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RECENT DEVELOPMENTS IN ELECTRIC ARC FURNACE OPERATION

by

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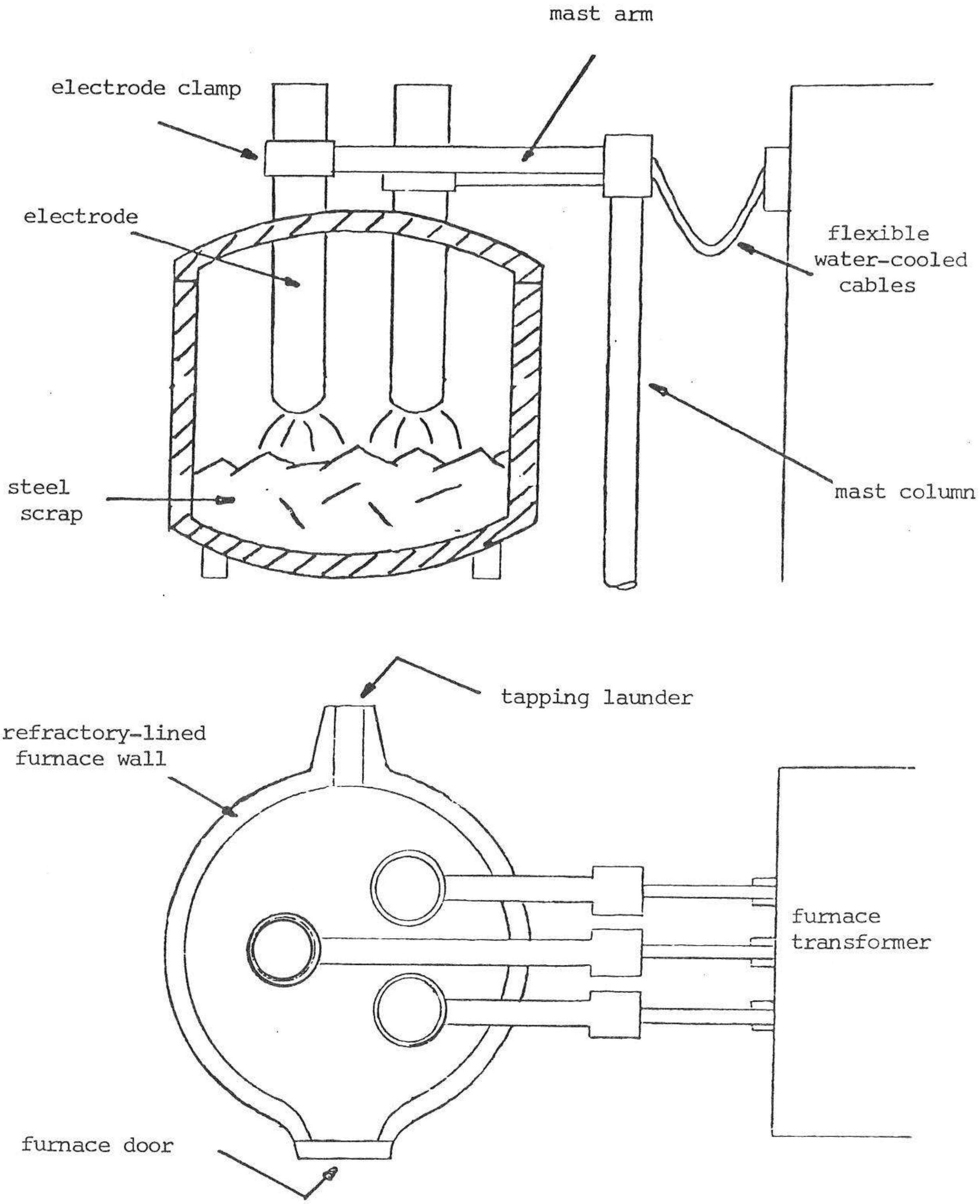
ABSTRACT

The paper presents the recent developments in arc furnace design and operation . The changes discussed include the introduction of water cooled furnace sidewalls and roofs, the increased use of direct reduced iron pellets in the raw material charge, and the use of solid-state devices in electrode drive systems. Of particular importance has been the implementation of digital computers, and their application in the various areas of control in furnace operation is discussed in detail.

