Physicochemical Properties of Slags in the System $MgO—Al_2O_3—SiO_2$ and Their Application to the Technology of Ferro-alloy Smelting

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SYNOPSIS

Smelting behaviour within an electric smelting furnace is considered, and a mechanism is proposed that depends on the slag formed.

The influence of the viscosity and conductivity of slags on smelting is examined, and these properties are measured for slags in the ternary system $MgO—Al_2O_3—SiO_2$ having an SiO_2 composition of 30 to 50 per cent and an MgO-to-Al_2O_3 ratio of 0,5 to 2,0.

There is no simple method by which these properties can be optimized for furnace production. However, the individual effects of viscosity and conductivity on various aspects of the smelting process can be calculated.

INTRODUCTION

It has frequently been suggested that the slag formed when chromite ores are smelted in an electric furnace exerts a direct and controlling influence both electrically and metallurgically on the furnace operation.

It has been thought and since verified[1] that there is a region of incipient fusion intermediate between the pre-heating and reaction zones of the furnace. This zone is particularly important in the smelting of low-grade ores because of the proportion of gangue material in the furnace charge. It is suggested that, in the zone of incipient fusion, the gangue material and some of the flux components are first to reach the solidus temperature (1365°C or above) and that this material forms a continuous matrix having reducing agent and chromite spinel isolated within it. The implication of this postulate is that the slag so formed is the first, and perhaps only, continuous path by which current can be transferred. Recent experiments[1] have shown that the electrical conductivity of the incipiently fused charge materials at 1500°C is of the same order as that of coke and carbonaceous material at the same temperature.

In accord with a model based on this postulate, the only occasion on which the alloy phase is continuously conductive is when it is in contact with the hearth of the furnace. One would expect the alloy to be formed as isolated spheroids within the slag matrix, and subsequently to settle and accumulate within the hearth of the furnace. Therefore, if this model is correct, the alloy temperature is a direct result of heat transfer from the slag (the continuous and heating phase) to the alloy. Moreover, a specific relation should exist between the liquidus temperature of the slag and the temperatures of the slag and alloy when tapped.

A brief experimental study of a 15 MVA electric smelting furnace producing high-carbon ferrochromium (having a silicon content of 4,0 per cent) was conducted. Tapping temperatures of the slag and alloy were measured by means of a commercially available 'Quick Immersion Thermocouple' system (Table 1). In all instances it can be seen that the slag has a higher temperature than that of the alloy, and the difference in temperature is considerable. The average tapping temperature of the alloy is 1620°C and that of the slag 1680°C, which represents an average difference of 60°C and is evidence that the slag constitutes the continuous heating medium within the furnace.

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Table 1

Tapping temperatures as measured by the 'Quick Immersion Thermocouple' technique

Temperatures when tapped, °C		A—B	Liquidus temp. of slag* °C
Slag (A)	Metal (B)	°C	
1685	1605	80	
1695	1640	55	1900
1670	1625	45	
1650	1610	40	
1655	1620	45	
	1630		1780
1670	1620	50	
1710	1630	80	
	1590		1800
	1625		
1705	1640	65	
1670	1605	65	
1705	1645	60	
1670	1595	75	1870
	1590		1840
	1610		1760
	1615		1860
1670	1625	45	1820
1640	1600	40	1870
1695	1635	60	
1680	1620	60	1860
1685			1810
1685	1635	50	1870
1680	1610	70	1800
1730	1665	65	1850

*In the measurements of liquidus temperatures of the slags, the Cr_2O_3 and FeO contents were ignored. This can lead to appreciably incorrect liquidus temperatures. At present, it is thought that the Cr_2O_3 will increase and that the FeO will decrease the liquidus temperatures.

In the processes involved in the single-stage production of high-carbon ferrochromium, medium-carbon ferrochromium, and ferrochromium silicide by a slag process, the overall composition of the slag produced lies predominantly within the following ternary region: SiO_2 25 to 50 per cent, and an MgO-to-Al_2O_3 ratio of 0,5 to 2,0. The representation of the multicomponent slag as a ternary

$MgO—Al_2O_3—SiO_2$ system assumes that the effects of Cr_2O_3 and FeO when dissolved in the ternary system can be assessed as a function of the various effects of the individual oxides MgO, Al_2O_3, and SiO_2 on the system.

LIQUIDUS TEMPERATURES

Liquidus temperatures were determined by hot-stage microscopy[2] with Pt—20%Rh/Pt—40%Rh thermocouples. Where the upper limit of these thermocouples was exceeded (1720°C), the liquidus temperature was determined from the pronounced discontinuity, coinciding with liquidus temperature, in the curves for $1 \text{ n } k$ versus $1/T(K^{-1})$. Liquidus temperatures and slag compositions are presented in Table 2, which shows that the liquidus temperatures up to 1720°C are accurate to within 8°C, whereas those determined from the discontinuity are accurate to within 15°C. These agree well with the liquidus temperatures predicted by Osborn and Muan[3].

Table 2

Nomenclature, analysis, and liquidus temperatures of slags investigated

Slag no.	MgO molar percentage	$AlO_{1,5}$ molar percentage	SiO_2 molar percentage	Liquidus* temperature °C
1	42,7	16,3	41,0	1520
2	34,4	23,5	42,0	1430
3	30,4	25,6	43,2	1406
4	28,9	28,6	42,4	1427
5	22,0	34,8	43,2	1463
6	46,0	18,8	39,0	1620
7	34,5	23,3	37,2	1530
8	35,1	27,5	37,3	1535
9	28,9	32,1	38,9	1532
10	24,7	37,3	38,0	1525
11	47,1	19,7	33,2	1643
12	41,2	25,8	33,1	1625
13	35,8	30,5	34,7	1644
14	31,0	34,9	34,1	1645
15	24,3	41,2	34,6	1640
16	46,7	24,9	28,4	1717
17	42,8	27,6	29,5	1725
18	42,2	29,5	28,3	1710
19	35,0	35,2	29,8	1725
20	27,5	43,0	29,5	1755
21	52,5	23,3	24,2	1725
22	48,1	27,8	24,1	1750
23	41,6	33,7	24,7	1790
24	36,4	38,3	25,3	1790

*Liquidus temperatures were determined either by hot-stage microscopy (below 1700°C) with an accuracy of ±8°C, or by the discontinuity observed on a plot of $\ln k$ versus $1/T$ with an accuracy of ±15°C.

