Modern Control Strategies for Vacuum Arc Remelting of Segregation Sensitive Alloys

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Abstract

There are several process variables which are crucial to the control of vacuum arc remelting of segregation sensitive alloys. These are: electrode gap, melt rate, cooling rate, furnace annulus, furnace atmosphere and electrode quality (i.e. cleanliness and integrity). Of these variables, active, closed loop control is usually applied only to electrode gap. Other variables are controlled by controlling furnace operational parameters to preset schedules (e.g. melting current is ramped or held constant to control melt rate in an open loop fashion), through proper maintenance and calibration of equipment (e.g. to ensure proper cooling water and gas flow rates, or to accomplish an acceptable vacuum leak rate), through proper practice of procedures, and by maintaining electrode quality control. Electrode gap control is accomplished by controlling an electrode gap indicator such as drip-short frequency (or period) to a specified set-point. This type of control, though often adequate, ignores information available from other electrode gap indicators and is susceptible to upsets. A multiple input electrode gap controller is described which uses optimal estimation techniques to address this problem.

Introduction

Vacuum arc remelting (VAR) is a process used to control the solidification of segregation sensitive alloys. A simplified schematic of the process is shown in Figure 1. A cylindrically shaped, alloy electrode (1) is loaded into the water-cooled, copper crucible (2) of a VAR furnace, the furnace is evacuated, and a dc arc is struck between the electrode (cathode) and some start material (e.g. metal chips) at the bottom of the crucible (anode). The arc heats both the start material and the electrode tip, eventually melting both. As the electrode tip is melted away, molten metal drips off forming an ingot (3) beneath. Because the crucible diameter is typically 50-150 mm larger than the electrode diameter, the electrode must be translated downwards toward the anode pool to keep the mean distance between the electrode tip and pool surface constant; this mean distance is called the electrode gap (g_e) (4). As the cooling water (5) extracts heat from the crucible wall, the molten metal next to the wall solidifies. At some distance below the molten pool surface, the alloy becomes completely solidified, yielding a fully dense ingot. After a sufficient period of time has elapsed, a quasi-steady-state situation evolves consisting of a "bowl" of molten metal situated on top of a fully solidified ingot base.

The success of VAR processing of segregation sensitive alloys depends on several criteria. First, the process must continually supply the advancing solidification front with liquid metal. Obviously, failure to meet this criterion results in the generation of porosity as well as segregation. Secondly, a steady-state melting environment must be provided by the process so as to establish steady-state solidification. Any abrupt variation in the solidification process that results in significant perturbation of the flow fields in the mushy zone will give rise to solute redistribution and, hence, macrosegregation.[1] The third criterion important to the success of the process has to do with establishing and maintaining an optimum pool shape. There is always a

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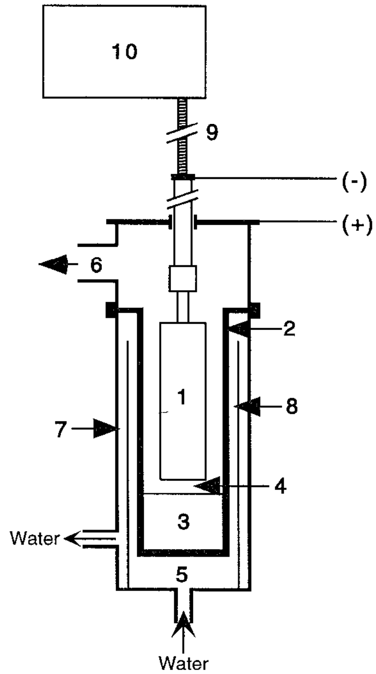

Figure 1. A simplified schematic of a VAR furnace. Key: 1) electrode; 2) copper crucible; 3) ingot; 4) electrode gap; 5) cooling water; 6) vacuum port; 7) furnace body; 8) cooling water guide; 9) ram drive screw; 10) ram drive motor assembly.

horizontal component of solidification in VAR. In regions where the local growth direction is mostly perpendicular to the ingot axis and, hence, the gravitational field, the probability of channel segregation arises.[2] This being the case, sufficient heat must be extracted from the ingot center to create and maintain a relatively shallow pool of constant depth. This places constraints on the ingot diameter and melt rate. Also, the energy input distribution on the pool surface must be such as to prevent the formation of excess shelf at the ingot/crucible interface. This requires the maintenance of a steady-state, diffuse arc, a flat electrode tip, and a minimum melt rate. Finally, there are portions of every VAR melt that are transient by nature, namely start-up and hot-top. Little is understood about how to optimize these portions of the melting process and every melt shop practices its own art. Solution of the transient problem awaits implementation of the new generation of transient VAR process codes currently being developed.