1. General Developments

The use of electric arcs for metal melting goes back to the very beginning of the electrical era, when it was realised that the electric arc excelled above all other energy sources as a means of obtaining high temperatures and a great degree of heat concentration . The electric arc furnace, invented by Heroult in 1905, is used to produce high quality carbon and alloy steels from a raw material of either steel scrap or a mixture of steel scrap and directly reduced iron pellets. Steel is produced to a degree of refinement considerably better than by its predecessor, the open-hearth furnace, and the modern electric arc furnace is now a very valuable tool in the steelmaking industry. Arc furnace production accounts for 20% of world steel output and this is predicted[1] to rise to 25% by 1990.

A typical furnace consists of a refractory lined metal shell of diamter 5-10M, having a removable roof, tapping launder at the rear to pour the finished steel from the furnace, and service doors at the front, as shown in Fig. 1. Three graphite electrodes, held in clamps on the end of a supporting mast arm, pass through holes in the furnace roof. The roof and electrodes can be raised and swung aside in a horizontal plane, allowing charging of raw materials into the furnace from steel baskets held by an overhead crane. Where it is the practice to use iron pellets as part of the charge, this is usually input to the furnace by a chute mechanism not shown in Fig. 1. Electrical power is supplied to the electrodes from a three-phase, multi-voltage-tap transformer, and the steel is melted by heat generated in arcs striking between the electrodes and the raw materials. Present day furnaces have power ratings up to 160 MVA and capacities up to 400 tonne[2].



CONSTRUCTION OF ARC FURNACE

(Front view and plan)

FIG 1

The electrodes are positioned by a controller to maintain the length of the electric arc at a preset value. The defined arc length value varies with the selected voltage tap and is optimised to suit particular conditions occurring at various stages of the melting process. Initially for instance, a medium voltage-tap with the controller set for a short arc length is used, as long, high-power arcs are very damaging to the roof and wall refractory materials exposed at this stage. After a short time, holes are bored into the raw material by the electrodes, shielding the furnace walls and roof from the arc, and allowing full power to be applied by a high voltage-tap and long arc.

As the bulk density of the raw material, particularly when it consists of a high proportion of steel scrap, is less than that of molten steel, the raw material has to be added to the furnace in two or more baskets. The charging procedure therefore consists of loading an initial basket of raw material, and then loading further baskets as soon as the reduction in volume of the melting material permits. Where iron pellets are used, this material is often continuously charged into the molten steel in the furnace rather than being loaded by baskets.

This procedure entails a programmed sequence of voltage-tap changes, optimised to maximise energy input to the steel whilst minimising expensive damage to refractory lining materials caused by arc flare. This program has to be modified according to initial furnace temperature and the weight and bulk density of raw materials charged.

Steelmaking consists of two distinct phases, the melting-down period during which solid raw material becomes molten, and the refining period during which alloys are added to the steel and unwanted elements oxidised out until it is of the required specification. Whilst both of these procedures can be carried out in the arc furnace, the injection of oxygen at atmospheric pressure to remove carbon as carbon monoxide also removes chromium, which has to be replaced by the subsequent addition of expensive low carbon, high chromium, ferro-alloys. In the case of high alloy steels, it is therefore common practice to use the arc furnace only for melting, and to carroy out refining in a secondary vacuum degassing vessel or the more modern argon-oxygen decarburising (AOD) vessel[2]. Both of these lower the partial pressure of carbon monoxide and allow the removal of carbon but retention of chromium in the steel.

The arc furnace continues to be used both for melting and refining to produce carbon and low alloy steels and in such cases the requirements for electrode position and tap-changing control extend to the refining phase. At the end of the melt-down period, a sample of the molten steel is analysed, following which oxygen is blown into the furnace via a lance pushed through a hole in the furnace sidewall, and bagged alloys are thrown in through the front service doors, with the aim of producing steel of the required specification. The correct temperature must be maintained during this refining process, with the necessary amount of heat being supplied both by the exothermic reaction of the oxygen and also by suitable choice of voltage tap for the electrical power supplied.

At the conclusion of the refining period in the arc furnace, the furnace is tilted backwards and steel is poured from the furnace at the tapping launder into pre-heated ladles. From here it is either teemed into ingots or fed into continuous casting plant.

Where a digital computer is available, this can be readily applied to electrode position control and voltage-tap control. A further task which naturally falls to a melting shop computer is least cost mix calculation. This consists of choosing the optimal mix of raw materials to produce a given steel specification[3,4]. Information on weight and bulk density of raw materials charged can be readily integrated with adaptive control of the tap-changing sequence[5].

