

Experiences in operation of various electric-arc furnaces under resistance control

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ABSTRACT

Mintek has been involved in research and development on submerged-arc furnaces for more than 30 years. During this time Mintek has studied various aspects of ferro-alloy production including the operation of DC-Arc furnaces, process metallurgy and the optimisation of submerged-arc furnaces.

To this day the submerged-arc furnace remains the predominant vessel used in ferro-alloy production. Through close collaboration with the ferro-alloy industry world-wide, Mintek has applied its patented resistance control system (Minstral) to over 50 submerged-arc furnaces producing a wide range of ferro-alloys.

The concept of resistance control has lead to a total paradigm shift in the control of ferro-alloy furnaces from traditional current and impedance control, and derivations thereof. The correct resistance setpoint plays an important role in optimising furnace performance. This is especially important in silicon and ferrosilicon production, where the C3 factor played an important role in setting current set points.

Mintek has studied a number of processes in order to establish criteria for selecting an optimum resistance. Each process has a certain range of typical resistances in which it operates. The optimal resistance for each operation depends on a number of factors, predominantly the size and composition of raw materials, feed recipe, and any pre-processing (pellitization, pre-reduction) performed on the raw materials.

Power control has become an increasingly important aspect of furnace optimisation. Mintek has developed and implemented an

advanced power control algorithm by compensating for imbalanced loads through the out-of-step (differential) operation of the furnace transformers. Implementations on inherently unstable operations, typically the production of ferro-chrome with a high percentage of fines present in the feed, have resulted in a dramatic improvement in production and utilisation of available energy.

Mintek has also extended the concept of resistance control to other applications besides the production of ferro-alloys.

This paper will examine Mintek's experience in optimising various processes using resistance and power control.

1. INTRODUCTION

The majority of ferroalloys are still produced in three-phase submerged-arc furnaces. The reasons are that the high temperatures and reducing conditions required are not easily created by other means. For economic reasons, larger furnaces, with bigger electrodes and transformers have been built. These furnaces have longer time constants, lower power factors and are generally much more difficult to operate and control than their smaller cousins. Maintaining power input and electrode penetration on these large furnaces is not a simple task that the operator can do efficiently with the traditional measurements of current, voltage and power.

2. RESISTANCE BASED CONTROL

Mintek developed and commercialised a resistance controller based on primary electrical measurements to solve some of the problems of maintaining electrode penetration based on current control or voltage measurements. This controller has

been used on a number of different sized furnaces and processes. The question that always arises is what the optimal resistance for a specific furnace and process is. The answer depends on a number of factors – the type of process, furnace size, electrode diameter, type and size of the raw materials – and usually needs to be determined for each individual operation.

When one looks at the operating resistances at different power levels of different processes, one sees some very distinct trends. Resistance was plotted against power for 26 different ferrochrome, ferromanganese-silicide and ferrosilicon operations. It was found that for ferrochrome production, there were two distinct modes of operation. Linear regression equations were calculated for each process and the results are given in Table 1 and plotted in Figure 1. The R^2 value (as defined in Excel) is a measure of the variance of the prediction. There are no R^2 values less than 0.7, showing reasonable linearity.

Process	Resistance equation	R^2
FeCr + fines	$-0.042MW + 3.8$	0.72
FeCr	$-0.021MW + 2.0$	0.70
FeSi	$-0.024MW + 1.7$	0.85
FeMnSi	$-0.015MW + 1.2$	0.71

Table 1. Linear resistance predictions

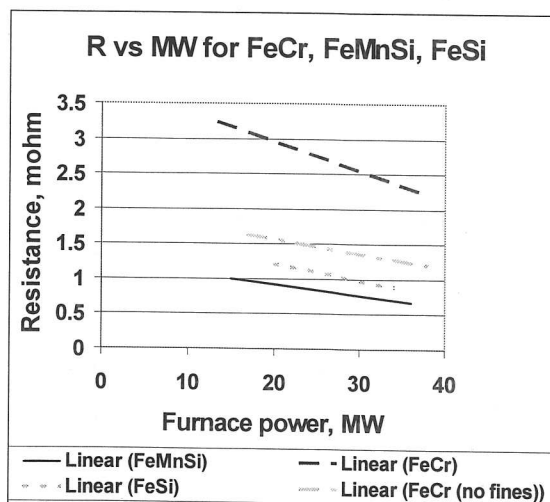


Figure 1. Typical resistance operation

3. THE DESIGN AND OPERATION OF FERROALLOY FURNACES

Many years ago F. V. Andrea¹ developed the idea that the electrode periphery resistance was a constant for each different ferroalloy process. W.M. Kelly² called it the "k" factor and presented a set of curves of the "k" factor versus electrode power density, which were typical of the operation at that time. Andrea further developed the concept that the heat that could be dissipated from the surface of a graphite electrode would limit the current carrying capacity. Thus we have two relationships that are as applicable today as they were then:

$$R \propto 1/D$$

$$I \propto D^{3/2}$$

For Soderberg electrodes, the maximum operating current is approximately:

$$I = 55D^{3/2}$$

where I is in kA and D is in meters. By selecting a reference resistance point, one can calculate resistances and powers for a range of electrode diameters.

J. Westley³ also looked at the operation of large number furnaces, in particular silicon and ferrosilicon furnaces. He found that good operation corresponded to the relationship:

$$I = C_3 P^{2/3}$$

where I is in kA and P is in MW. One can use this relationship to plot resistance against power and compare these different predictions with the regression line for ferrosilicon production derived from the operational data.

Table 2 gives the calculated linear regression equations for the data plotted in Figure 2. Although neither the C_3 nor the theoretical relationships are linear, the linear regression line differs little from the prediction over the range of operation.

Process FeSi	Resistance equation	R ²
Theoretical	$-0.025MW + 3.8$	0.96
C ₃	$-0.016MW + 1.5$	0.97

Table 2. Linear predictions for FeSi

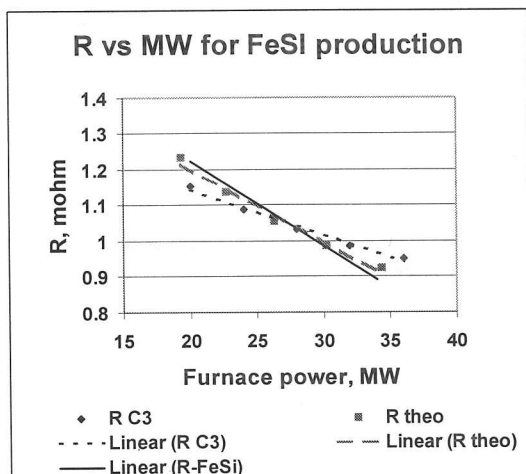


Figure 2. Actual and predicted FeSi resistances

Any of these regression lines could be used to specify the transformers for ferrosilicon production at a required power level. The actual operating resistance depends very much on the type and sizing of the reductant. Charcoal, coke and coal will all have different operating characteristics. The choice of reductant is usually determined by availability and price.

4. OPERATING RESISTANCES

The operating resistance graphs clearly show that there are distinct operating modes for each type of process. These modes vary from totally resistive conduction to total arcing. Investigations on a ferrochromium furnace⁴ using lumpy ores and briquettes showed that 15 to 30% of the resistance was generated in the arc zone immediately beneath the electrode. Economic considerations have necessitated the use of increased quantities of fine chromite ore. This has had a destabilising and cooling effect on the arc producing the very high resistances that are common today. Unfortunately, individual electrodes can switch from a high arcing mode to a low resistive mode

in seconds, leading to control problems as will be discussed subsequently.

Ferrosilicon furnaces require high intensity arcs to reach the temperatures required for silicon production. As a result, the electrodes are positioned close to the metal bath and small changes in tip position can result in large changes in resistance. But that is not really the problem. Maintaining the porosity of the bed and the carbon balance within the furnace is much more difficult. Short and long term changes in resistivity and electrode penetration result from the crater around each electrode growing and collapsing, silicon monoxide jets tunneling through the burden, and slag or silicon carbide fluctuations. The interaction effect compounds the problems that these fluctuations present for conventional current controllers, and results in excessive electrode movement. Even resistance controllers need some constraints on their movement.

Because of the low vapour pressure of manganese, ferromanganese production requires minimal arcing. Thus almost all the conduction is through the low resistivity slag resulting in the low operating resistances shown in figure 1. Since the interaction between the electrode currents increases as the power factor decreases (and the power factor is less than 0.7 on all these furnaces), resistance control is essential on most manganese furnaces. But resistance control alone will not solve the penetration problem. Ferromanganese-silicide needs a coke bed to maintain the silicon grade. This bed grows and decreases along with the carbon balance and will change the electrode penetration. Arcing can and does occur sometimes and this will also affect the penetration.

