

CONF-970232--2

SAND96-2995C
SAND-96-2995C

A SIMPLE ARC COLUMN MODEL THAT ACCOUNTS FOR THE

RELATIONSHIP BETWEEN VOLTAGE , CURRENT AND

ELECTRODE GAP DURING VAR

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Abstract

Mean arc voltage is a process parameter commonly used in vacuum arc remelting (VAR) control schemes. The response of this parameter to changes in melting current (I) and electrode gap (g_e) at constant pressure may be accurately described by an equation of the form $V = V_0 + c_1 g_e I + c_2 g_e^2 + c_3 I^2$, where c_1 , c_2 and c_3 are constants, and where the non-linear terms generally constitute a relatively small correction. This general form has been verified at several melt shops around the country. If the non-linear terms are ignored, the equation has the form of Ohm's law with a constant offset (V_0), $c_1 g_e$ playing the role of resistance. This implies that the arc column may be treated approximately as a simple resistor during constant current VAR, the resistance changing linearly with g_e . The VAR furnace arc is known to originate from multiple cathode spot clusters situated randomly on the electrode tip surface. Each cluster marks a point of exit for conduction electrons leaving the cathode surface and entering the electrode gap. Because the spot clusters are highly localized on the cathode surface, each gives rise to an arc column that may be considered to operate independently of other local arc columns. This approximation is used to develop a model that accounts for the observed arc voltage dependence on electrode gap at constant current. Local arc column resistivity is estimated from elementary plasma physics and used to test the model for consistency by using it to predict local column heavy particle density. Furthermore, it is shown that the local arc column resistance increases as particle density increases. This is used to account for the common observation that the arc "stiffens" with increasing current, i.e. the arc voltage becomes more sensitive to changes in electrode gap as the melting current is increased. This explains why arc voltage is an accurate electrode gap indicator for high current VAR processes (e.g. remelting of various Zr and Ti alloys) but not low current VAR processes (e.g. remelting of nickel-base alloys and other segregation sensitive grades).

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Introduction

Vacuum arc remelting (VAR) is used throughout the specialty metals industry to produce high quality ingots of a wide range of segregation sensitive and/or air reactive alloys. A schematic of the process is shown in Figure 1. The furnace consists of a water-cooled copper crucible (or mold) housed in a vacuum-tight furnace chamber. An electrode composed of the alloy to be remelted is mounted in the furnace, the furnace chamber evacuated, and an electric arc struck between the electrode (cathode) and the crucible bottom (anode). Heat generated from the arc melts the electrode tip and molten material drips off eventually forming an ingot. As the ingot grows, the electrode is driven downwards to maintain a constant electrode gap. Under optimum process conditions, an ingot is produced that is fully dense, free of macrosegregation and solidification defects.

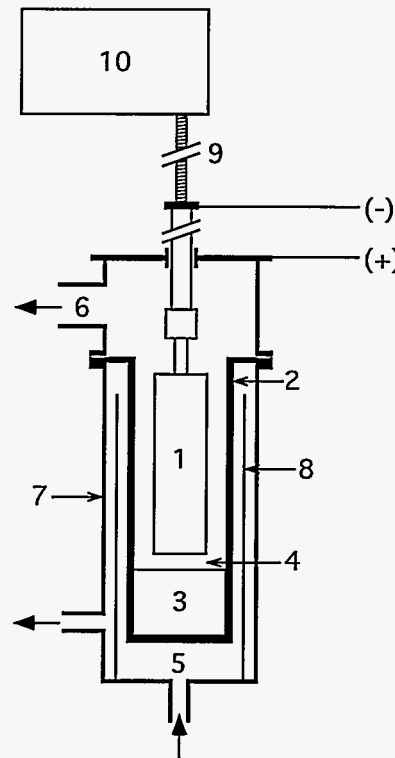


Figure 1 - Schematic of a VAR furnace. Key: 1 - electrode; 2 - crucible; 3 - ingot; 4 - arc gap region; 5 - cooling water; 6 - vacuum exhaust; 7 - furnace body; 8 - cooling water guide; 9 - electrode drive screw; 10 - drive motor.