Computers can also be used to advantage in calculating the optimum addition of alloys to make following initial melt-out analysis[6], particularly where this analysis function is also computerised[7]. Computers also provide a 'get-out' clause in the form of cast-rescheduling, where it becomes either impossible or uneconomic to refine the steel to the required specification because of some mistake in the constitution of the raw material loaded into the furnace. In this case, the computer scans the order book looking for a suitable alternative cast to make[8].

The other common control function of the process computer in melting shops is maximum demand control. A single electric arc furnace imposes a large load on the electrical supply grid system, matching the domestic power needs of a large city in fact. Special tariffs are agreed with the supply authorities for the power consumed by arc furnaces, which generally give a very favourable price per unit, but which have a penalty clause setting a very high cost per unit during notified periods of high power demand. In this way, the electrical supply authorities impose a soft constraint on power usage, allowing them to cope with periods of high demand such as cold spells in winter by causing arc furnaces to be shut down. It is totally uneconomic to produce steel during such 'maximum demand' periods, but power remains available for emergency and safety reasons. Maximum demand control is an obvious application for direct digital control and this has been well discussed in technical publications[3,9].

The fundamental concepts of arc furnace structure have remained largely unchanged since top-charged furnaces were first introduced around 1920 (earlier furnaces having been charged via the front service doors). However, a succession of design modifications over the years have resulted in improvements such as reduction of electrode and refractory consumption and general control melioration through the application of computers.

One particularly important recent development has been the introduction of water-cooled refractory walls and roofs. These consist of water-cooled steel panels lined with refractory material, and they have brought about a typical saving of 50% in refractory material costs[10]. A reduction of 50% in electrode consumption through the use of water-cooled walls has also been reported[11], attributable to the reduction in temperature of the furnace atmosphere. These savings are offset to a small extent by an increase in electricity input requirements to match the energy loss in the cooling panels.

A further recent trend has been a significant increase in the use of sponge iron pellets at installations around the world[12,13]. The extent of use of these is greatly influenced by the relative availabilities of sponge iron and steel scrap, and this factor often dominates over strict economic considerations. Sponge iron (otherwise known as pre-reduced or direct-reduced iron) is produced either in a blast furnace or in a purpose built direct-reduction plant, by the reaction of iron ore with carbon, carbon monoxide or hydrogen. Iron pellets are not normally used by themselves, because in a cold furnace problems arise through the pellets sticking to the furnace sidewalls. The usual practice is to use scrap for 25-50% of the charge: this is first melted to a molten pool into which the iron pellets are subsequently continuously charged.

Sponge iron is more expensive than steel scrap as a raw material but its use leads to several savings in production costs. The avoidance of an irregular scrap raw-material surface during much of the process leads to improvements in power utilisation efficiency and a reduction in incidence of electrode breakages. Continuous charging of iron pellets saves downtime for raw material loading and also saves on charge handling costs. As the composition of sponge iron is accurately known, metallurgical control is easier. A further benefit of using sponge iron is a reduction in furnace noise of 10-15 dB.

2. Electrode Position Controllers

When raw materials containing steel scrap are charged into a furnace, the solid surface of the scrap forms an uneven surface with random contours. As parts of the scrap are melted by the electric arc, holes are bored into the scrap as the surface level immediately beneath the electrode falls. From time to time, the sides of these holes suddenly cave in and are filled by solid scrap, thus abruptly reducing the arc length. Such movements of the surface contours of the scrap also sometimes bring about step increases in arc length, as scrap falls away from beneath an electrode, generally because of the melting action of other electrodes.

The melting phase is therefore characterised by a succession of random step changes in arc length occurring at random points in time. Power utilisation efficiency in the arc furnace is dependent on maintenance of the arc length at a set value however, as maximum power only occurs for a particular value of arc current and either increase or decrease in current from this level causes a decrease in arc power. In order to maximise power input efficiency therefore, such disturbances must be corrected in the shortest possible time. This task is assigned to the electrode position controller, which drives the electrode up or down in response to a change in scrap position, to restore the arc length to its set point.

The earliest electrode position controllers used relays and contactors to apply power to the electrode drive system. Such bang-bang controllers have survived to the present day in some small furnace installations. The second generation of controllers used rotating machine amplifiers such as Ward-Leonard sets to apply a voltage proportional to the error signal to the electrode drive system. Whilst these are no longer chosen for new furnace installations, such systems are still widely used. The newest generation of controllers now employ sold-state amplifiers to apply arc length error signals to the electrode drive mechanism.

