

The mode of current transfer between electrode and slag in the submerged-arc furnace

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SYNOPSIS

An account is given of a laboratory experiment in which the resistivity of a primary slag like those produced in the manufacture of high-carbon ferrochromium was measured at current densities typical of operation in a submerged-arc furnace. It was shown that the current flow from graphite electrode to molten slag obeys Ohm's Law when electrode current densities are less than 12 A/cm². At higher current densities, arcing occurs from the electrode tip to the slag, causing an imbalance in the rate of heating in the furnace burden.

SAMEVATTING

Daar word verslag gedoen oor 'n laboratoriumeksperiment waarin die spesifieke weerstand van 'n primêre slak soos dié wat in die vervaardiging van koolryke ferrochromium verkry word, gemeet is by stroomdigtheid wat tipies is van werking in 'n dampelboogdoend. Daar is getoon dat die stroomvloeï van die grafietelektrode na die gesmelte slak die Wet van Ohm gehoorsaam wanneer die elektrode se stroomdigtheid minder as 12 A/cm² is. By hoër stroomdigthede vind daar oorslag van die elektrodepunt na die slak plaas wat 'n wanbalans in die verhitings tempo van die oondlading veroorsaak.

In the last twenty years several dramatic changes have occurred in the field of high-temperature smelting. One of these changes was the introduction of electric power for the generation of high temperatures, in place of fossil fuels. The ever-increasing shortage of coking coal has resulted in the submerged-arc furnace becoming a valuable metallurgical tool for the production of ferro-alloys. The energy requirements for the production of ferro-alloys vary from 2 to 10 MWh per tonne of alloy produced, and the cost of electric power is sufficiently high for economy of operation to be essential.

It has been maintained that the production from electric reduction furnaces is a direct function of the resistance of the burden in the furnace¹. The heating in a ferro-alloy furnace is not uniform because the constituents of the burden undergo physical and chemical alteration as they progress down through the furnace. This has motivated studies on the variation, with temperature, of the electrical resistivity of the individual burden components, of the mixed burden components, and of the molten slag¹⁻⁷. In addition, it has been shown that the major proportion of the power in a submerged-arc furnace is dissi-

pated in the region of the tips of the electrodes⁸. However, a certain amount of confusion seems to exist about the manner in which this power is dissipated. Some authors^{9,10} claim that the heating is mainly resistive, whereas others favour the theory that the main heat is generated in the arc zone at the tips of the electrodes¹¹.

EXPERIMENTAL INVESTIGATION

In order to investigate the mechanism of current transfer from electrode to molten slag, a simple experiment was designed to measure the resistivity of the slag at current densities typical of operation in a submerged-arc furnace. In a single-phase circuit, current at 50 Hz frequency was made to flow via a graphite electrode through a primary slag typical of those produced in the manufacture of high-carbon ferrochromium (22 per cent MgO, 28 per cent Al₂O₃, 50 per cent SiO₂, saturated in carbon). The experimental apparatus is shown in Fig. 1. The current density on the graphite electrode could be varied between 0 and 15 A/cm², the graphite crucible acting as the second electrode.

Experiments were performed in a molybdenum-wound resistance furnace at slag temperatures in the region of 1500°C. The voltage across and the current flowing through the molten slag were observed on an oscilloscope screen. The graphite electrode and crucible were pro-

tected against oxidation by purging of the system with argon gas. At electrode current densities of less than 12 A/cm², it was found that the oscilloscope trace of the current flow pattern was sinusoidal and Ohm's Law obtained. Figs. 2 (a) and (b) show the form of the oscilloscope traces for the potential across the slag and the current flowing through it. However, it should be remembered that the magnitude of the slag resistivity under these 'submerged-arc furnace-like' conditions of high current density and low frequency is higher than the absolute resistivity as determined in fundamental studies in the laboratory⁶.