VISCOSITY OF THE SLAGS

Viscosity was measured by use of a commercially available Brookfield viscometer, which measures the torque imposed on a spindle rotating at constant angular velocity within a fluid. The relation between the torque measured (Brookfield Viscosity Number) and the viscosity for each spindle was determined by calibration at room temperature in oils of known viscosity at known temperatures. These oils, supplied by the U.S. Department of Commerce and Canon Instrument Co., were guaranteed to conform to ASTM oil standards.

Two cylindrical spindles differing only in length (20 mm and 25 mm) were used. For both, the outer diameter was 10 mm, the inner diameter 7 mm, and the diameter of the connecting shaft 2 mm. The spindles were immersed in the slags or calibrating oils in such a way that they were concentric with the crucible axis and approximately equidistant from both the upper and lower surfaces of the slags. Variation in the overall height of the slag or calibrating oil up to 5 mm on either side of 40 mm altered the measured reading by not more than 3 per cent. Similarly, off-centre alignment of the spindle by up to 2 mm altered the measured reading by less than 2 per cent.

Experimental Technique

Each sample of slag (50 g) was prepared from portions of chemically pure oxide compounds that had been sintered at 1000°C for four hours. Viscosities, electrical conductivities, and liquidus temperatures were all determined on the same sample, which was subsequently analysed chemically (Table 2). The furnace used was an 18 kVA (output) Intertherm high-frequency (500 kHz) induction furnace fitted with a coil of inductance of 6,0 mH.

Molybdenum was used for the manufacture of crucibles and ancillary equipment, i.e., spindles and electrodes. The crucibles were 35 mm in outside diameter, 25 mm in internal diameter, and 50 mm in internal depth, and were heated by radiation from a graphite susceptor, the atmosphere within the furnace being pure argon.

Most of the temperature measurements were taken direct by use of a Pt—20%Rh/Pt—40%Rh thermocouple located 2 mm above the rim of the crucible. Temperatures higher than 1880°C were measured by an extrapolation technique using a second thermocouple positioned approximately 30 mm higher than the first. In all the measurements, corresponding increases in temperature were sensed by both thermocouples over the range 1750 to 1880°C, thereby justifying limited extrapolation (1880 to 1950°C).

Each experimental run was started at some 100 to 150°C above the liquidus temperature. The period of initial equilibration was assessed by the attainment of constant measured values at constant temperature. Subsequent measurements were taken after ½-hour equilibration at each new temperature – generally 20 to 25°C lower. Temperatures were decreased in this manner until the liquidus temperature was reached and further effective measurement was prohibited. Following this, temperatures were raised and similar measurements again made above liquidus with ½-hour equilibration times at each new temperature. This technique eliminated any errors due to possible hysteresis of structure and was found satisfactory even for the most viscous slags.

Experimental Results

The results are presented in Figures 1 to 5 as contours of constant viscosity (isokoms) within pseudobinary sections corresponding to constant SiO_2 contents of 50, 45, 35, and 30 per cent (by mass). The following points should be noted.

(1) At constant SiO_2 concentration, the viscosity increases with decrease in the ratio of MgO to Al_2O_3. The order of change is approximately the same for the various levels of SiO_2 concentration.

(2) At constant MgO-to-Al_2O_3 ratios, the viscosity values increase with increase in the concentration of SiO_2. Increases in the silica content bring about a very marked

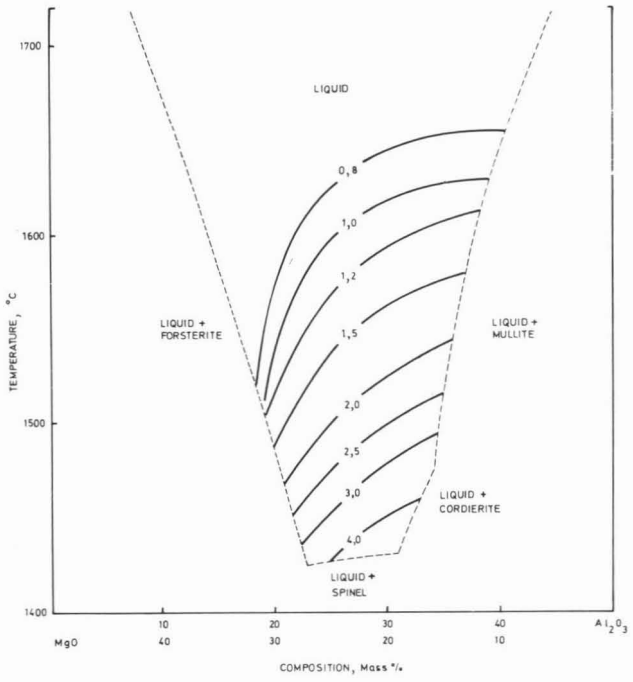

Figure 1

Constant viscosity contours (isokoms, in N s/m²) within the pseudobinary section at a constant SiO_2 content of 50 per cent (by mass)