Certain constraints have to be applied to the operation of the electrode controller such that electrode acceleration is insufficient to cause the electrode to overshoot its required position excessively. Overshoot in a downwards direction can cause electrode breakage if the electrode hits solid scrap, or injection of carbon into the steel in the case of a molten bath. Overshoot in the upwards direction causes extreme refractory wear through its exposure to arc flare. Electrode acceleration also has to be limited to avoid stresses due to high acceleration which weaken and eventually break electrodes. It is particularly important that the control system has the capability of adapting to the large changes which can occur in the characteristics of the electric arc because of random changes in arc plasma ionisation. Constraints also apply to the resonant frequency of the control system which should be much less than the natural frequency of the oscillatory, cantilever-like structure of the mast supporting the electrode and power supply conductors. This is because oscillations of the electrode are reflected back onto the grid system, causing greatly annoying lighting flicker.

Whilst the purpose of electrode position control is maintenance of the arc length at a set value, it is impossible to measure the arc length directly in a production situation, and so a signal proportional to arc length must be derived from variables which are measurable. The most common method employed is to constitute an error signal as the difference of two signals proportional to arc voltage and current, such that when the arc voltage and current have values corresponding to the correct arc length, the error signal is zero. Any change in arc length away from the set point results in either increased arc voltage and decreased arc current or vice-versa, resulting in both cases in a non-zero error signal.

This technique of using voltage and current signals is known as impedance control and is by far the most common method found in arc furnace installations. The major alternative is current control, using an error signal proportional to arc current. Current control offers faster and more accurate control action than impedance control but is not commonly used because of certain practical operational difficulties[14]. A further alternative to impedance control, of a control signal derived from arc voltage, arc current and power factor measurements, has been proposed[15].

Discussion so far has centred on the derivation of a control signal proportional to arc length error, and on the choice for amplification of this error signal. The amplified error signal is applied to an electrode drive system which moves the electrode following changes in scrap position, thereby keeping the arc length constant. Both hydraulic and electromechanical forms of electrode drive system exist and the choice between these classes of system depends very much on the weighting attached to the various advantages and disadvantages of each type.