5. MAINTAINING ELECTRODE PENETRATION AND POWER INPUT

Ferrochromium production provides a classic example of the problems experienced on large high power furnaces. The objective is to maintain both electrode penetration and power input. But each

electrode will behave individually and depending on the arcing conditions, will experience changes in resistance of several hundred percent under extreme conditions. Moving an electrode in to compensate is not a problem if you know its resistance. If you only know the current, you need to be careful not to get too close to the hearth. But there is a limit on how far one can pull an electrode out before the furnace starts to freeze up.

6. CONTROL IMPLICATIONS

Suppose one wishes to operate a furnace at 25MW. The approximate resistances for this operating point can be read off from figure 1. Assuming a reactance of 1.1 milliohm, one can calculate the furnace MVA and transformer secondary voltages required for the different processes. On an axis of total furnace power against electrode current, one can draw curves of constant resistance, transformer voltage and MVA. On Figure 3, points A, B, C and D are at the intersection of the operating resistance and transformer voltage, corresponding to the production of ferrochromium with fines, without fines, ferrosilicon and ferromanganese-silicide respectively. The MVA ratings required for the different processes increase progressively as furnace power factor decreases.

Suppose the arcing characteristics change and the resistance at point A drops from 2.76 to 1.47 milliohm. If no corrective action were taken, point A would move to point "A high" at 35MW and in excess of 42MVA. But long before that happened, the protection circuitry would have tripped the furnace. The options are to tap the transformer voltage down, move the electrodes out or both. Although these sudden changes in resistance do occur, it is usually only in one electrode and only that one should be moved. For most processes, there is a limited distance that the electrode can be moved without creating other problems. The result is a relatively low resistance on one phase, which will usually result in tapping the transformers down and a loss of power.

Fortunately, most large furnaces have individual tap changers on three separate transformers. It is thus possible to lower the voltage on one or more transformers to remain within the protection limits, while minimising the power loss. To avoid excessive unwanted tap changes, an accurate model of the secondary circuit is required and all possible combinations need to be examined, before any action is taken⁵. A computer can perform this analysis in milli-seconds, and is the reason why computer control is essential on most furnaces these days.

The converse of this situation is that if the resistance at point B increases rapidly and the operating point moves to point "B low" resulting in a considerable loss of power. Provided, higher voltages are available, differential tapping of the transformers can limit the power loss.

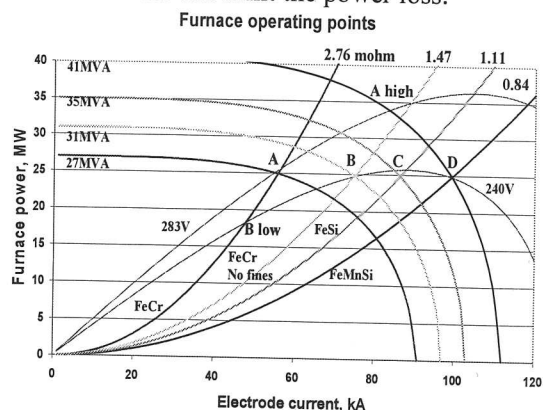


Figure 3. Operating points for different processes at 25MW.

Although the production of charge chrome using fine ore is a particularly difficult process, all high power, high current processes are potentially unstable at some stage. Maintaining electrode penetration within a narrow band and using differential tapping to correct for the unbalanced electrical circuit appears to offer the best short-term solution until the process returns to normal or corrective metallurgical action can be taken.

7. CONCLUSIONS

Different ferro-alloy processes still follow the same trends that were identified fifty years ago. The difference is that modern

furnaces are operating at much higher power levels, closer to their design limits and at much lower power factors. For these reasons and the economic constraints imposed on the use of raw materials, most processes will experience greater or lesser degrees of instability. This manifests itself as sudden and sometimes large changes in the furnace resistance, leading to problems with electrode penetration and power input. These changes are difficult for the operator to understand or correct for using traditional measurements and control techniques. Unfortunately, three separate transformers and intensive processing are required to achieve an optimal degree of compensation.

8. REFERENCES

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