In this paper, the VAR process is discussed from a controls point of view. Specific questions of interest to the discussion are: What are the important VAR process variables and why? Which of these variables can be controlled and how? After this discussion, a modern, multi-input electrode gap control system will be described.

Important VAR Process Variables And Associated Control Issues

The process to be controlled in VAR is ingot solidification. In short, solidification must be controlled in such a way as to produce a homogeneous, fully dense ingot. There are several process variables that are of great importance in determining the state of the solidification process. They are: 1) electrode gap; 2) melt rate; 3) cooling rate; 4) furnace annulus; 5) furnace atmosphere; and 6) electrode quality. These variables affect solidification because they directly affect the flow and distribution of electrical and thermal energy in the process. They will now be briefly discussed along with the issues involved in their effective control.

Electrode gap

Electrode gap (g_e) is the average distance between the electrode tip and pool surface. If this variable becomes too large, the arc will search for a less resistive path to ground with the result that a greater percentage of the arc energy will be collected by the crucible wall above the pool surface. This gives rise to both a decrease in, and a redistribution of, the energy flux to both the electrode tip and anode pool. If the condition persists for more than a few minutes, the electrode tip will become rounded, all of the molten metal from the electrode will drip into the center of the pool, and the pool will begin to freeze in from the sides. This constitutes a severe disruption of the solidification process. If g_e becomes too small (<6 mm, which is of the same order as the amplitudes of the liquid motions on the pool and electrode tip surfaces), transient arc interruptions occur due to multiple, nearly simultaneous contacts between the electrode and ingot. This leads to decreased melt rate, process instability, and disruption of the solidification process. Process stability requires that g_e be controlled at a constant value (±1 mm) within the acceptable range. For VAR of nickel-base alloys such as Alloy 718, the acceptable range is usually considered to be 6-10 mm.

Several methods of g_e control are available. They all involve monitoring a g_e indicator and controlling the value of that indicator by adjusting ram position or speed. The most common g_e indicators are mean arc voltage ($\overline{V}_{arc}$) and mean drip-short frequency ($\bar{f}_{DS}$) or period ($1/\bar{f}_{DS}$). Some older furnaces use "hash."

Gap control based on $\overline{V}_{arc}$ is attractive because the signal is easy to collect and its response to changes in g_e is nearly linear. Generally, for small changes in g_e, the response may be approximated by[3]

$$\overline{V}_{arc} = V_0 - k_V \cdot g_e \cdot I_{melt} \qquad (1)$$

where I_{melt} is the steady-state melting current and k_V is an empirically determined "constant." Note that Eq. (1) is just Ohm's law with $R=-k_V g_e$. In applying this equation it must be remembered that k_V is actually a function of both g_e and I_{melt} and may be considered constant only for small changes in these variables. Significant changes in g_e and I_{melt} give rise to changes in the plasma density and, hence, the arc resistance.[3] The major drawback of voltage based control is that k_V is relatively small for values of I_{melt} typically used for VAR of segregation sensitive alloys, usually ~0.01 V per kA per mm for I_{melt}<10 kA. Thus, it is not a very sensitive indicator and requires extensive averaging for accurate control. As I_{melt} increases, k_V becomes larger and linearity improves. Hence, most high current VAR furnaces use voltage-based gap control. Voltage-based gap control has been practiced since the 1950's.

Most modern low current (<10 kA) VAR controllers use $\bar{f}_{DS}$ (or $1/\bar{f}_{DS}$) to control electrode gap during melting of premium grade material. Though three patents were issued in the last decade associated with various forms of drip-short control[4], the basic phenomenon was discovered in the late 1950's and a drip-short based VAR control system was patented in 1960 by Johnson.[5] The basic drip-short phenomenon has been carefully investigated[6] and will not be described in detail here. Suffice it to say that molten metal dripping from the electrode surface sometimes comes in contact with the anode pool before separating, causing a momentary arc disruption that lasts for 10^{-4}-10^{-3} seconds. There is a characteristic voltage signature associated with this phenomenon that may be easily detected allowing the average number of such interruptions per unit time ($\bar{f}_{DS}$) to be determined. $\bar{f}_{DS}$ turns out to be a very sensitive indicator of g_e at values of g_e smaller than ~10 mm and it responds on a time scale that is more than adequate. The response may be described by the following power law:[7]

$$\bar{f}_{DS} = k_{DS} \cdot g_e^{-a} \cdot I_{melt}^{-b} \qquad (2)$$

where a and b are both positive quantities. The major drawback of drip-short based control is that the response is highly non-linear and the control range very limited. Also, $\bar{f}_{DS}$ is dependent on electrode tip shape. If the tip becomes rounded, the dripping dynamics change and the process can enter a mode where $\bar{f}_{DS}$ remains constant as g_e opens.