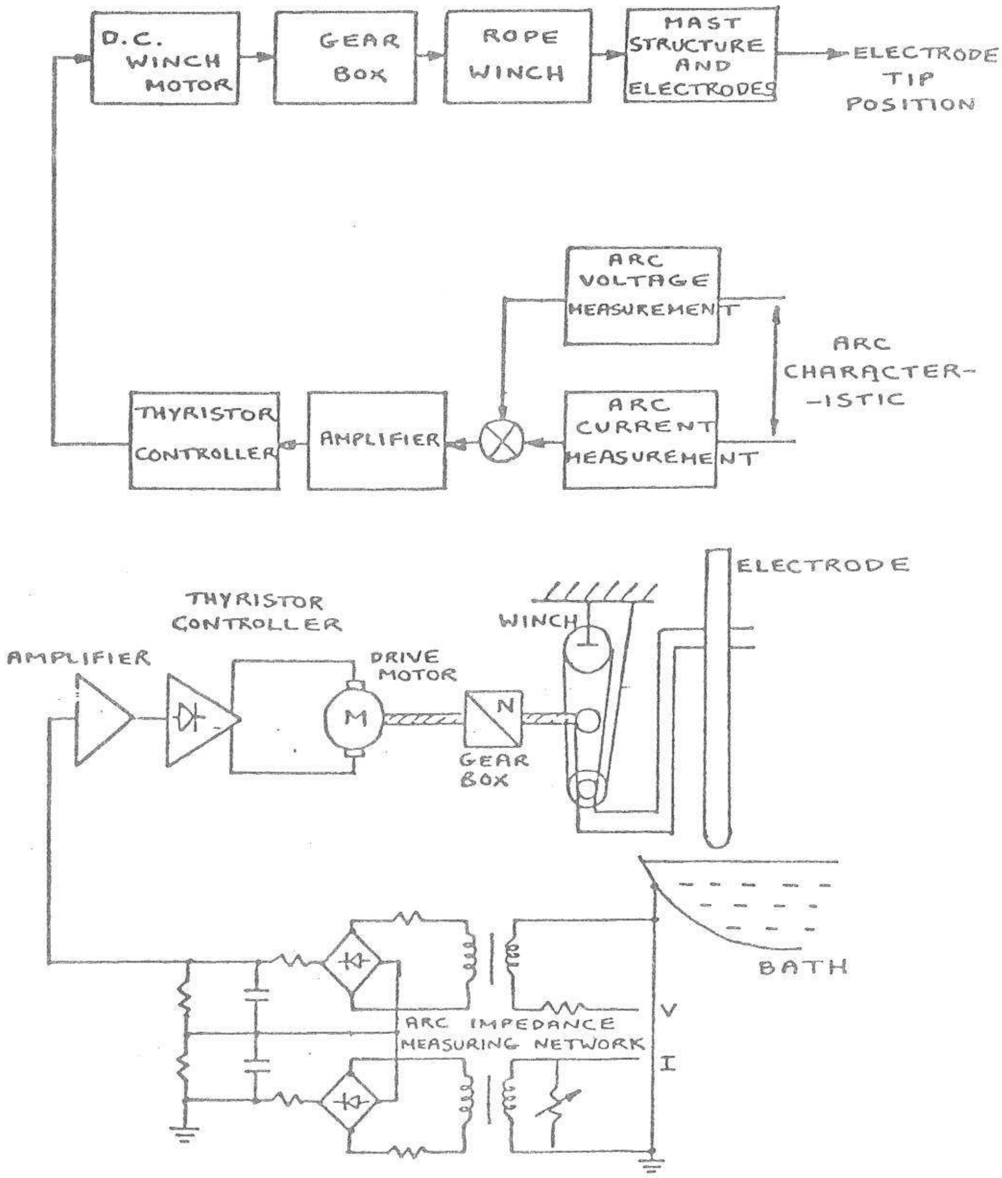
In the hydraulic system, the amplified arc length error signal is applied to a valve, which varies hydraulic pressure and drives the electrode-carrying mast directly. Whilst the small time constant of a hydraulic system potentially makes this a fast-response electrode drive, constraints often have to be placed on system acceleration for reasons explained earlier. A disadvantage of hydraulic systems is their high maintenance requirements through proneness to leaks, and a gradual deterioration in performance as uncorrected hydraulic leaks develop.

Electromechanical systems consist of an electric motor driving the mast indirectly through a gearbox and rope winch system. Pneumatic counterbalancing of the mast weight is often employed, so that the motor only has to provide sufficient power to accelerate the mast, i.e. not to support its mass as well. Both A.C. and D.C. drives are found in electromechanical systems. Whilst electromechanical systems have significantly larger time constants than hydraulic drives and hence give relatively slower control action, they have less maintenance problems and less drift in their performance characteristics.

A more thorough discussion of the range of electrode drive systems in use and the arguments in favour of each is to be found in reference 16. An understanding of the principles of operation of electrode controllers can be gained by consideration of the common system shown in Fig. 2. This is an impedance control system in which the arc length error signal is derived as a function of arc current and voltage measurements.

The arc length error signal is amplified by a phase-controlled thyristor amplifier which powers a d.c. motor. In steady-state, sufficient power is applied to the motor to support the mast weight by the motor's stalled torque. In response to an error in arc length, this mean power level is either increased or decreased to drive the electrode-carrying mast up or down via reduction gearing and a rope winch system. The control loop is closed by the electric arc. A critical feature in the design of this type of system in minimisation of gear backlash by using a rack type of gear and by carefully finishing the gear teeth. The major maintenance requirement of this type of system is the motor commutator.

The control system described above is known as a proportional control system, where the signal applied to the thyristor amplifier and motor is proportional to the error in arc length. This is by far the most prevalent system found in electrode control systems but has the disadvantage of giving an oscillatory response where the electrode overshoots its



A direct-haul d.c. motor driven electrode position controller

FIG 2

required position before settling down. Much improved controller performance can be achieved by using a three-term controller where the control signal is composed of proportional, integral and derivative of arc length error terms. This is particularly easy to implement in a digital controller.

3. Direct digital control

The availability of fast, inexpensive digital process computers is being used to great benefit in many furnace installations. The extent to which computers are now used and the control aspects to which they are applied varies widely, being affected by the age of existing plant, its suitability for computer implementation and the attitude of employers and employees to computerisation. The control aspects to which computers can be applied have already been mentioned and are discussed in more detail below.