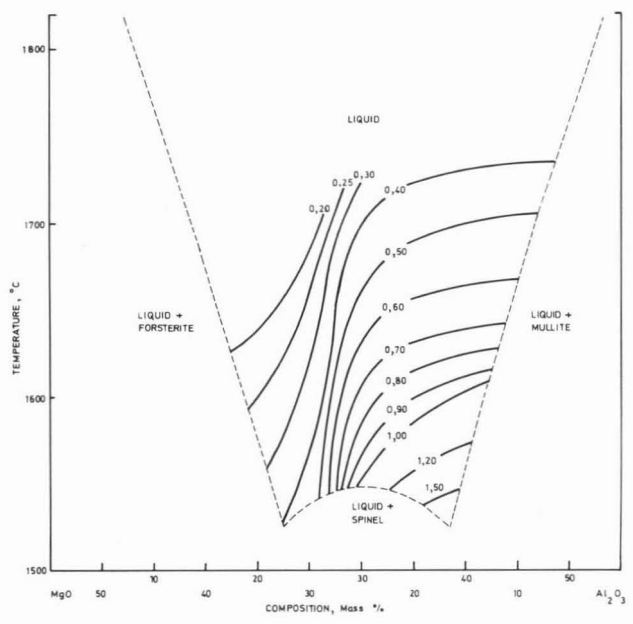

Figure 2

Constant viscosity contours (isokoms, in N s/m²) within the pseudobinary section at a constant SiO_2 content of 45 per cent (by mass)

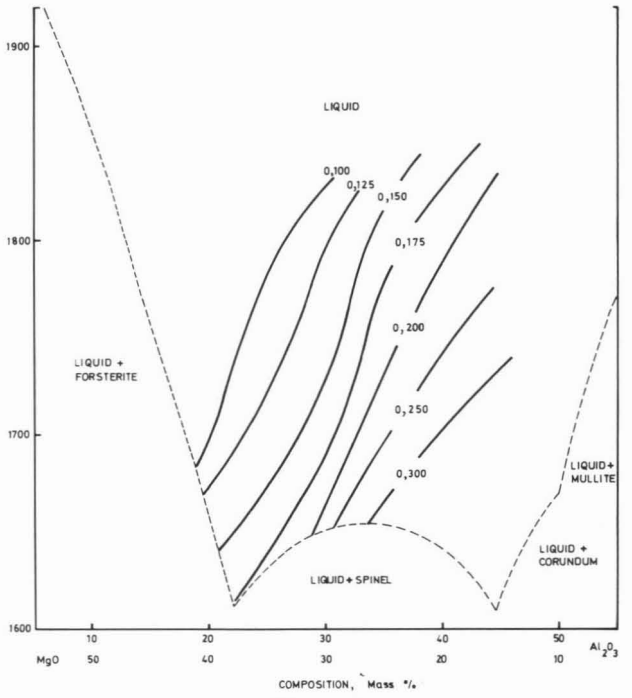

Figure 3

Constant viscosity contours (isokoms, in N s/m²) within the pseudobinary section at a constant SiO_2 content of 40 per cent (by mass)

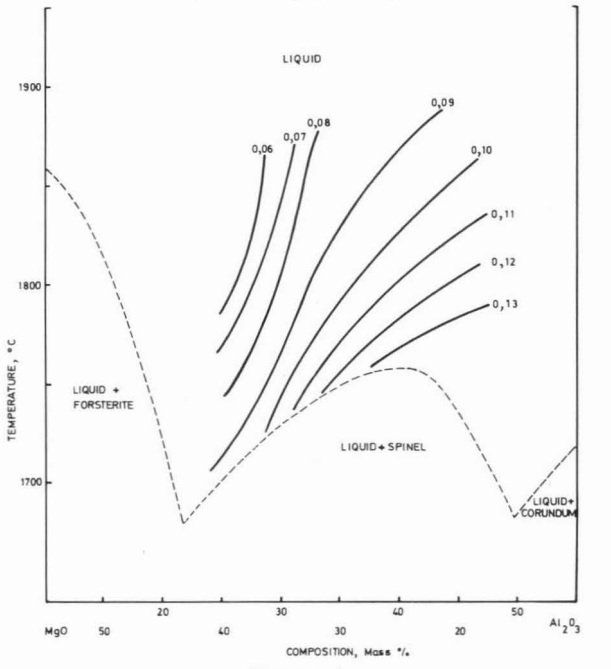

Figure 4

Constant viscosity contours (isokoms N s/m²) within the pseudobinary section at a constant SiO_2 content of 35 per cent (by mass)

increase in the viscosities of all slags. The same effect was observed at all temperature levels and at all MgO-to-Al_2O_3 ratios.

(3) The character of the change of viscosity with composition does not vary much from one temperature to another, indicating a regular disruption of the anionic lattice.

Without exception, the relations between viscosity, temperature, and composition presented are those based on measurements above the liquidus temperatures. Many investigators have neglected this requirement and have attempted to measure viscosities below the liquidus temperature. However, it is not possible to measure the viscosity of such dispersed mixtures of solid and liquid accurately under equilibrium conditions.

The most general comparison made for slag viscosities is that between blast-furnace and open-hearth slags, where typical viscosities are about 0,2 to 0,4 N s/m². A 'sticky' slag for these furnaces is one having a viscosity of more than 0,8 N s/m². By comparison, the slags in the system MgO—Al_2O_3—SiO_2 are remarkably fluid under all conditions above liquidus, except possibly those with

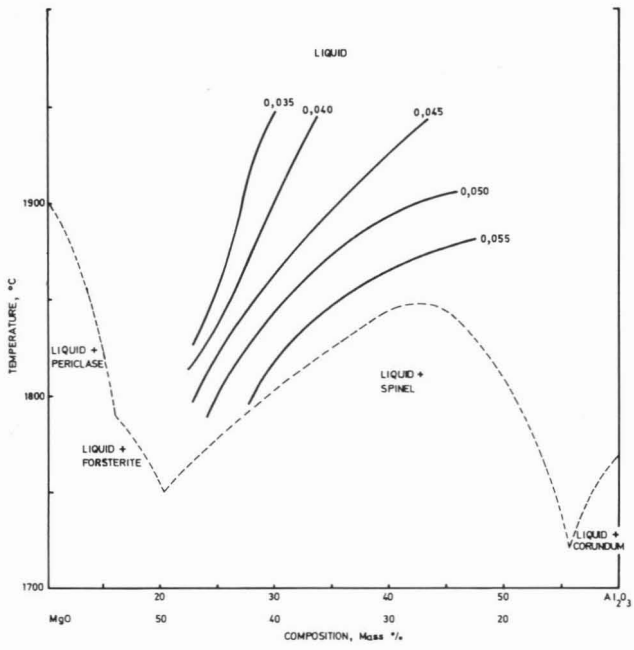

Figure 5

Constant viscosity contours (isokoms, N s/m²) within the pseudobinary section at a constant SiO_2 content of 30 per cent (by mass)

SiO_2 contents of 50 per cent (by mass). However, one should remember that the liquidus temperatures of the slags investigated in this system are considerably higher than those of the slags used in iron-making. Nevertheless, the apparent fluidity of slags in this system is contrary to observations of furnace conditions, which find that, for high-carbon ferrochromium, the slags are typically of a 'sticky' nature. It is not known whether this reflects the true viscosity effect of dissolved oxides of chromium, or a sub-liquidus effect resulting from the presence of undissolved chromite.