Another means of controlling electrode gap is to adjust electrode ram speed in response to melt rate. Obviously, as melt rate increases (decreases), the electrode gap must open (close) if ram speed is not changed. The response is described by the following equation:

$$\dot{g}_e = \frac{\dot{m}}{\rho}\left(\frac{1}{A_{elec}} - \frac{1}{A_{ing}}\right) - V_{ram} \quad (3)$$

where $\dot{m}$ is the melt rate, $\dot{g}_e$ the time rate of change of g_e, V_{ram} the ram speed, ρ the material density, and A_{elec} and A_{ing} the electrode and ingot cross-sectional areas. Melt rate based control of electrode gap is not commonly used because load cell output is neither sufficiently accurate nor precise to allow for accurate calculation of $\dot{m}$. This problem may be partially alleviated by long term (~20 minutes) averaging; however, this causes the system to be highly damped and unresponsive to process transients. To address this problem, Roberts developed a means of VAR electrode gap control wherein melt rate is used to establish the base electrode feed rate and drip-short period is used to trim the feed rate.[8] He claimed that this type of control system eliminates response problems by combining a relatively fast, accurate control signal (drip-short period) with the melt rate signal.

Other indicators of g_e are arc ion distribution temperatures and arc voltage distribution skewness. Arc ion distribution temperatures respond very quickly to process changes, but monitoring this response requires specialized, relatively expensive, custom equipment.[9] However, the arc voltage distribution skewness is easily and cheaply acquired and is an approximately linear function of g_e.[10] The skewness of the arc voltage distribution is given by

$$\zeta_V = \frac{1}{n\sigma_V^3}\sum_{i=1}^{n}\left(V_i - \bar{V}_{arc}\right)^3 \quad (4)$$

where σ_V is the standard deviation of the arc voltage distribution. The response has been described by the following equation during VAR of Alloy 718 for relatively modest changes in g_e and I_{melt}:

$$\zeta_V = a_{sk} + b_{sk}g_e + c_{sk}I_{melt} \quad (5)$$

ζ_V responds as quickly as V_{arc} and has been demonstrated to be very sensitive to changing arc conditions, such as those due to tip rounding. Unfortunately, it is not particularly sensitive to changes in g_e and, for that reason, is not suitable as a stand-alone gap control parameter.

Melt rate

Melt rate directly affects both pool depth and the thermal distribution in the pool. If $\dot{m}$ becomes too high, the pool deepens and the slope of the solid/liquid interface increases in the outer regions (from edge to mid-radius) of the ingot. As discussed above, this raises the probability of channel type defect formation. If $\dot{m}$ is too small, the pool begins to chill and becomes too shallow. This causes shelf formation which adversely affects side-wall quality and raises the probability of white spot formation in nickel-base alloys. $\dot{m}$ transients are frequently introduced by electrode quality problems. For example, lateral cracks, voids and intermittent glows due to slag contamination all severely perturb $\dot{m}$ and, hence, the solidification process. $\dot{m}$ is also coupled to g_e because of this variables effect on V_{arc} and the arc energy distribution.

$\dot{m}$ is obviously strongly coupled to arc power and, therefore, I_{melt}. Modern VAR furnaces typically do not employ active control of $\dot{m}$ but apply a preset I_{melt} schedule derived from experience. Such practice assumes that other variables affecting $\dot{m}$ are under control. Because process upsets that affect $\dot{m}$ often occur, even in shops with excellent melting practices and procedures, variations in $\dot{m}$ are introduced to the process that are de-coupled from the control action. This constitutes open loop control of $\dot{m}$. Given the sensitivity of the process to this variable, it seems prudent that it be controlled in some type of closed-loop fashion. A simple $\dot{m}$ feedback controller was patented in the late 1970's by Roberts aimed at addressing this issue.[11]