3.1 Electrode position control

In digital control of electrode position, the analogue derived arc length error signal is sampled at discrete intervals of time and the necessary control input to the electrode drive system calculated. Proportional control is the simplest algorithm to implement, being expressed simply as

$$u_n = K_p e_n$$

where u_n, e_n are the control input and arc length error signals at the nth sampling interval and K_p is the proportional gain constant.

A digital three-term controller is more complicated, the general form of the algorithm being

$$u_n = K_p e_n + \frac{K_d}{\Delta t}(e_n - e_{n-1}) + K_i \Delta t \sum_{r=o}^{n} e(n-r)$$

where u_n, e_n, K_p are as before

Δt is the sampling interval

K_d, K_i are the derivative and integral gain constants

Fig. 3 shows the simulated response of digital proportional and three term controllers to a step change in scrap level with both controllers set to give the same response time. The superiority of the three term controller in terms of its suppression of electrode oscillation is evident.

3.2 Maximum demand control

Maximum demand control entails monitoring the operating power level of the furnace and shutting the furnace down, if safety factors permit, whenever the power level exceeds a special 'maximum demand' level set by the power supply authorities. This 'maximum demand' level is set by the supply authorites to enable them to cope with periods of high general power usage, such as cold spells in winter. The financial penalty imposed if the maximum demand power level is exceeded during these periods is so severe that it is prudent to assign this control task to a computer lest human error should allow furnaces to continue operating.

3.3 Least cost mix calculation

Least cost mix calculation involves the selection of the optimum weights of alternative raw materials which will produce the required specification of steel for the lowest cost.

If n raw materials are available, and are assigned code numbers 1,2...n, then the problem can be expressed as minimising a cost function J given by[4]

$$J = \sum_{i=1}^{n} c_i x_i$$

subject to the following constraint applied separately to each chemical element required in the target steel specification:

$$p_{min} W \leq \sum_{i=1}^{n} p_i x_i \leq p_{max} W$$

where c_i is price per kg. of raw material i

x_i is weight used of raw material i

p_i is the percentage of the chemical element in raw material i

p_{min}, p_{max} are the minimum and maximum limits of the chemical element in the target steel specification

and
$$W = \sum_{i=1}^{n} x_i$$

A similar algorithm can be applied to calculate the optimum alloy additions to make to bring the steel exactly to the correct specification following melt-out analysis at the end of the melting-drum phase of operation.

3.4 Energy input control

Energy input control embodies a philosophy of minimising the total production cost per tonne of steel, where cost is expressed as a function of energy costs, refractory costs, electrode costs and time.

A prerequisite for energy input control is knowledge of the weight and bulk density of raw material charged to the furnace. The control computer is then able to calculate the energy input necessary to melt the raw material and bring the steel to the required temperature. This calculation is based on a thermal model of the furnace. The correct balance between heat supplied electrically and heat arising from the exothermic reactions due to oxygen injection is derived using a metallurgical process model.

Electrical power input is subject to constraints on refractory and electrode erosion. The optimal power input level at various stages of the melt is usually calculated taking account of a refractory wear index due to Schwabe[17], which relates refractory wear to arc voltage, arc current and arc length. Electrode erosion is a function of furnace atmosphere temperature[18], and hence of power input level, but is frequently ignored in calculating input energy levels as the time-cost penalties of operating at low power levels to reduce electrode consumption outweigh the savings achieved in electrode costs.

The furnace transformer offers multiple voltage-tap settings. A particular arc length, maintained by the electrode controller, is associated with each setting. Immediately following the charging of new raw material to the furnace, a medium voltage, short arc-length transformer tap is used, minimising damage to the furnace roof through arc flare. After a short while, when holes have been bored into the raw material, a high voltage, long arc-length tap is used. Later, during refining phases of operation, low to medium voltage, about arc-length voltage taps are used.

The control computer uses knowledge of the raw material input to calculate a schedule of automatic voltage tap changes. It also uses this information to calculate when the raw material will be sufficiently melted, and can thus instruct the furnace operator when to load the next charge of raw material. In a similar fashion, it is able to guide the operator about the correct time to sample the steel to obtain a melt-out analysis. Following this, it calculates the best power input program to melt alloys added following the melt out analysis and bring the steel to the required temperature.