The heart of the VAR process is the electric arc. Process conditions that maintain a steady, diffuse arc between the electrode tip and ingot pool surfaces give rise to uniform heating of the ingot top. This, in turn, give rise to steady solidification in the ingot and minimizes the possibility of defect formation brought on by process transients. The most commonly monitored furnace parameter that relates directly to arc condition is the arc voltage. Typically, the voltage is measured and recorded on a strip chart. VAR metallurgists can read important information from the voltage trace. For example, one can tell that the electrode was cracked, or that there was a glow, or that the electrode gap closed or opened. In many shops, voltage is used as the primary input to the VAR process controller. It is assumed that the electrode gap is held constant if the voltage set-point is maintained by adjusting the electrode feed speed.

Given the importance of the arc voltage as a process monitoring and control parameter, it is of great interest to understand why it behaves the way it does. This necessitates relating it to the

physical processes taking place in the electrode gap. In this paper, an arc model is proposed that consists of multiple, independent arcs operating in parallel between the electrode and pool surfaces. The model is used to account for the general arc voltage behavior as observed in melt shops throughout the industry. Additionally, it is used to estimate arc column resistivity and pressure.

General Arc Voltage Characteristics

There are a few general arc voltage characteristics for which the model must account.

Arc voltage varies with changing electrode gap (g_e) and melting current (I) according to the following empirical formula [1,2]:

$$V_{\text{arc}} = V_0 - c_1 g_e I + c_2 g_e^2 - c_3 I^2 \quad (1)$$

V_{arc} and V_0 are taken as negative quantities by convention. V_0 is a constant and accounts for most of the voltage drop. Physically, it is due to the voltage drop across the cathode sheath as well as other voltage drops in the furnace circuit that are independent of gap or current. g_e is defined as the average distance between the electrode and ingot surfaces. It is necessary to use the average distance because these surfaces are molten and in constant motion from drips and waves. The behavior of the voltage as a function of g_e and I is illustrated in Figure 2 for $g_e < 0.030$ m and $I < 10,000$ A. Under these small gap, low current conditions, c_2 is zero to within a good approximation and the arc voltage varies linearly with g_e , the slope of the gap dependence increasing with I . (To describe this increase in slope with current, melters often say that the arc "stiffens" as melting current is increased.) As the gap is opened beyond 0.030 m, the slope of the dependence falls off until the voltage eventually becomes unresponsive to changes in g_e . The second term in Eq. 1 is by far the most statistically important in determining the response of V_{arc} to changes in g_e and I . Typically a model in this parameter alone accounts for 85-95% of the variance in the V_{arc} data. Thus, the voltage response may be approximated by an Ohm's law type of equation with a constant offset (V_0) and with $c_1 g_e$ playing the role of resistance.

At relatively small g_e , molten material drips from the electrode and contacts the ingot pool surface momentarily causing a short circuit during which the arc is extinguished. The arc voltage remains unaffected as the hanging protuberance tip draws near the ingot pool surface until the time of actual physical contact.[3] After a few tens of microseconds, the arc re-ignites when the contact point is ruptured by intense Joule heating. This process is referred to as a drip-short and the frequency of such events is often used as a control parameter during low current VAR. High speed cinematography has shown that, subsequent to a drip-short, cathode spots migrate from the point of rupture beneath the hanging protuberance and re-establish the arc uniformly throughout the electrode gap region within a few milliseconds after the rupture. However, the arc also remains active beneath the protuberance tip where re-ignition was initiated. In this local region, cathode spots operate within a fraction of a millimeter of the anode surface. The current passing through this local arc is often a few hundred amperes. During this period of time when the anode and cathode are in very close proximity with current passing locally between them, the arc voltage is normal. Hence, though arc voltage varies with average electrode gap, it is independent of local arc gap. Only when the entire arc is momentarily concentrated under a protuberance immediately after arc re-ignition is the arc voltage measurably perturbed, being increased by a few volts.