SPECIFIC ELECTRICAL CONDUCTIVITY OF THE SLAGS

The method selected for measurement of electrical conductivity was a modified a.c. Wheatstone-bridge technique operated at a frequency of 10 kHz. The modifications involved the addition of filtering and inductance-balance facilities. The electrode design chosen was that of two parallel dipping electrodes, which were made from molybdenum wire 1,0 mm in diameter and were spaced 8,0 mm apart (between centres).

Since the relation between resistance (measured) and resistivity is of the form

$$\log R = -\log k + \log G, \quad \ldots\ldots 1$$

it is usual to determine the cell constant *(G)* from the relations between resistance and conductivity for standard solutions of sodium chloride and potassium chloride. These relations were determined for two fixed depths of electrode immersion, the precision of depth of immersion being 0,1 mm for the present geometry. The corresponding cell constants *(G)*, as evaluated, are presented in Table 3, which compares these values with those calculated on the assumption that conduction occurs between two parallel infinite wires. The lower experimental values resulted from the crucible effect, the finite dimensions of the electrodes, and end effects.

Table 3

Cell constants measured for the present electrode geometry, compared with those calculated

	G measured	*G* calculated
8 mm immersion	81,9	111,1
15 mm immersion	43,1	58,7

Capacitance

By definition, capacitance arises from the separation of opposite charges with which a voltage difference is associated. For the standard electrolyte solutions, the capacitance measured was a direct function of concentration, reflecting an overall permittivity or dielectric of constant-charge distribution. One would also expect slags to exhibit a capacitance effect, and capacitance was, in fact, observed for many of the slags investigated. However, the values determined were neither reproducible nor interpretable as functions of composition or temperature, and capacitance effects, when present, were therefore balanced so that an accurate resistance could be determined.

Experimental Results

The specific electrical conductivities (in S m^{-1}) of individual slags in the system $MgO—Al_2O_3—SiO_2$ are presented in Figures 6 to 10. The following can be observed:

(1) the specific conductivity increases with increasing MgO-to-Al_2O_3 ratio at constant SiO_2 composition,

(2) the specific conductivity increases with decreasing SiO_2 composition at constant MgO-to-Al_2O_3 ratio, and

(3) in all instances, the values of specific conductivity are sufficiently high to permit the assumption that the mechanism of conduction is ionic.

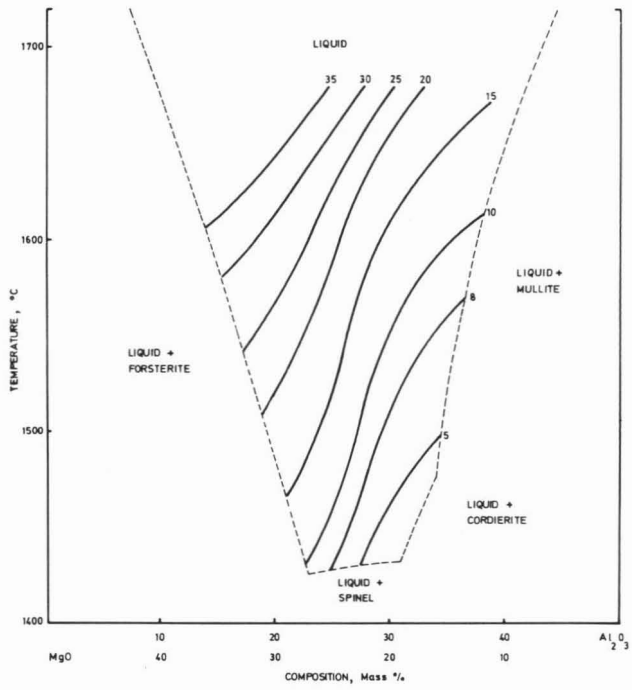

Figure 6

Contours of constant specific electrical conductivity (S m^{-1}) within the pseudobinary section at a constant SiO_2 content of 50 per cent (by mass)

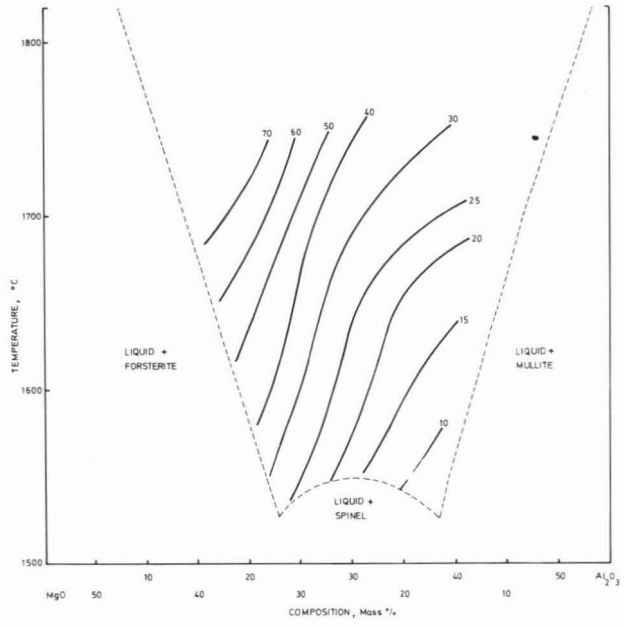

Figure 7

Contours of constant specific electrical conductivity (S m ^{1}) within the pseudobinary section at a constant SiO_2 content of 45 per cent (by mass)

