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ESR MELTING UNDER CONSTANT VOLTAGE CONDITIONS

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ABSTRACT

Typical industrial ESR melting practice includes operation at a constant current. This constant current operation is achieved through the use of a power supply whose output provides this constant current characteristic. Analysis of this melting mode indicates that the ESR process under conditions of constant current is inherently unstable. Analysis also indicates that ESR melting under the condition of a constant applied voltage yields a process which is inherently stable. This paper reviews the process stability arguments for both constant current and constant voltage operation. Explanations are given as to why there is a difference between the two modes of operation. Finally, constant voltage process considerations such as melt rate control, response to electrode anomalies and impact on solidification will be discussed.

Introduction

Electro Slag Remelting (ESR) is a consumable electrode process that is regularly used to produce various steels and nickel based products. ESR has the ability to readily produce ingots in either round or slab configurations. In addition, inherent to the process are chemical, electrochemical and gravimetric refinement mechanisms[1]. It is for these reason that ESR is a process which enjoys widespread utilization throughout the world.

Typically the ESR process utilizes a single electrode which is melted to form the final ingot. During steady state operation, the electrode is immersed in a pool of molten flux or slag. This slag is contained within a water cooled copper mold, and floats on top of the forming ingot, Figure 1. An AC current is passed from the electrode, through the slag, into the solidifying ingot and out the base plate. The molten slag, usually a mixture of calcium fluoride, calcium oxide and alumina, has a high resistivity such that the resistance of the slag cap is much higher than the combined impedance of the metal electrode, the ingot and the power delivery system. A consequence of the high resistance of the slag cap is that the majority of the real component of the system impedance is the slag cap resistance. As a result, the slag cap is the location where most of the power in the system is dissipated. The I^2R heating which occurs within the slag cap raises the temperature of the slag cap above the melting point of the electrode, and as a consequence, the electrode melts. The melting electrode coalesces into drops, which then leave the electrode, fall through the slag cap and form an ingot at the bottom of the crucible. As the electrode melts, the ingot grows until such time as the electrode is completely consumed.

Within the ESR process, several refinement processes are active[2]. The electrode and ingot pool surfaces are sites where electrochemical purification can occur. Mechanical or gravimetric separation of low density inclusions (such as a ceramics) occurs, as does chemical purification of the droplets as they pass through the slag. Additionally the process produces a homogenous ingot, typically free of significant porosity.

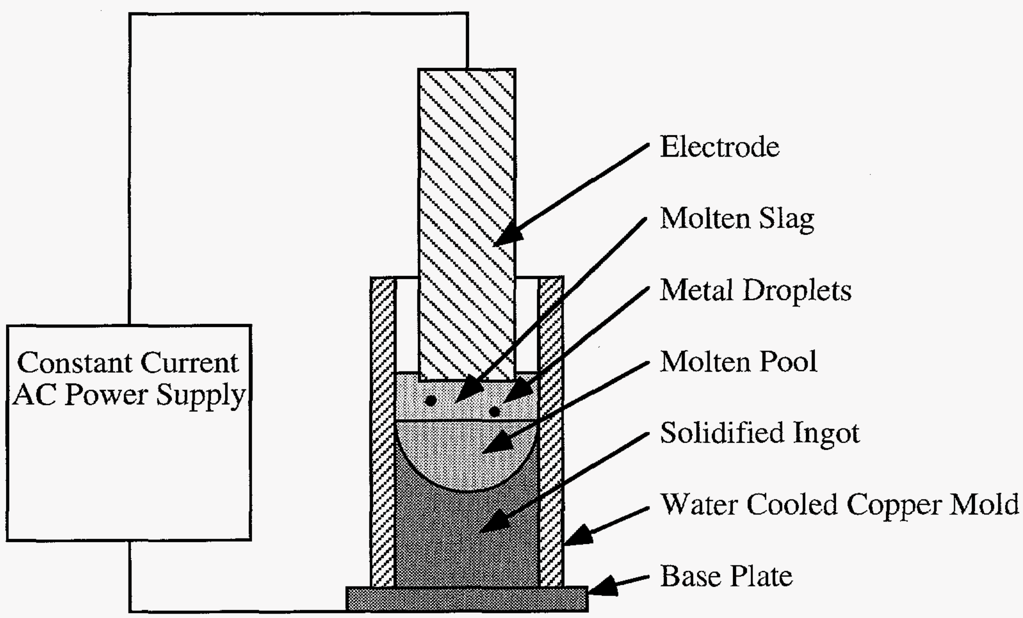

Figure 1
ESR Furnace Schematic

The primary process quantities used in ESR control schemes are voltage, current and electrode weight (melt rate), and electrode position or velocity. The current is typically an applied quantity which is held essentially constant[3] by means of the power supply. The voltage or electrode voltage, is the product of the applied current and the slag resistance and may be considered a result of Ohms Law (Equation 1). The electrode weight is monitored via a system of load cells and is converted to a melt rate. The electrode position or velocity is used in the electrode feed servo system.