Cooling rate

Typically, 100-300 kW of electrical power are applied during VAR of segregation sensitive alloys. At any given time during the steady-state portion of the process, 80-90% of this energy is removed by the cooling water, the remainder being stored in the ingot as heat. Quite often, helium gas is injected into the bottom of the crucible so as to fill the shrinkage cavity formed between the ingot and crucible wall to a pressure of several hundred Pascals. The cavity is sealed at the top where the ingot is still hot and metal mush encounters the wall around its circumference. The addition of cooling gas to the shrinkage gap causes the dominant means of thermal transport from the ingot surface to be conduction rather than radiation. Thus, cooling efficiency increases and this enables the use of higher melt rates without freckle formation. Empirically, alloy manufacturers have found that melt rate can be increased by 15-25% when melting Alloy 718 into 0.51 m diameter ingot with He cooling. However, as the ingot diameter increases, He cooling becomes less effective because thermal diffusion from the center of the ingot becomes the rate controlling step in ingot cooling, not conduction across the shrinkage gap. As a measure of the importance of heat transfer across the shrinkage gap relative to conductive heat transfer within the ingot to the overall process of heat transfer to the crucible wall, the Biot number, $Bi=hR/k$ (h=heat transfer coefficient; R=ingot radius; k=thermal conductivity), may be calculated. $Bi<<1$ indicates that thermal conduction in the ingot dominates the system and that cooling is limited by heat transfer across the gap. $Bi>>1$ indicates that heat can be transferred across the gap much more efficiently than it can be conducted to the ingot surface. Using values for R, k, h_{rad} and h_{He} appropriate for 0.51 m diameter Alloy 718 with P_{He} = 400 Pa (3 Torr),[12] Bi_{rad} and Bi_{He} were calculated to be ~0.3 and ~2.5, respectively. The low value of Bi_{rad} demonstrates that, under vacuum conditions where only radiative heat transfer across the gap is allowed, the system is sensitive to He cooling. However, because $Bi_{rad}<<1$ does not hold, the cooling process is impeded somewhat by conduction in the ingot. $Bi_{He}>1$ indicates that the process is entering a regime where heat flow to the crucible is limited more by ingot conduction than by resistance to heat transfer across the shrinkage gap. Hence, increasing the pressure of He beyond this should have little or no effect, as has been observed.[12]

Cooling rate is typically controlled in a semi-open loop fashion; water temperature is controlled closed-loop but both water and gas flow rates are simply set to constant values. Usually a two-step control system is employed to maintain water temperature. During the process, water is recirculated through the furnace until it reaches a specified maximum set-point at which time cold water is added to the system to bring the temperature down to the minimum set-point at which time the water addition is terminated. Given that the water and gas systems are consistently and adequately maintained, this form of cooling rate control is adequate. However, if conditions are allowed to deteriorate sufficiently so that the cooling rate becomes insufficient, the probability of producing freckle-type defects increases as does that of crucible damage due to higher peak wall temperatures.

Furnace annulus

Furnace annulus is defined as the space between the electrode and crucible wall for the entire length of the electrode. The annulus dimension is set by the relative dimensions of the electrode and crucible. Typically, this ratio lies in the range of 0.80-0.85. If the annulus is set too small relative to the electrode gap, arc energy is partitioned to the crucible wall diverting it away from the melt pool. This gives rise to shelf formation and an overall decrease in pool depth, a condition conducive to the formation of solute-lean defects (white spots). If the condition persists and the arc attaches to the crucible wall for long periods of time, crucible damage can occur due to excessive heating. On the other hand, if the annulus is too large, insufficient arc power is directed to the ingot-crucible boundary. This also results in the formation of shelf with the concomitant deleterious effects.

Furnace annulus is controlled by ensuring proper stub-electrode alignment. The most common problem in VAR associated with annulus is annulus asymmetry due to a crooked stub weld which causes the stub and electrode not to lie on the same axis. An asymmetric annulus leads to asymmetric energy input into the pool; the result is shelf formation on one side of the ingot which gives a poor ingot surface and an increased probability of forming solute-lean defects. Some furnaces are equipped with x-y centering capability to allow the operator to keep the arc centered. However, with very poor stub-electrode alignment, such adjustments can sometimes bring the electrode top into near contact with the crucible which can lead to arcing in this region.