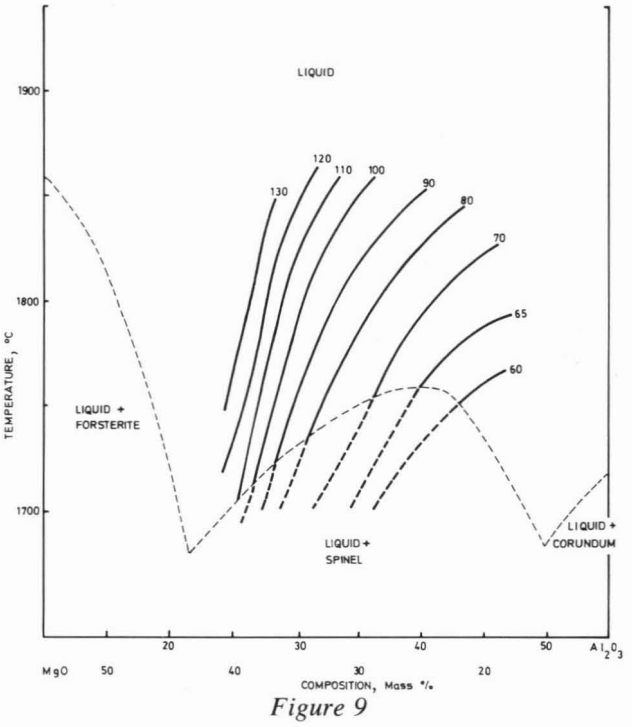

Figure 9

Contours of constant specific electrical conductivity (S m^{-1}) within the pseudobinary section at a constant SiO_2 content of 35 per cent (by mass)

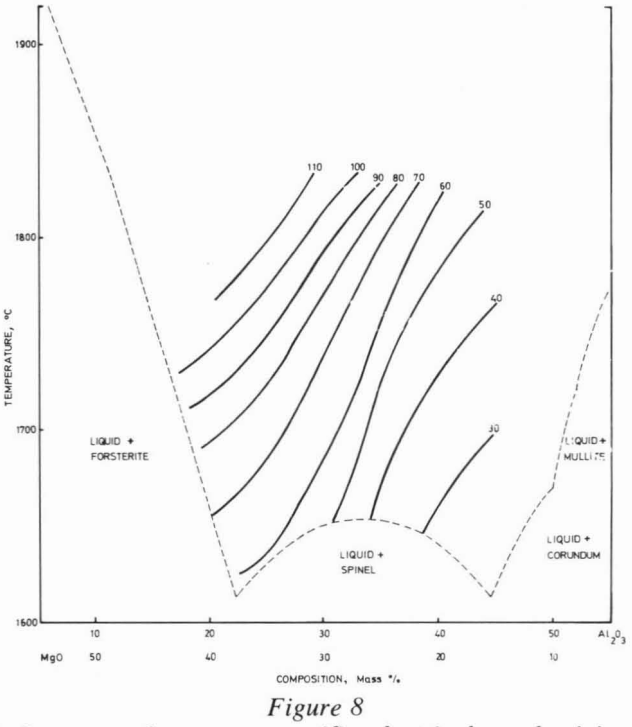

Figure 8

Contours of constant specific electrical conductivity (S m ^{1}) within the pseudobinary section at a constant SiO_2 content of 40 per cent (by mass)

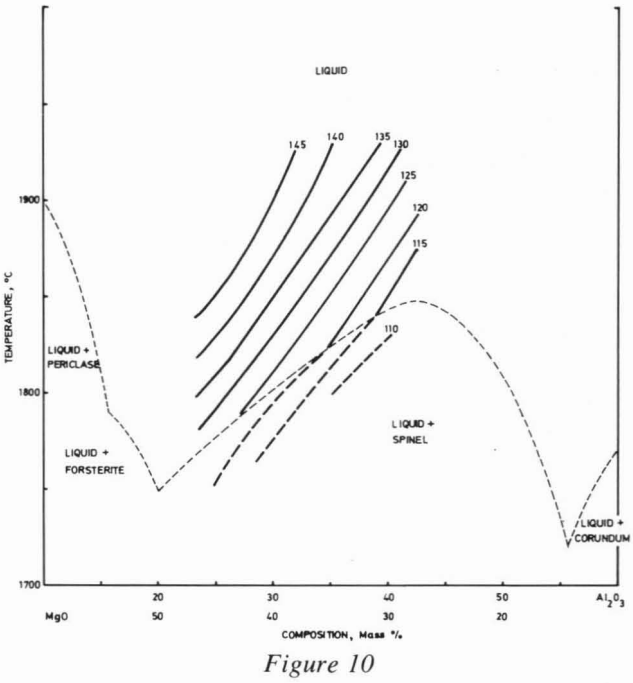

Figure 10

Contours of constant specific electrical conductivity (S m ^{1}) within the pseudobinary section for a constant SiO_2 content of 30 per cent (by mass)

VISCOSITY, CONDUCTIVITY, AND PRODUCTION

From the binary sections depicting viscosity and electrical conductivity as a function of MgO-to-Al_2O_3 ratio for various SiO_2 contents, it can be deduced that no simple optimization of these two physicochemical parameters is possible. However, at any particular SiO_2 level, those slags with relatively high MgO-to-Al_2O_3 ratios will display the lower viscosities, whereas those with the lower MgO-to-Al_2O_3 ratios will display the lower conductivities. Hence, for relatively low viscosities and conductivities, equal proportions of MgO and Al_2O_3 are indicated.