At current densities in excess of 12 A/cm², the pattern of current flow as shown on the oscilloscope was characterized by the occurrence of unstable arcing. The voltage and current waveforms typical of those obtained at current densities greater than 12 A/cm² are illustrated in Figs. 2 (c) and (d). As all the experiments were done with the graphite electrode immersed in the molten slag, the occurrence of arcing was at first puzzling. However, with the high current densities at the tip of the electrode, extreme localized heating occurs that leads to an increase in the rate of reaction between the carbon electrode and the slag, resulting in the formation of gaseous products, CO, and SiO. The rate of reduction of SiO₂ to SiO by carbon is rapid at temperatures

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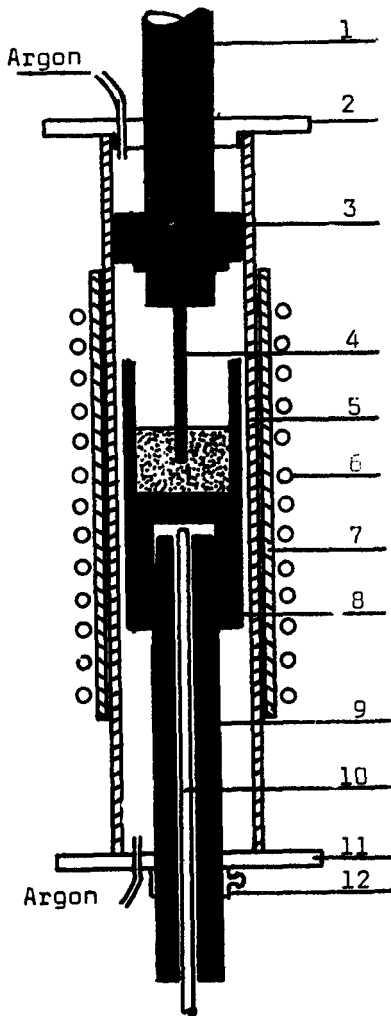


Fig. 1—The apparatus used in the experimental determinations

- 1 Graphite rod
- 2 Sindanyo collar
- 3 Graphite spacer ring
- 4 Electrode
- 5 Inner alumina tube
- 6 Furnace heating coils
- 7 Outer alumina tube
- 8 Graphite crucible
- 9 Graphite support rod
- 10 Alumina thermocouple sheath
- 11 Sindanyo disc
- 12 Support collar

greater than $1500^{\circ}\text{C}^{12}$, and confirmation of this mechanism was obtained by the presence of a precipitated film of silica in the upper regions of the experimental furnace. The electric circuit for the system under arcing conditions is shown in Fig. 3. As shown in Fig. 2 (c), the voltage waveform represents the total voltage drop across the series combination of the arc and slag resistance, that is, the sum of the square wave voltage drop across the arc and the sine wave voltage drop across the slag resistance. The