$$V = I\ R$$
$$P = V\ I \tag{1}$$

where V = Electrode Voltage, I = Applied Current, R = Slag Cap Resistance & P = Power

Typical ESR Control

In operation, two control loops are used. The first loop is used to control the melt rate. Melt rate control is accomplished by comparing the time rate of change of the electrode weight to a desired melt rate and then adjusting the applied current accordingly. Melt rate control is complicated by buoyancy effects which occur as a result of immersion of the electrode into the slag and apparent melt rate perturbations are in fact caused by variations in electrode immersion depth. Melt rate control is most often addressed as being fully de-coupled from the electrode positioning.

The second loop controls electrode feed. The goal of this control loop is to maintain the electrode at a constant immersion depth within the slag. Typically, a shallow immersion provides better ingot surface quality and as a result, the immersion depth is usually under 25 mm. This control is accomplished by servoing the electrode to maintain a constant electrode voltage. This is termed a "Voltage Error" loop. If the voltage is too high, the electrode is driven down. This electrode motion decreases the distance between the electrode and the ingot, (while increasing the volume of slag in the annulus), thereby shortening the distance current must pass through the molten slag on its path to the ingot. The shorter distance translates directly to a smaller slag resistance, and since the current is held constant by the power supply, the voltage decreases. The target voltage, or voltage set point is automatically chosen to maintain a constant level of swing. Voltage swing is the short term, (on the order of seconds), variation in the electrode voltage which occurs as a result of the servo action of the electrode. At shallow immersions, the system resistance does not behave in a linear fashion, with the time averaged resistance gradient increasing dramatically as the immersion decreases. Since the measured voltage is the product of the applied current and the resistance of the slag, the non-linearity in resistance with immersion depth results in a non-linear voltage response to changes in electrode position. This non-linearity couples with the tuning of the servo mechanism and the resulting instability can be a major component of the voltage swing. It is important to note that swing signals may be significantly affected by the tuning of the voltage error control electronics and by the electromechanical response of different furnaces. Therefore, depending on these parameters, the swing signal measured may actually represent differing immersion depths. As a result, process repeatability from furnace to furnace can be difficult to achieve.

A change in current which may occur as a result of the action of the melt rate control loop will interact with the electrode, at its present immersion depth, to change the voltage at the electrode. As an example, if the applied current is instantaneously increased, the electrode voltage will also increase. However, this change in the electrode voltage, will be counteracted by the electrode voltage error positioning loop. The action taken by this loop will be a an increase in electrode immersion, effectively lowering the resistance and thereby maintaining a constant voltage. This increase in immersion can only occur if slag is displaced into the annulus between the electrode and the crucible and as a consequence, the apparent electrode weight will decrease by the weight of the volume of slag so displaced. This change will appear to be an instantaneous increase in melt rate.

Clearly the action of the melt rate controller and the voltage error loop are coupled. In fact there are even further complications. The increase in immersion depth which occurred as a result of the increase in current, will decrease the swing level in the voltage. The swing controller will respond to the decrease in the swing level by increasing the voltage set point, driving the process back towards a shallow immersion. However, the action of the swing controller is necessarily slow. The resultant gradual decrease in immersion depth adds a gradually increasing component of electrode weight, and as such the calculated melt rate will be too small until such time as the appropriate immersion depth has been achieved. It is the coupled action of these control loops that is largely responsible for the complexity of the ESR control task.

Process Stability Under Constant Current Conditions

There is another factor of potential significance that is masked by the action of the electrode servo mechanism, and may be an additional factor in the generation of voltage swing. In short, analysis of the melting environment yields the result that the ESR process is inherently unstable. This can be demonstrated as follows:

Let equation (2) describe the gap (g). This equation then states that the gap is equivalent to the previous gap plus the difference between the melt rate 'M' and the feed rate 'F' multiplied by the time increment. The constant K takes into account the electrode and ingot diameters and the difference between them.

$$g_{i+1} = g_i + (M - F)K\Delta t \quad (2)$$

Conceptually this is understood by noting that if the melt rate exceeds the feed rate the gap increases, whereas if the feed rate exceeds the melt rate, the converse holds true. Additionally, it may be stated that to a first order approximation, the melt rate is proportional to the power input. From (1), this relationship is expressed as:

$$M = A\,V\,I \quad (3)$$

Where 'A' is a proportionality constant. If, as is typical, a constant current power supply is used, then regardless of the load, the current will be maintained at a constant value. Under these conditions, the electrode voltage is the product of the slag resistance and the applied current, (4).