For each particular smelting operation there is a limited range of slag composition that can be employed; this applies particularly to the SiO_2 content, since this factor has the major effect on the liquidus temperature and hence the major effect on the operating temperature of the process. The SiO_2 content of the slag is also of major importance for the production of ferrochromium silicide, since a high SiO_2 content in the slag is required to obtain the high

partition of silicon in the alloy. It has been established from plant practice that the silicon and carbon contents of high-carbon ferrochromium alloys are affected to a considerable extent by the MgO-to-Al_2O_3 ratio of the slag. Therefore, the complex relations that exist in the various smelting processes do not permit the deduction of a simple optimization of viscosity and conductivity.

However, it is possible for the parameters of viscosity and conductivity to be considered separately and for the separate effects on some aspects of smelting to be determined.

Effects of Viscosity

It is known that the viscosity affects the rate of settling of alloy droplets and the rate of bulk transport.

Rate of Settling

When formed by reduction of the chromite, the alloy falls as metal reguli through the slag layer. These conditions do not conform with Stokes's Law, because of turbulence in the furnace and because of turbulence and drop formation when the alloy is tapped through the slag layer (in the ladle). More applicable is a hindered settling equation, for example:

$$\eta_s = \frac{\eta}{1-2{,}5\gamma-14{,}1\gamma^2}, \quad \ldots\ldots\ldots 2$$

where γ is the volumetric fraction occupied by the solid, and η is the effective viscosity for conditions of hindered settling.

Previous work[4] has shown that the average metal reguli entrapped in high-carbon ferrochromium slags represent 3 per cent by mass of the total alloy produced. The conditions of production under which these samples were taken suggest a slag viscosity of, perhaps, 0,4 N s/m². If this is used as a datum point, together with the inverse relation between viscosity and limiting velocity in accordance with Stokes's equation, it is assumed that the limiting velocity correlates direct with the metal loss. Therefore, if the minimum average volumetric fraction of solids produced is 0,08 and a cumulative effect of change in viscosity is assumed (a factorial expression with reference to the datum point), a relation between metal loss and viscosity can be derived, as shown in Figure 11. This relates to overall processes, viz, conditions both in the furnace and in the ladle, because of the overall nature of the datum point. The relation predicted corresponds closely to data obtained under operating conditions.

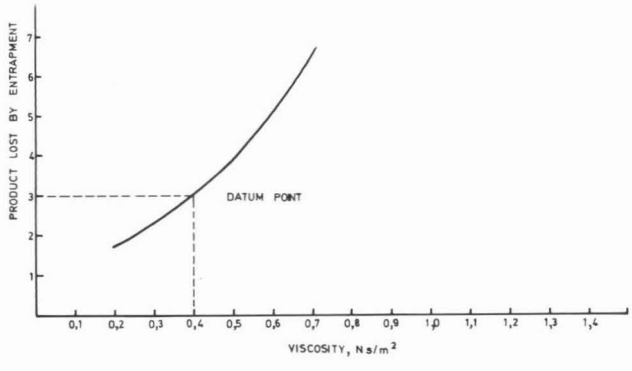

Figure 11

Percentage of alloy lost by entrapment as reguli in the slag versus the viscosity of the slag

Rate of Bulk Transport

Urquhart[1], investigating the smelting reactions involved in the production of high-carbon ferrochromium, determined reduction rates as a function of time for isothermal conditions. An example is shown in Figure 12. For the conditions of reduction investigated, the activation energy of reduction of chromium was found to be about 419 kJ, which is similar to the activation energy for diffusion through the slag. This implies that diffusion through the slag layer (either of reducing agent or of reduced species) is the rate-limiting step. Exact mathematical description of the mass transport under such conditions is extremely difficult, but the elementary description offered by the Nernst equation can be considered:

$$Q = \frac{D(C_s - C_o)S}{\delta}, \quad \ldots\ldots\ldots 3$$

where Q = amount of material dissolved per unit time,
S = surface area,
C_s, C_o = concentration at the surface and in the bulk,
D = diffusion coefficient, and
δ = a constant representing the thickness of the diffusion layer.

It has been shown that

$$\delta \propto \frac{1}{v^n}, \quad \ldots\ldots\ldots 4$$

where v = velocity of the moving fluid, and
n varies from $\frac{1}{2}$ to 1.

But it is known that

$$\eta \propto \frac{1}{v}. \quad \ldots\ldots\ldots 5$$

Therefore one can assume that

$$\delta \propto \eta^n, \quad \ldots\ldots\ldots 6$$

or, more correctly,

$$Q \propto \frac{1}{\eta^n}. \quad \ldots\ldots\ldots 7$$

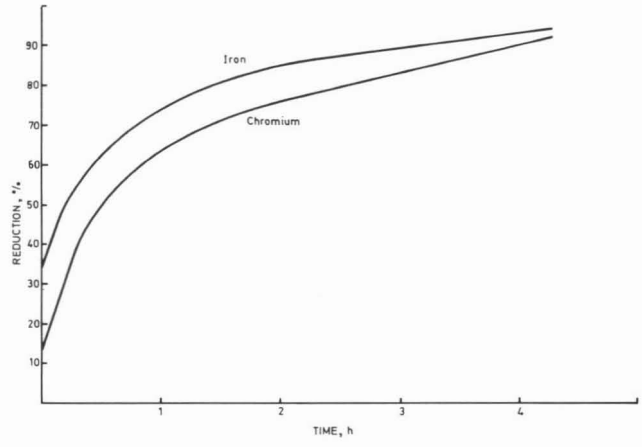

Figure 12

An example of the reduction behaviour of iron and chromium during smelting at 1600°C (after Urquhart[1])

If the exponent n is equal to 0,5, the reduction behaviour shown in Figure 12 can be predicted to change within limits as a function of viscosity (Figure 13).