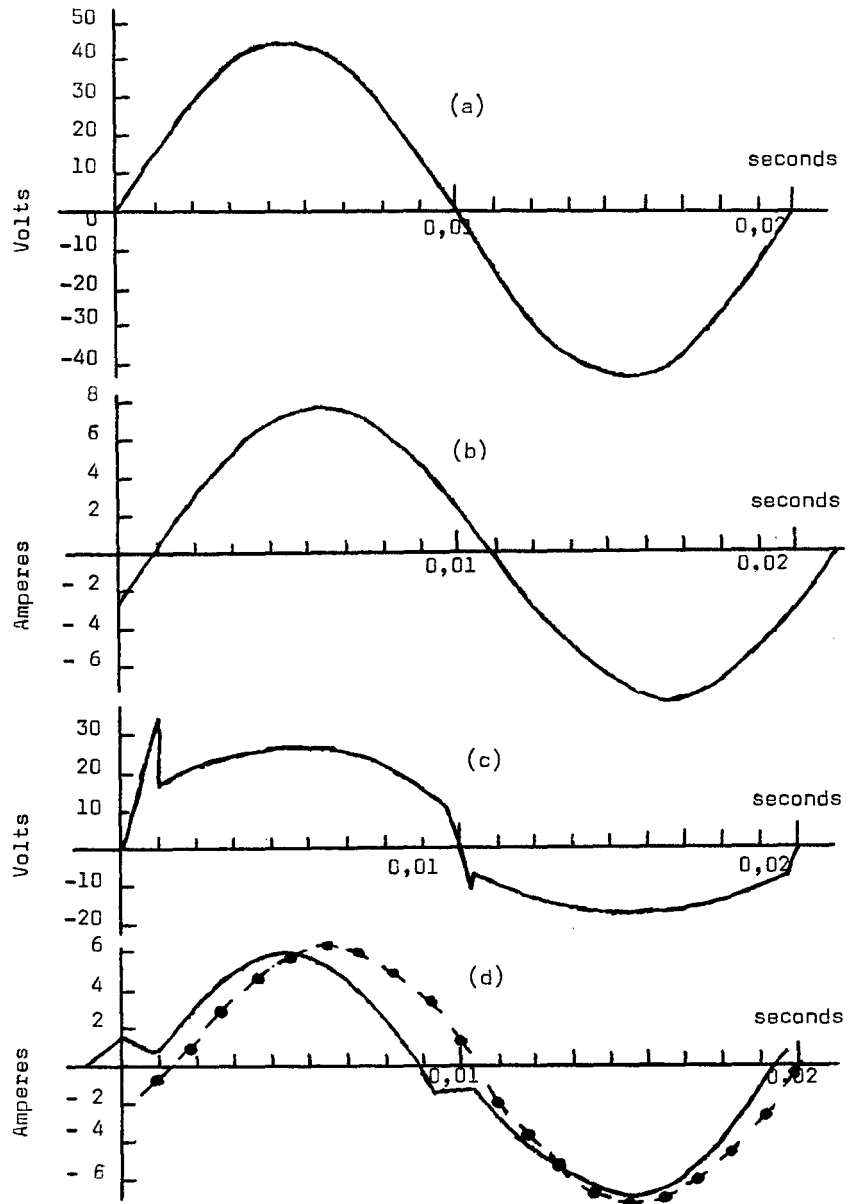


Fig. 2—Waveforms obtained for conduction experiments in the slag medium
 (a) Sinusoidal voltage drop across slag resistance.
 (b) Sinusoidal current flowing through the slag. The current lags the voltage by 18° .
 (c) Voltage drop across the arc and the slag resistance.
 (d) Arcing current and theoretically predicted arcing current.

voltage trace is characterized by a sharp rise to the peak voltage required to re-ignite the arc (e_i). As soon as the arc strikes, current flow is re-established and the voltage drops to the arc voltage (e_a), which remains constant for the remainder of the half cycle. The sinusoidal cap on the voltage trace represents the voltage drop across the slag resistance.

It is of interest at this point to call attention to the fact that, in

Figs. 2 (c) and (d), the ignition and arc voltage, as well as the current, differ in each half cycle. This effect is primarily due to the differences in cathode behaviour of the graphite electrode and the slag surface as the polarity reverses with the alternating current. During the second half-cycle, when the graphite electrode was the cathode, the arc conductivity was superior as shown by the lower arc voltage and higher current. This is in agreement with a similar finding