Furnace atmosphere

It is of great importance to the success of VAR to control furnace atmosphere. As its name implies, the process is meant to be carried out under low pressure, usually <1 Pa (7.5 microns) for segregation sensitive grades. However, absolute pressure is only part of the story. Absolute pressure is determined by both leak rate and pumping rate. Most VAR furnaces are equipped with large capacity vacuum pumps and blowers. Hence, it is quite often the case that furnaces with unacceptably large leaks can be pulled down to relatively low absolute pressures. This constitutes the proverbial "wind tunnel" furnace. Furnace atmosphere is controlled by proper overall vacuum practice. This involves establishing and maintaining adequate leak rate standards as well as keeping the pumping system in good condition. A good leak rate for an industrial furnace is ~0.01 Pa/s (~5 microns/min.). Leak rates an order-of-magnitude less than this are readily achievable but not necessary. An excessive leak rate not only leads to material high in oxygen and nitrogen content, but often causes glow. Glow, sometimes called ionization, is a furnace condition during which diffuse arcing directly to the crucible wall becomes the dominant mechanism of energy transfer between the anode and cathode. Glow can be caused by contamination of the pool with slag due to poor VIM or ESR practice, surface oxidation due to excessive oxygen or carbon monoxide in the furnace atmosphere, or by excessive partial pressure of an unreactive gas (e.g. N_2, Ar, He, etc.). Melting is severely curtailed or stopped altogether during a glow, and energy input into the pool surface is drastically reduced. The result of prolonged steady or transient glow is shelf formation and a shallow pool. Again, this condition often leads to the formation of solidification defects.

Electrode quality

The final process variable to be described is electrode quality. As noted in the above discussions, electrode quality plays a pivotal role in determining the success of VAR. Slag contaminated electrodes will give rise to intermittent glows which perturb both melt rate and energy input into the pool. Cracked electrodes or electrodes with voids cause spatially localized melt rate variations which produce variations in electrode gap as a function of position. In short, a dirty and/or cracked electrode produces melt conditions that cause solute redistribution in the mushy zone, and this increases the probability of producing solidification defects. Therefore, it is extremely important to ensure a steady source of electrodes of uniformly high quality.

A Modern Electrode Gap Control Strategy

General strategy

Several criticisms may be directed at modern methods of g_e control. First, nearly all controllers are single input controllers; they rely completely on the information available from one input parameter (e.g. drip-shorts). This ignores the fact that multiple g_e indicators are available which, if combined, would produce statistically superior, more robust estimates. Secondly, modern g_e controllers make no estimates of g_e, the control variable. Control is achieved by maintaining the chosen g_e indicator near its set-point. This is especially problematic for highly non-linear indicators such as drip-short frequency. Non-linear controllers are difficult to design and analyze because no general theory exists. If a linear controller is used to regulate drip-short frequency, the gains of the controller will be dependent on the operating conditions. In connection with this, it should be remembered that all of the gap indicators discussed above are non-linear to varying degrees. Thus, accurate control based on any one of them is limited to relatively small excursions about the average values of the process variables. This is usually not a problem during the steady-state portion of the melt. However, control during transient portions of the melt as well as through upsets can be severely limited by this problem. Finally, single input controllers are vulnerable to upsets that affect that particular input. For example, suppose during VAR of Alloy 718 that a minor glow is encountered. During glow, melting is suppressed and drip-short frequency decreases. Hence, a drip-short based controller would respond by increasing ram speed to shorten the gap. On the other hand, arc voltage decreases during a glow, indicating that the gap is too tight. A voltage based controller would, therefore, respond by slowing down the ram speed to open the gap. Of course, neither action is correct since the gap is not changing. In either case, when the glow subsided, the g_e indicator would be far from its set-point and a further process transient would have been introduced. Because of the non-linear character of the indicators, this may even cause the controller to go unstable. At the very least, an effective controller should detect and log process upsets while providing a means to control during the upset so that when the upset subsides, the control variable is within it operational range.