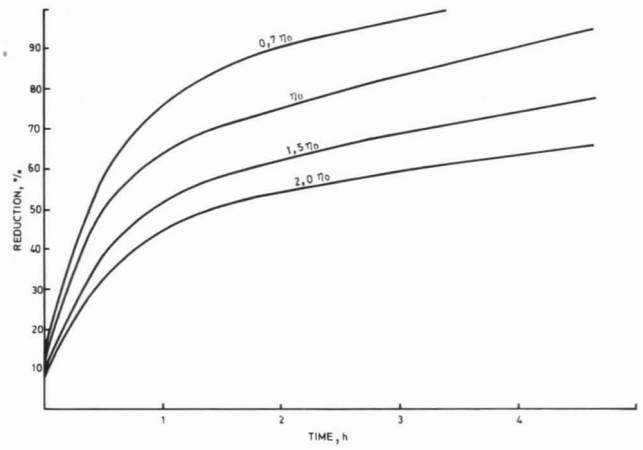

Figure 13

The effect of change in viscosity on the percentage of reduction as a function of time at 1600°C

By definition,

production = $\int$ (rate of reduction). dt 8

Therefore the integral of the curves shown in Figure 13 will give the effect of change in viscosity on the actual production based on bulk transport considerations (Figure 14).

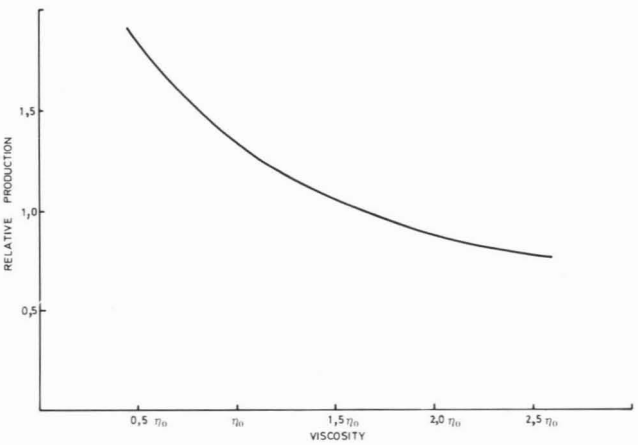

Figure 14

The effect of viscosity on production (relative) at constant temperature, based on bulk-transport considerations

Effects of Conductivity

Particularly in the larger furnaces, the small resistance of the burden limits the power that can be drawn by the furnace (since active power = I^2R, where I can be considered constant and close to the permissible maximum). Therefore, for a fixed power consumption per unit of alloy produced, an increase in resistance will be directly responsible for an increase in production as shown in Figure 15 within the limits of the corresponding transformer. For this calculation, an electrode current capacity of 80 kA and a furnace resistance of $1,0 \times 10^{-3}$ Ω are assumed. The active power given is that per electrode.

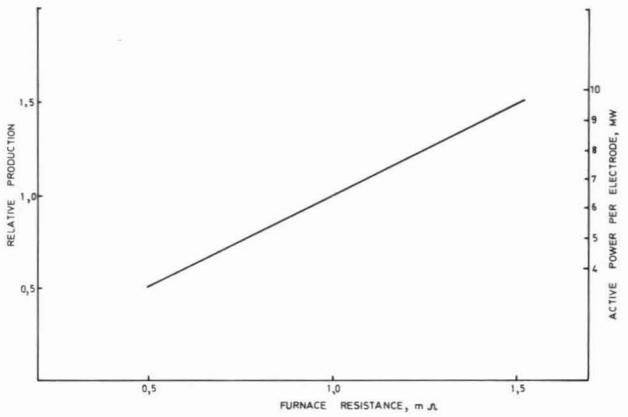

Figure 15

The relation between production, active power supplied per electrode, and resistance of a furnace operating at maximum electrode current loading, i.e. amp.

CONCLUSION

The deduction that the slag is the continuous heating medium within an electric smelting furnace producing high-carbon ferrochromium justifies the importance of the slag properties of viscosity and conductivity. The complex interactions involved in smelting do not permit a simple optimization of the two parameters, but it can be shown that the individual effects of each parameter on various aspects of the smelting process can be characterized. Because these interactions cannot be predicted from measurements of individual parameters or from an analysis of individual aspects of the smelting process, the integration of all these interactions should be evaluated on a pilot plant.

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4. GRIESSEL, H.J. Metal entrapped in high-carbon ferrochromium slags. Johannesburg, National Institute for Metallurgy, Techn. Memo. 2nd Apr., 1970. (Unpublished).

Professor Howat ended his presentation as follows.

The latter part of our paper comprises some of the mathematical tricks one can play with the data we had accumulated. None of us would consider that they should be taken seriously or regarded as accurate predictions of what will happen in the furnace. We admit that these interactions cannot be predicted from measurements of individual parameters or from an analysis of individual aspects of the smelting process, and we recommend that the integration of all these interactions should be evaluated on a pilot plant.

This gives rise to many questions and serious reflections in regard to research of this type carried on within a university. Research carried on within a department in the Faculty of Engineering should, I am convinced, have a really close association with industry and with day-to-day problems. I believe that, to a large extent, my Department has been able to do that. No research projects have been initiated without full discussions with the technical people in the industry, and they have all been assessed in relation

to the possible benefit that might accrue in practice from the results obtained. Throughout the project, we endeavour to have discussions with the technical people to keep them informed of the progress made and to have their observations and comments.

On our side, we believe we are equipped to make reasonably precise and accurate determinations of physicochemical values, such as liquidus temperatures, viscosities, electrical conductivities, and activities of oxides in slags.

Such determinations can probably best be made in a university and are made, mainly, by men working for higher degrees, a state of affairs that has advantages and disadvantages. So far as the disadvantages are concerned, this means that the investigations must have a definite and clear-cut academic content and not just be aimed at getting an answer to a specific problem. This often means that the investigation takes longer and covers more ground than the industry considers necessary. The advantages include the establishment of a close link between the university department and the industry. Men carry on research work with a heightened awareness of the problems of industry and with the incentive of doing work that may find a practical application in a problem area. Another advantage, although it is one we do not shout about, is that research carried out in the universities usually costs a lot less than work carried out in other institutions.