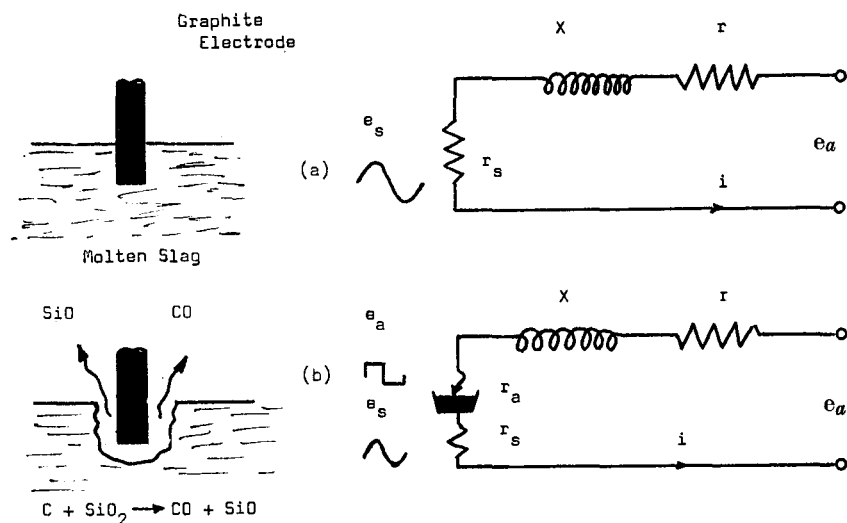


Fig. 3—A schematic diagram illustrating the two possible means of conduction (a) Ohmic conduction as shown by the equivalent circuit and the sinusoidal voltage drop across the slag resistance. (b) The equivalent circuit under conditions of arcing and the corresponding voltage drop across the arc and slag resistance.

by Schwabe¹³ and Bowman *et al.*¹⁴ concerning open-arc steel-melting furnaces.

The equation describing the arcing circuit of Fig. 3 is:

$$L \frac{di}{dt} + iR + e_a = E_m \sin(\omega t - \phi),$$

where $\omega t \geq \phi$

and ϕ = arc ignition angle with respect to the supply-voltage zero crossing,

$$\sin \phi = \frac{e_i}{E_m},$$

L = the inductance of the circuit, and

R = the resistance of the slag and circuit.

In the case of open-arc steel-making furnaces, the voltage drop across the busbar resistance (ir) is small compared with e_a , and so this term is usually neglected in the above equation. However, in the submerged-arc equivalent, the voltage drop across the slag resistance is not insignificant. A solution of the above differential equation has been given as:¹⁵

$$i = \frac{E_m}{Z} \left\{ \sin(\omega t - \phi) - \sin(\phi - \alpha) \exp \left[\frac{-R(\omega t - \phi)}{X} \right] - \frac{e_a Z}{E_m R} \left[1 - \exp \left(\frac{-R(\omega t - \phi)}{X} \right) \right] \right\}$$

where X = inductance of the circuit

$$Z = \text{impedance of the circuit} = \sqrt{R^2 + X^2}, \text{ and}$$

$$\tan \alpha = X/R.$$

The current flowing in the circuit shown in Fig. 3 was calculated from the above equation and for the following experimental conditions:

$$\begin{aligned} e_a^+ &= 17 \text{ V} & e_a^- &= 7 \text{ V} \\ e_i^+ &= 35 \text{ V} & e_i^- &= 10,5 \text{ V} \\ \alpha &= 18^\circ \\ r &= 6,5 \ \Omega \\ r_s &= 5,5 \ \Omega \\ R &= 12,0 \ \Omega. \end{aligned}$$

The calculated current is shown in Fig. 2 (d). On the positive half-cycle there appears to be a significant divergence between the measured current and that calculated from the equation shown above. On the negative half-cycle, the measured and calculated current values show significantly better agreement.

A larger variation from the measured value is experienced on the positive half-cycle, and this is probably due to the variation in the arcing voltage (17 to 11 V) for this half-cycle.

The presence of an inductive load in the circuit serves to introduce a phase lag of the current behind voltage. This is illustrated in Figs. 2 (a) and (b), where the current trace passes through zero $\alpha = 18^\circ$ after the voltage trace. This tends to stabilize the arc because the voltage can reach the required ignition value

while the current is approaching zero on the negative cycle. A low-power factor then has the tendency to stabilize arcing. With the trend towards larger and larger production units, the furnace resistance decreases with respect to reactance leading to low-power factors¹⁶, causing conditions where the elimination of arcing may prove more difficult than with smaller units.