$$V = I\,R \quad (4)$$

For the sake of simplicity, it is assumed that the resistance 'R' is a linear function of the gap between the electrode and the ingot. This is expressed in (5) with a proportionality constant 'B' taking into account the resistivity and furnace geometry.

$$R = B\,g \quad (5)$$

Combining equations (4) & (5) then substituting into (3) provides an expression for the melt rate as a function of electrode voltage and gap:

$$M = A\,B\,I^2\,g \quad (6)$$

Utilizing (6) in the expression for gap of (2), yields a difference equation for the gap that is expressed in terms of the starting gap, the applied current and the feed rate:

$$g_{i+1} = g_i + \left(A\,B\,I^2\,g_i - F\right)K\,\Delta t \quad (7)$$

Although this is in effect the same equation as (2), the system dynamics are more readily visualized in (7). For instance, assume a solid electrode is being fed into the slag at a constant feed rate. Further, assume that neither the crucible or electrode is tapered. If the melt rate matches the feed rate, then the gap will remain constant. This balance between electrode feed and electrode melting will, under these conditions, manifest itself as constant gap between the electrode and ingot. However, equation seven is of the form of a feedback expression where the result is based upon the sum of two terms: 1) an initial state g_i, and 2) a correction term $(ABI^2g_i-F)K\Delta t$. When considered in this fashion, it is observed that from a gap control viewpoint, the system exhibits positive feedback and hence is inherently unstable. As such any deviation from the balance between electrode feed and melting will result in a subsequent amplification of that deviation. This is illustrated by the following example.

Given the above described equilibrium condition, assume that a small perturbation is experienced which results in an increase in the gap. Since the resistance of the system is proportional to the gap, the resistance will increase. Further, because the power is I^2R, and the power is proportional to the melt rate, the power and melt rate both goes increase (see equation (6)) as a result of the slight increase in gap. At this juncture, the melt rate is greater then the feed rate and the electrode is melting off faster than it is being fed into the slag. The gap therefore continues to increase, increasing the melt rate, which increases the gap ad infinitum. Ultimately this situation will continue until the electrode pulls completely out of the slag. Conversely, if the gap becomes a bit too small, the power will decrease, the melt rate will decrease, the gap will decrease and the electrode will eventually collide with the ingot.

This behavior is a direct result of the constant current characteristic of the typical ESR power supply. Constant current operation is a hold over from the days when electronic control was difficult. As such ESR power supplies are AC saturable reactor devices which are inherently constant current devices. Power supplies of this sort are often operated in an open loop fashion where the saturating current is set and no response is taken to minor variations in the output current.. However, modern electronics and controls provide an opportunity for other power supply configurations. Specifically, it may be shown that the application of a constant voltage eliminates the above described inherent instability.

Process Stability Under Constant Voltage Conditions

With modern power supply control electronics, the ESR process may also be operated under conditions of constant voltage. In this case, the power supply is operated in a closed loop fashion that maintains the output voltage at a constant value. It should be noted that a power supply that provides an "approximately" constant voltage may not be sufficient. When an ESR furnace is operated under constant voltage conditions, the current must necessarily fluctuate as the load varies. From Ohm's Law (1), this may be expressed as:

$$I = \frac{V}{Z} \tag{8}$$

When (8) the equation for current, is combined with (5) the expression for resistance and substituted into (6) the equation for melt rate, the results is:

$$M = \frac{A\,V^2}{B\,g} \tag{9}$$

This melt rate expression may be substituted into (2), the gap expression to reveal the difference equation for the gap under constant voltage conditions:

$$g_{i+1} = g_i + \left(\frac{A\,V^2}{B\,g_i} - F \right) K\,\Delta t \tag{10}$$

Examination of (10), which describes gap dynamics under constant voltage conditions, reveals a very different behavior than the expression for constant current, (7). From (10), it may be seen that the correction term now applies a negative feedback and therefore the system will be stable. This is understood by examining (9), the expression for melt rate. In (9), it may be seen that an increase in the gap causes a decrease in melt rate. Since melt rate is a direct result of electrode consumption, then the greater the gap, the lower the rate of electrode consumption. Keeping this in mind, examination of (10) reveals that the automatic response of the system to an increase in the gap is a reduction in the melt rate. This melt rate reduction drives the electrode gap back to the equilibrium condition. Conversely, if the electrode is driven deep into the slag, melt rate will automatically increase in an effort to regain equilibrium. As the equilibrium point is approached, the consequential behavior is one in which the melt rate is gradually reduced until the equilibrium melt rate, and gap, have been re-established. An interesting aspect of constant voltage operation occurs in the case where the feed rate is dropped to zero. In such a situation, melting slows as the power supply phases back to maintain a constant voltage under conditions of increasing resistance. Eventually, the electrode melts out of the slag, at which time the applied power is effectively zero.