A general g_e control scheme is depicted in Figure 2. A g_e reference or set-point is input into the process controller. The process controller may be any of several types. (A PID controller, modified to respond appropriately to the upset detector output, is used on the VAR furnace at Sandia.) The controller output is used to control the furnace ram velocity. Process data used in the g_e estimators are output from the furnace. Shown are arc voltage, arc voltage skewness, drip-short frequency and melt rate, but other data may also be used. The heavy arrow in the figure represents measured furnace parameters (e.g. arc voltage distribution properties, melting current, electrode ram position and speed, electrode weight, furnace pressure, cooling water inlet and outlet temperatures, and drip-short frequency, etc.) used by the upset detector. Other outputs, such as arc light emissions and electrostatic probe data, are less commonly measured, but available when needed. The system models (g_e estimators) consist of experimentally determined models with known error characteristics which map the furnace outputs to independent estimates of g_e. By using system models to form g_e estimates, the control system is effectively linearized. It should be understood that these estimates are independent with respect to time as well as method. Thus, they arrive at the optimal g_e estimator at all different times and with independent frequencies. The estimates vary in accuracy and precision as determined experimentally, and are input into the optimal estimator where they are weighted appropriately to determine the optimal g_e estimate. The optimal g_e estimate is fed to the controller where it is compared to the set point and an error signal generated. This error signal is used to determine the control action to the furnace. In addition, the output of the upset detector is fed into the controller where it is used to modify the controller response as needed to control the process through periods of anomalous process behavior. The upset detector output may also be input into the optimal estimator where the information would be used to modify the input weightings.

Optimal estimation

The Optimal Electrode Gap Estimator shown in Figure 2 has the task of converting multiple g_e estimates arriving at different times with different noise characteristics into a single, optimized (statistically more accurate) estimate. A device ideally suited for such a task is a Kalman filter.[13] A Kalman filter is a device that provides an estimate of some variable based on a set of noisy measurements. The filter accounts for the noise in the measurement signals and provides an estimate of the variable which minimizes the mean square error between the true value of the variable and the estimate. An example is provided here that shows the basic idea of Kalman filtering.

Consider the goal of determining the value of g_e in an unobtrusive manner. Assume that two independent estimates of g_e are available, y_1 and y_2. These estimates might be formed by using the voltage and drip-short frequency. Each of these estimates has associated with it some amount of error, and these errors are randomly distributed about zero with variance of σ_1^2 and σ_2^2, respectively. These errors represent the uncertainty of each of the gap estimates. Figure 3

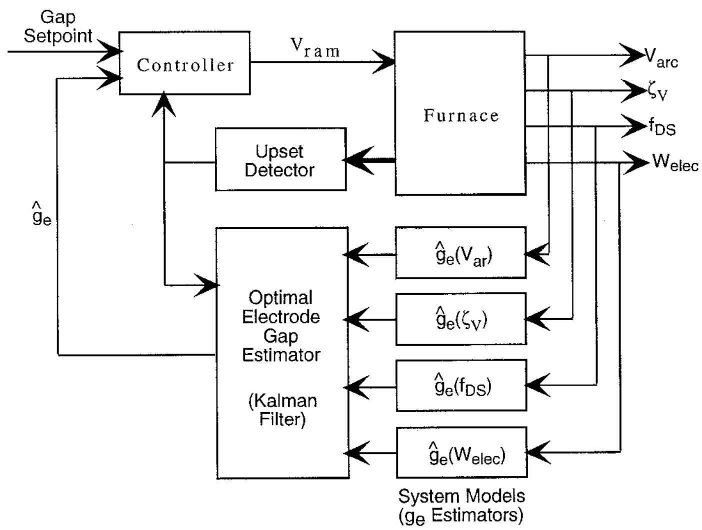

Figure 2. A block diagram of a multiple input, electrode gap controller as described in the text.

