confirm at which THD-value there is foaming slag in the furnace. A low THD means that the arcs are covered by foaming slag. Then the power can be increased by changing the tap position to raise the electrodes.

Fig.15- THD break points

The effects of injections on the THD were investigated but the implementation of the injection varies. This means that no effect can be seen due to the injections.
5. Discussion
Due to lack of time and equipment only one method was evaluated.

The THD measurements showed that the disturbances during refining decreases and when it reaches 3% all scrap should be melted and the arcs are stable.

The results are however hard to verify because the calculations are done after the heat is finished. With new equipment the measurements can be done online and are therefore easier to verify.

6. References
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7. Appendix

7.1 THD

![Graph 21924](image)

![Graph 21925](image)
22194

22195
7.2 THD - Effect of injections

![Graph 21924](image1)

![Graph 21925](image2)

![Graph 21926](image3)