Development of an acoustic sensor for electric arc furnaces

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Abstract

In this paper, the development of a prototype sensor for electric arc furnaces is described. The novel sensor uses the sound generated by the plasma in electric arc furnaces to predict the length of the plasma arc. Although arc length is the most important variable that is controlled in these furnaces to achieve a desired power throughput, it is not directly measured at present. In principle, the acoustic sensor can improve on current methods that rely on voltage measurements made external to furnaces, and can therefore lead to significant reduction in cost of smelting operations.

Electric arc furnaces

It is generally accepted that economic growth relies on the development of infrastructure and that the steel industry plays an important role in this context. The South African steel industry, ranked 19th largest in the world (2005, [1]), produces approximately 75% of the crude steel in Africa. Chrome is a principal constituent in steel imparting desirable properties, such as corrosion resistance and is introduced to the steel alloy in the form of ferrochrome. About 85% of ferrochrome is produced in submerged arc furnaces (2005, [2]), a configuration of electric arc furnace, via the reduction of chromite ore with carbon or silicon.

More generally, electric arc furnaces (EAF) are smelters or reactors that find application not only in the steel industry, but in the smelting of various ferrous and nonferrous metals. The electric arc furnace conducts large currents via a graphite cathode and the materials to be processed that act as an anode. The material and reagents resist the flow of current, causing it to heat up, in what is known as ohmic heating. During operation, the more dense metal separates from a variety of impurities that settle into a less dense slag on top of the metal in the furnace bath, as illustrated in Figure 1.

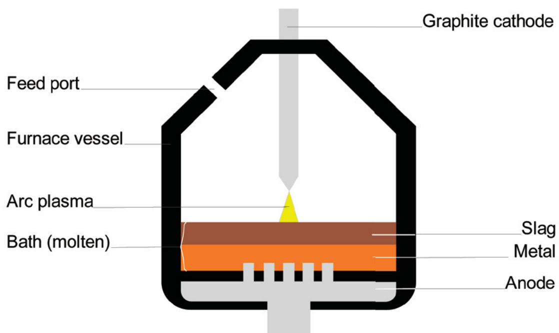

Figure 1: Electric arc furnace and principal components.

The plasma arc plays an important part in the drawing of electrical current and hence the delivery of thermal energy to the electric arc furnace and its contents.

Plasma

Plasma is sometimes referred to as the fourth state of matter after solids, liquids and gases. Plasma is essentially partially ionized gas containing electrically neutral particles, like photons and molecules and electrically charged particles, like ions and electrons. In the presence of an electric field, the charged particles are accelerated in the direction of the field, which constitutes an electric current and hence electrical conductivity is achieved.

Like fluids, plasmas exhibit a surface tension and when in motion this surface tension acts as a membrane that generates pressure waves in the air surrounding it. If the pressure waves fall within the audible frequency range (20 Hz - 20 kHz) our ears recognize them as sound.

Steady state melting conditions are realized by keeping the arc length (D) and arc current (I_{arc}) constant at a desired working point, as indicated in the diagram in Figure 2.

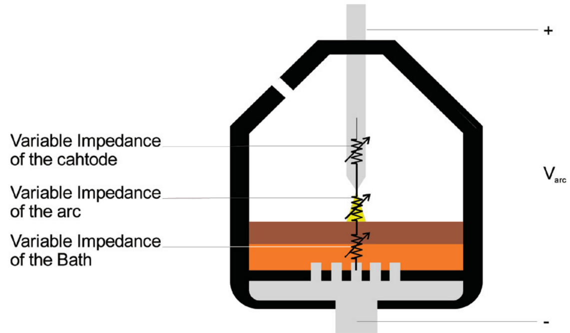

Figure 2: Plasma arc inside a furnace.

Currently the arc length is controlled using impedance control, where the voltage to current ratio (V_{arc}/I_{arc}) is held constant at a desired working point. The problem with this method is that the voltage measurement (V_{arc}) is taken external to the furnace and measures more than just the voltage of the arc. The inevitable erosion of the cathode, the variable impedance of the bath, as well as disturbances on the power grid that supplies the furnace can influence the voltage measurement and consequently has an undesired effect on impedance control of the plasma arc length, as indicated in Figure 3.

The accurate control of the arc length is very

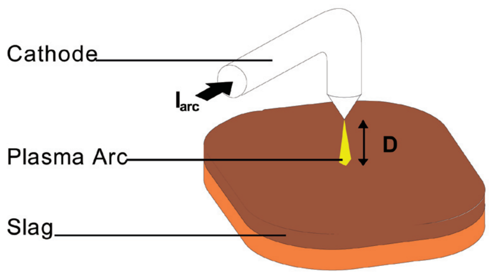

Figure 3: Variability of the arc voltage (V_{arc}) as used for the control of arc length in furnaces.

important, since it in effect controls the power throughput to the furnace melt and hence influences the profitability of the furnace.

Novel acoustic sensor

The acoustic sensor for arc length measurement is of interest to us, since the acoustics of the arc can be measured outside the hostile furnace environment, without distortion by external factors. The relationship between arc length and arc acoustics is sometimes exploited by experienced furnace operators who can predict operating conditions in EAFs by listening to the sound inside the furnace. Figure 4 gives a diagrammatic representation of the proposed acoustic sensor.