If the average value for the current is obtained from the positive (3,4 A) and the negative (4,2 A) half-cycles, an average value for the equivalent resistance of the arc can be calculated based on the positive and negative arc voltages. In the experiment, the arc resistances for the positive and negative half-cycle were 5 and 1,7 Ω respectively, as compared with a slag resistance of 5 Ω . It follows, of course, that the resistance of the arc is quite different from an ohmic resistance, the arc resistance varying with voltage and current.

It is apparent that, if arc formation occurs during conduction from a graphite electrode to a molten slag, the resistance of the system is increased, and therefore, at a constant supply voltage, the total power dissipated in the circuit will decrease. This phenomenon is evident in Fig. 2, where the first two waveforms represent the voltage drop across the slag resistance and the current flowing through the resistance if arcing did not occur. The last two waveforms in Fig. 2 represent the voltage drop across the arc and the slag resistance and the current flowing. The average power dissipated in the system can be determined by the voltage multiplied by the current over the period of interest. The power dissipated in the slag under conditions of ohmic conduction was 162 W and the power dissipated in the arc combined with the slag was 73 W, a decrease of 55 per cent at the same applied voltage. In this sense, the occurrence of an arc at the tip of the electrode is undesirable because the amount of useful power dissipated in the burden is reduced.

SUBMERGED-ARC FURNACE OPERATION

In normal submerged-arc furnace operation, the current density is usually less than one-half of the

12 A/cm² determined as the limit for ohmic conduction in this study. It is expected that this value would be larger than that for a production unit owing to higher heat losses from the laboratory system. However, areas of high current density may occur at the tip of the electrode, and consequently an arc might be struck from the electrode to the slag. If an arc strikes from the tip of one electrode in a three-electrode submerged-arc furnace, then the resistance of this phase will be higher than that of the remaining two phases, resulting in an unbalanced three-phase load. This imbalance in the three-phase load will be further aggravated by the difference in arc resistance between the positive and negative cycle. The power in the arcing phase will be lower than in the other two phases, and, as a consequence, the total power dissipated in the furnace will decrease. Although an imbalance in the three-phase load is not detrimental to the workings of the furnace transformer, it will result in uneven heating in the furnace burden and this may cause difficulties in operation. On furnaces producing high-carbon ferrochromium, it has been observed that fluctuations of the voltage and current meters may occur for short periods following a furnace tap. This is probably caused by burden falling away from the tip of the electrode and an arc being struck as a result. Reactance meters, or similar devices that can detect changes in phase angle, can be used to warn of the occurrence of arcing. The operator's reaction is to decrease the electrode-to-electrode voltage and/or to raise the electrode slightly. In short, a decrease in the voltage gradient will serve to extinguish the arc.

It seems that, in the design of submerged-arc furnaces, the current density in the electrode is chosen so that arcing in the furnace will be avoided. In Table I it appears that

the permissible current density increases as the endothermic nature of the reduction reactions increase. The lower limit appears to occur for the smelting of copper-nickel concentrates in which there is virtually no endothermic heat of reaction.

TABLE I

Product	Current density A/cm ²
FeCrSi (Single step) . .	6,5
FeCr (High carbon) . . .	5,0
FeMn (High carbon) . . .	4,0
CuNi matte	1,5

CONCLUSIONS

The laboratory experiment has shown that current flow from a graphite electrode to a molten slag obeys Ohm's Law at electrode current densities of less than 12 A/cm². With current densities in excess of 12 A/cm², arcing occurs from the electrode tip to the slag. Arcing is not desirable in furnaces designed for resistance heating because it results in a decrease in power delivered to the furnace at a given voltage. The striking of an arc from one electrode effectively increases the resistance of that phase with respect to the others, causing an imbalance in the rate of heating in the furnace burden. Since the presence of an inductive load in the circuit, with its effect of decreasing the power factor, tends to create conditions for stable arcing, large smelting units with their inherently low power factors may be subject to some arcing problems.

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