3.5 Cast rescheduling

The discussion so far has assumed raw materials of constant, known composition. However, the assumed composition of raw materials can vary both because of human error in analysis and because of unrepresentative samples being analysed. At the time of melt-out analysis during the steelmaking process the predicted and actual steel composition will vary, and sometimes it may be uneconomic, or even impossible, to bring the steel to the required specification. In such cases, the computer is usefully employed to scan the order book and select a suitable alternative cast to make where the target specification sufficiently matches the melt out analysis, a procedure known as cast-rescheduling.

4. Summary and future trends

The areas of recent change in electric arc furnace design and operational practice have been presented. The most important developments have been the provision of water-cooled walls and roofs, the increased use of iron pellets in the raw material charge, the use of sold-state devices in electrode drive systems and the application of digital control.

Future developments are likely to be based on the integration of computer control of the separate aspects of arc furnace operation into an optimal direct digital control strategy for the furnace, minimising steel production costs using a cost function based on raw material and energy costs, refractory and electrode consumption, and furnace time. D.C. plasma torches may also soon emerge as a viable alternative to the A.C. electric arc as an energy source. Potential advantages of these include reduced energy costs, use of non-consumable electrodes, and non-contamination of steel by electrodes. An operational 40 tonne D.C. plasma torch furnace in East Germany has been reported[1].

5. References

1. SHARP, J.D. 'The role of the electric arc furnace in the 1980's' Proc. electric arc steelmaking conf., Sheffield, England, 1979, Inst. of Metallurgists, pp. 1-12.

2. MOORE, C. and MARSHALL, R.I. 'Modern steelmaking methods', Inst. of Metallurgists, Monograph No. 6, 1980.

3. GIFFORD, J.D., MORRIS, A.S. and ROEBUCK, R. 'Arc furnace controls in the electric melting shop', Fourth Special Steels Division Steelmaker's Conf. (British Steel Coropration), Harrogate, England, 1972.

4. CUSSON, J.G. 'Computerised charge calculations at Dominion Engineering Works Ltd.' Elec. Furnace Proc. (AIME), 36, 1978, pp. 184-193

5. GILL, L.L. 'Operational aspects of arc-furnace computer control' Ironmaking and Steelmaking, 5(5), 1978, pp. 217-223.

6. BRANDT, S. 'Automation of Electric Arc Furnaces', AEG - Telefunken Progress, 2, 1977, pp. 42-5.

7. PALMER, L.W. 'Automation of Polyvac Melt Analysis', Iron and Steel International, 51(6), 1978, pp. 363-372.

8. MENON, U. 'Computer control of arc furnace operations' Fourth Special Steels Division Steelmaker's Conf. (British Steel Corporation), Harrogate, England 1972.

9. JONES, D.R. and MONTIETH, W.F. 'Arc furnace power demand control', Electric Furnace Proc. (AIME), 29, 1971, pp. 187-194.

10. PARKIN, B and SLVITER, G.T. 'Water-cooled panels and their influence on manufacturing costs and furnace life', Proc. electric arc steelmaking conf.,Sheffield, England, 1979, Inst. of Metallurgists, pp. 49-56.

11. STROHMEIER, B. 'Operation of UHP arc furnaces 'Electric furnace Proc. (AIME), 39, 1981, pp. 156-167.

12. BROWN, J.W. and REDDY, R.L. 'Electric arc steelmaking with sponge iron' Ironmaking and Steelmaking, 6(1), 1979, pp. 24-31.

13. TURCOTTE, S.F. et al 'The use of direct reduced iron in the electric arc furnace', Iron and Steelmaker, 7 (11), 1980, pp. 16-27.

14. MORRIS, A.S. 'Design and performance optimisation of an electric arc furnace electrode position controller', Ph.D.Thesis, University of Sheffield, 1978.

15. LUBBECK, W. 'Specifying regulating equipment for high powered automatic arc furnace operation' Electric Furnace Proc. (AIME), 38, 1980, pp. 270-273.

16. MORRIS, A.S. and STERLING, M.J.H. 'Analysis of electrode position controllers for electric arc steelmaking furnaces', Iron and Steel International, 48(4), 1975, pp. 291-298.

17. SCHWABE, W.E. 'Arc heat transfer and refractory erosion in the electric steel furnace', Proc. Electric Furnace Conf. (AIME), 1962, pp. 195-206.

18. SCHWABE, W.E. 'The mechanics of consumption of graphite electrodes in electric steel furnaces', Journal of Metals, 1975, pp. 65-71.