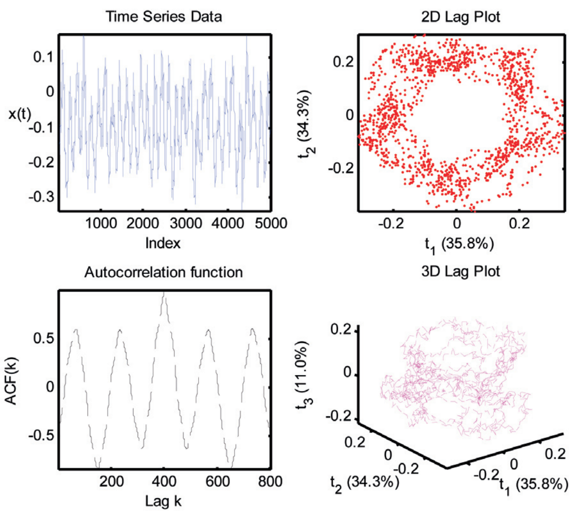

Figure 4: Typical acoustic signal properties, showing the original signal (top left), 2-dimensional and 3-dimensional attractors (top and bottom right) and the autocorrelation function of the signal (bottom left).

The sensor consists of the following components:

- *Microphone*: Used to convert the acoustic signal into a voltage signal which can be processed by a computer.
- *Preamplifier*: Boosts the voltage signal to a reasonable range to be accepted by the analogue to digital (A/D) converter.
- *A/D converter*: Converts the continuous voltage signal to a digital one, which allows it to be processed by a computer.
- *Computer model*: Using trained models, the arc length is predicted from the measured acoustic signal.

Typical results from laboratory scale tests

Experiments were performed on a 60 kW furnace charged with mild steel. Fifty thousand samples/second recordings of the acoustics of the plasma arc were made, together with arcs that ranged from 5 mm to 17 mm in length. A typical acoustic time series and its properties are presented in Figure 5, which shows the acoustic signal itself (top left), the auto-correlation function of the signal (bottom left), and two- and three-dimensional lag plots of the signals (signal attractors), top and bottom right.

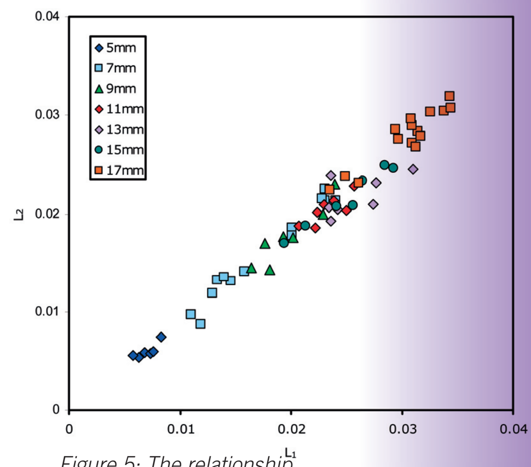

Figure 5: The relationship between the properties of the acoustic signal and the arc length (see legend for arc lengths).

The relationship between arc length and acoustic signal can be observed by comparing the shape of the attractors of the acoustic recordings (top and bottom right in Figure 5) associated with varying arc lengths. This is presented in Figure 6 where L_1 and L_2 are feature vectors that describe the attractor shapes in phase space. As can be seen from Figure 6, the linear features indicate a strong correlation between arc length and arc acoustic.

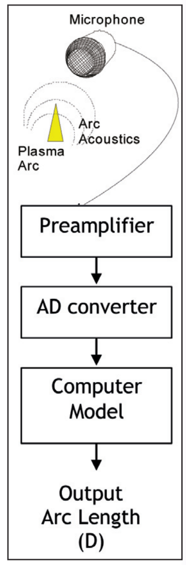

Figure 6: Block diagram of an acoustic sensor for the estimation of arc length in an electric arc furnace.

Conclusions

The development of the acoustic sensor is primarily concerned with the establishment of a relationship between the acoustic emissions of an arc and its arc length. Experiments were performed on a laboratory scale electric arc furnace where acoustic recordings were made at varying arc lengths. Feature vectors extracted from the attractors of different acoustic recordings could be related to the arc length, which means that the sensor could be used online for rapid estimation of the arc length in the furnace. In principle, these measurements could be used as the basis for advanced control of the furnace, and with that significant savings in the production cost of the metal from the furnace.

Currently, more work is being done on a broader range of ferrous and non-ferrous systems, while nonlinear feature extraction and calibration models are being developed to improve arc length estimates.

References

[1] Bonga, MW, "An Overview of the South-African Iron, Manganese and Steel Industry During the Period 1984 - 2003", Report R45/2005, Directorate: Mineral Economics, Department of Minerals and Energy, South Africa, 2005

[2] Kweyama, N, "South African Ferrous Minerals Production Trends 1994-2003", Report R48/2005, Directorate: Mineral Economics, Department of Minerals and Energy, South Africa, 2005.