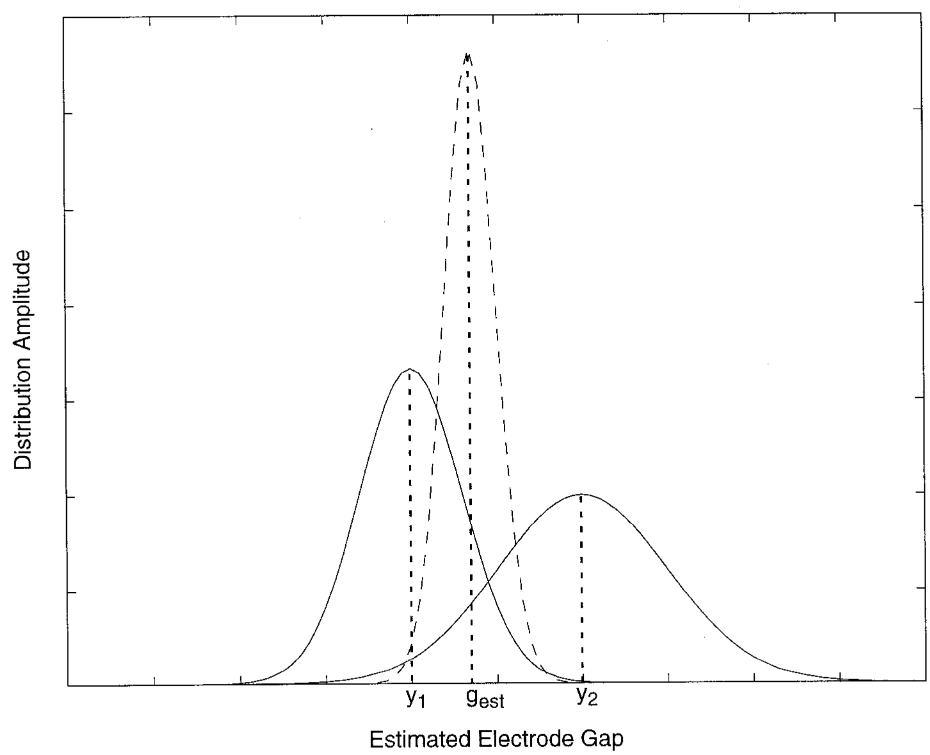

Figure 3. Example of combining two independent gap estimates to obtain an optimal estimate of statistically greater certainty.

represents the measurement scheme graphically. The two estimates of gap are represented as realizations of a random process with a frequency distribution shown by the solid curves. The variance of the estimates is equal to the variance of the frequency distributions. The actual gap is within the area of intersection of the errors of each of the independent gap estimates. The estimate of gap formed by considering both of the independent gap estimates is represented as g_{est} and has a frequency distribution corresponding to the dashed line. The variance of the dashed frequency distribution is equal to the variance of g_{est}. It can be shown that if the independent estimates are combined in a linear manner, that is

$$g_{est} = K_1 \cdot y_1 + K_2 \cdot y_2 \tag{6}$$

where $K_1 = \dfrac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2}$ and $K_2 = \dfrac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}$, then the estimate is the best linear estimate possible, provided that the errors of the two independent measurements are white zero mean processes. The resulting uncertainty in the estimate obtained from the linear combination of the independent estimates is given by

$$\sigma_{est}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \tag{7}$$

where σ_{est}^2 is less than either σ_1^2 or σ_2^2. Thus, the combined estimate has less uncertainty than either of the individual independent estimates.

Novel aspects of multiple input electrode gap control

The novel aspects of this general VAR electrode gap control scheme relative to single input controllers are as follows:

1) This control scheme uses system models to make multiple, independent estimates of electrode gap of known accuracy. Hence, this is a true electrode gap controller and not a voltage or f_{DS} controller. Because the controller is model based, the feedback signal is linearized, allowing for the use of linear control theory. System models must be developed using experimental data and are specific for the material and furnace employed. Therefore, the accuracy of the various models and their range of application are well characterized.

2) This control scheme uses well documented optimal estimator (Kalman filter) techniques to combine the various electrode gap estimates and form a statistically optimal estimate. This incorporates all relevant information into the control decision, taking advantage of the redundant estimates discussed in (a), and allowing for new estimate inputs as these become available. Hence, multiple input control constitutes an inherently more robust means of electrode gap control.

3) This control scheme allows for adaptive gains to be used in the optimal estimator (Kalman filter) which has the advantage of allowing estimator inputs to be weighted differently in response to changes in the state of the process. For example, the gains may be made responsive to melting current so that, as melting current is increased, the controller de-emphasizes drip-short based input in favor of input based on arc voltage.

4) This control scheme incorporates process upset detection, the output of which can be used as input to the process controller and/or the optimal estimator. In the former case, the input is used to modify control decisions. For example, the system may be set up to detect the glow condition. When the upset detector senses a glow condition, the controller may be set to halt the ram drive until normal melting resumes. This would enhance the ability of the controller to maintain a stable electrode position relative to the ingot pool surface.

Summary

Relevant aspects of VAR process control have been discussed. The control variables reviewed in the discussion were electrode gap, melt rate, cooling rate, furnace annulus, furnace atmosphere and electrode quality (i.e. cleanliness and integrity). Lack of control of any one of these variables leads to an increased probability of solidification defect formation. Various types of electrode gap control were reviewed and the major disadvantages of each type pointed out. A multiple input electrode gap controller was described which uses optimal estimation techniques to address these problems.

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