Even under the conditions outlined, we do find ourselves sometimes wondering: Was this particular piece of work really worth while? I need go no further than think of the great amount of work Dr Johnston carried out on the conductivities of slags. At the present, we can see little practical significance in these many results. Can the work be justified on the grounds that we have provided basic scientific data, or should the time and effort of our research team have been directed along a line of more apparent practical value? Or is it possible that the proper application of these basic scientific data might conceivably result in a major advance in smelting? We, in the universities, just do not know the answer. Our work must inevitably be primarily carried out as a laboratory project. What of the application of these results? Are they capable of being applied on an industrial basis, and in what way can we collaborate with you technical people in the industry in such an application? Would you welcome our collaboration? Can we get together in such a way that, within the framework and limitations of the academic requirements for a higher degree, we can provide scientific data and results of value to the industry. And can they be applied, and how?

DISCUSSION

Mr L.A. Kok:*

The ferro-alloy industry in South Africa certainly does not underrate the work done at the universities and especially the work done by Professor Howat and his team. They train metallurgists for us, who are ready to enter industry without having to be taught too much by industry about slag technology.

Mr S. Selmer-Olsen•:

Professor Howat may feel somewhat distressed that the industry does not appear to have made use of the laboratory results obtained so far. The time between obtaining laboratory results and their application on plants can sometimes be rather long because it is not easy for plant men to experiment with furnaces while production schedules have to be met. On the other hand, larger furnaces with larger problems are being designed. Such factors as furnace resistance and slag conductivity are of considerable importance. I therefore highly appreciate the fact that the resistance distribution in the furnace was stressed. It is not sufficient to increase the resistance in the slag or the coke bed if the resistance between the electrodes is low enough to allow most of the current to pass through that region. Thus, it is also necessary to increase the resistance between the electrodes. We have installed centre chutes in our new furnaces to be able to charge extra material there to increase the resistance between the electrodes. When that is done, we shall try to increase the resistance of the material between the electrodes and the bottom of the furnace. So, as we try to increase the furnace resistance and the furnace load, it is obvious that all these investigations will be of the greatest value to us. But please excuse us, Professor Howat, if we cannot do this in a month – it could take years. I should like to take this opportunity to thank Professor Howat, the University, and NIM for all the work they have done so far. I shall do my very best to see that they carry on with it.

Dr D. Slatter†:

Looking at Table 1, it is immediately apparent that the slag and metal were tapped at temperatures below the liquidus temperature of the slag. Is this substantially correct, and was the plant slag 'sticky' or was it fluid, in which case does this perhaps point to the possibility of our techniques of liquidus-temperature measurement being less accurate than we believe? Or perhaps that the liquidus temperatures published in the $MgO—Al_2O_3—SiO_2$ system are incorrect? It is stated that the Cr_2O_3 and FeO contents of the slags were ignored. However, it is considered that the very small amounts of FeO in the slags would not lower the liquidus temperature to the equivalent of the given tapping temperatures, and, moreover, the Cr_2O_3 content of the slag may well raise the liquidus temperatures even higher than those given in Table 1.

Professor Howat:

It is correct, I think, that the slag and metal were tapped at temperatures considerably below their liquidus temperatures. However, one has to accept that, as far as the simple $MgO—Al_2O_3—SiO_2$ system is concerned, the results that we have are, in fact, substantially correct. The Cr_2O_3 and FeO contents of the slags were ignored in this investigation. Since that time, some work has been done on the addition of Cr_2O_3 and FeO to slags of this type. This work was carried out by Mr Myles Rennie and has been published in the *Journal of the South African Institute of Mining and Metallurgy*. I think it is true, as Dr Slatter suggested, that the Cr_2O_3 content of the slag raises the liquidus temperature.

Mr W.A. Gericke:*

Has the substitution of MgO by CaO been investigated with respect to the viscosities and electrical conductivities of the system $CaO—MgO—Al_2O_3—SiO_2$? If so, what was the effect of partial or total substitution of MgO by CaO on these two slag characteristics?

Professor Howat:

I am afraid Mr Gericke expects me to read another paper on this problem. Perhaps Dr Jochens will comment.

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Dr P.R. Jochens†:

This four-component slag system has been investigated by Mr D.I. Ossin, and the results were presented at the AIME Electric Furnace Conference in Chicago in 1970. If my memory serves me correctly, the following generalization can be made: CaO and MgO in the slag produce a lower viscosity accompanied by a lower resistivity.

I should like to enlarge on Professor Howat's answer to Dr Slatter's question on whether these slags were tapped below liquidus temperature. The answer is Yes, but not quite to the same degree as might be expected from the figures published. The slags as tapped contain considerable quantities of iron and chromium oxides, the effects of which were not considered in the investigation. It should be noted that FeO decreases the liquidus temperature. It should also be noted that it is not Cr_2O_3 that is present in these highly reduced slags but CrO, as Russian investigators have shown, and this again reduces the liquidus temperature. So I do not really believe that the slag is being tapped so much below its liquidus temperature.

Mr L.A. Kok:*

Microscopic examination of slags tapped from charge-chromium furnaces where Transvaal chromite fines are used as raw material have shown that they contain chromite particles that are in various stages of reduction. This implies that analyses of slags may be misleading if this factor is not taken into account.

Mr K.J. Edwards‡*:*

Does Professor Howat envisage, in time, the publication of viscosity and electrical-conductivity data for real slags that could be utilized by furnace managers in the same way as slag-liquidus diagrams are used today?

Professor Howat:

Our answer is undoubtedly Yes. We have tried in the paper to indicate some of the ways – some of the mathematical 'tricks' – that we adopt in the hope that these results can be extended. There are researchers that are working towards a mathematical model, and I am quite sure that these data are essential constituents required for the formulation of such mathematical models.

Mr R.J. Botte‡*:*

The slags of high-carbon ferrochromium contain a certain amount of chromium oxide. Do you know the influence of chromium oxide content on the results of conductivity and viscosity?

Professor Howat:

We have done work on the additions of chromium and iron oxides to these slags. These results have already been published.

Professor G.T. van Rooyen:*

Theory requires that there should be a correlation between conductivity and viscosity since both are dependent on the mobility of the ions. Was any direct correlation found between viscosity and conductivity?

Professor Howat:

We found a correlation to exist in the general way that was shown in the diagrams.

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