Constant Voltage Operating Characteristics

Functionally, constant voltage operation has some differences when contrasted to constant current in that voltage and electrode feed rate are specified while the current varies. As in the case of constant current, the operating voltage sets the immersion depth. However, under constant voltage conditions, the voltage is maintained by the power supply. The other difference is that the melt rate is no longer a function of the applied current, rather, it is solely a function of the electrode feed rate. Hence, under constant voltage melting, the voltage and feed rate are set. As long as the electrode is fed into the slag at a constant mass per unit time, the electrode gap will tend towards stability.

In production, the voltage set point may need to be adjusted as slag is lost to the slag skin and the slag chemistry changes. However, the necessary changes are small and occur over extended periods of time, and may, depending on process requirements, be neglected. It should be noted that experiments have shown that the tendency towards self stabilization, coupled with the constant electrode velocity enable operation at shallower immersion depths than are typically achievable with standard voltage error controllers.

By operating the furnace in a regime where the immersion depth is maintained as a consequence of the process, without external intervention, constant voltage operation effectively de-couples the melting response of the system from the electromechanical response. As a result, furnace to furnace repeatability is enhanced.

CV Response to Electrode Anomalies

This is not to imply that all process variability problems have been addressed. In particular, and unlike constant current operation, electrode pipe represents a challenge. Under constant current conditions, the system responds to pipe with an increase in the feed rate, a direct consequence of the action of the voltage error controller. Under constant voltage conditions, the system responds to pipe with a decrease in melt rate, thus stabilizing the gap. Clearly the natural response of the system is not optimum. However, a combination of feedback signals derived from both the load cells and the melting current can be used to effectively detect and respond to electrode pipe. On the other hand, a constant voltage system will not be effected by an electrode crack.

Under constant current conditions, an electrode crack behaves as a barrier for thermal diffusion. This results in less heat being conducted up and out of the electrode. As a consequence, the ESR furnace becomes more efficient. Since, in effect, the power in a constant current system is maintained at a constant value, the result of a crack is an increase in the melt rate. The melt rate controller may respond to this by decreasing the current. This action exacerbates the situation which occurs when the crack melts past and the system must contend with a cold electrode. However, under CV conditions, the same amount of metal is continuously fed into the system per unit time. The system then automatically adjust itself to maintain an equilibrium melt rate.

Current Fluctuations Under CV Conditions

ESR melting under constant voltage conditions has an inherent characteristic that may be of some concern. Since both the electrode feed rate and the electrode voltage are held constant, naturally occurring process fluctuations must manifest themselves in the remaining process characteristics. Under such conditions there is but one degree of freedom and that is associated with the melting current. As a result, variations which drive the melting process away from steady state, and the consequential restorative action imposed by the system, manifest themselves as fluctuations in current. Such current fluctuations have been a cause for concern in that it has been conjectured that associated with these fluctuations there should be a change in the Lorentz forces. However, unpublished modeling efforts have shown that in the absence of slag skin breakouts, Lorentz forces are negligible. Further, it has be shown that the process perturbations associated with such breakouts are perhaps of greater concern. Sectioning of a full sized ingot of alloy 625 has not shown any deleterious effects of constant voltage melting.

Summary

It has been shown that ESR melting under conditions of constant current is an inherently unstable process, and that operation of this process under constant voltage conditions results in a process that is inherently stable. Constant voltage ESR has been demonstrated at three industrial sites, utilizing a variety of slags and melting a number of different alloys. To date, more than 40 melts have been conducted under constant voltage conditions. The process has been successfully demonstrated for both round and slab configurations. Round ingots have been produced in sizes ranging from 2.5 inches up to 22 inches in diameter. Slabs have been produced in thicknesses ranging from 4 x 16 inches up to 20 x 53 inches. Good ingot surfaces have been achieved and the ability to operate in a stable fashion at extremely shallow, and previously unobtainable, immersion depths has been demonstrated.

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References

1 Buckentin, Joanna, M., Melt Decontamination of Radioactive Stainless Steel by Electroslag Remelting, Ph.D. Thesis, Oregon Graduate Institute of Science and Technology, Beaverton OR, (1996)

2 Turkdogan, E.T., Physicochemical Properties of Molten Slags and Glasses, pp. 460-473, The Metals Society, London, (1983)

3 Duckworth, W.E. and Hoyle, G., Electro-slag Refining, pp. 96-97, Chapman and Hall ltd., London, (1969)

4 US Patent[4] # 5568506, Constant Voltage Electroslag Remelting Control, issued Oct. 22, 1996