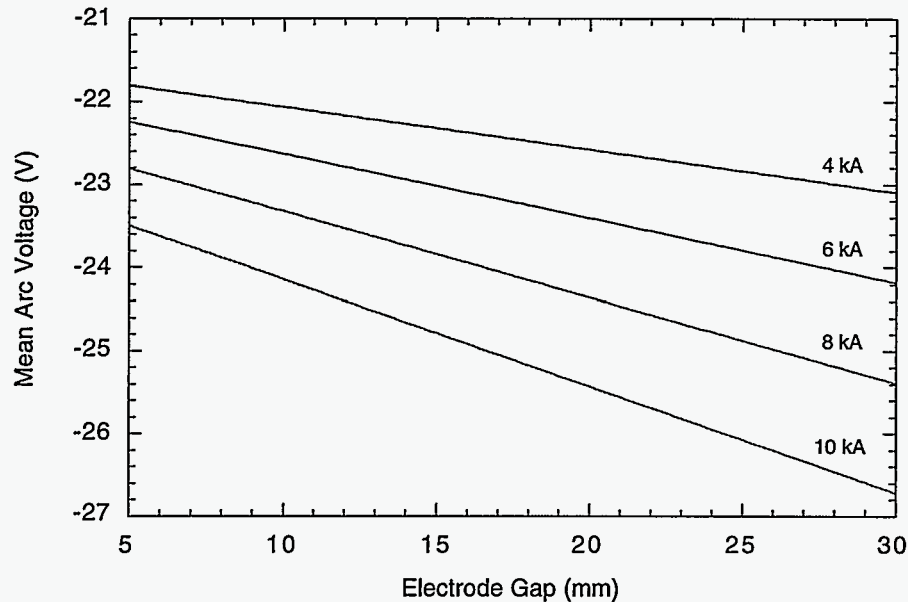


Figure 2 - Arc voltage as a function of electrode gap at different melting currents. The linearity falls off as g_e is increased beyond 30 mm.

A Simple Parallel Arc Model

As mentioned above, the response of V_{arc} may be approximately described by an equation similar to Ohm's law where $c_1 g_e$ plays the role of resistance. At this level of approximation, the arc column (i.e. the space between the anode and cathode sheath regions) acts like a variable resistor with resistance changing linearly as a function of column length. What changes, then, as the electrode is raised or lowered during constant current melting is the average arc column resistance, R_{col} . It is of interest to estimate the magnitude of R_{col} . For purposes of calculation, it will be assumed that 0.430 m (17 inch) diameter round electrode is being melted into 0.510 m (20 inch) diameter ingot at a melting current of 6,400 A.

When calculating R_{col} , it will be assumed that the plasma between the electrodes may be modeled as a Lorentz gas under conditions where magnetic field and high frequency electric field effects may be neglected. The first condition is met because the low average current density in the arc, $J_{ave} = I_{total} / A_{electrode} = 4.4 \times 10^4 \text{ A/m}^2$, gives rise to only a very small self-induced field; no external magnetic field is applied. The second condition is met because the VAR process uses a dc arc. In the Lorentz model, conduction electrons are free to move in a relatively stationary background gas of ions and neutral atoms which acts as a viscous medium due to collisions.[4] Thus, an electron in the dc arc column is accelerated uniformly by the electric field until it undergoes a collision with an ion or atom, or is collected by the anode. It must be kept in mind that this plasma model applies only to the arc column and not to the cathode or anode sheath regions. It is in these regions, especially the cathode sheath region, where most of the voltage fall occurs, and this fall is independent of g_e . The fall across the arc column, V_{col} , is relatively small, typically ~ 1 volt under the conditions of interest.

It has been shown that conduction between the large diameter electrodes used in VAR is not uniform but significantly localized in partially ionized metal vapor columns bridging the electrode gap.[5] Thus, the usual assumption of a uniform arc plasma between the electrodes [6]

will not be made. Each local conduction column is associated with an area of the cathode surface where a cathode spot cluster is active. Figure 3 depicts an idealized multiple parallel arc columns model. In the idealized model, all conduction columns are independent (i.e. do not overlap) and are approximated as cylinders containing uniform plasma density. For a nickel base alloy arc operating in the diffuse mode, a single spot cluster typically conducts ~ 100 A current.[7] Suppose that a single cathode spot cluster with a local current, I_{loc} , of ~ 100 A is active and that conduction through the associated metal vapor column takes place in a localized cross-sectional area (A_{loc}) of $\sim 10^{-4}$ m² across a potential of 1 V. From Ohm's law, the resistivity of the localized arc column, ρ_{col} , is $V_{col}/g_{loc}I_{loc} = V_{col}A_{loc}/g_{loc}I_{loc} \approx 10^{-4}$ ohm-m, where g_{loc} , the local electrode gap in the vicinity of the spot cluster, was taken to be 0.01 m. Note that this resistivity is about four orders-of-magnitude greater than that of a good conductor ($\rho_{Cu} = 1.7 \times 10^{-8}$ ohm-m) and significantly smaller than would be predicted assuming a uniform current density, J_{ave} , between the electrodes. The local column resistance, R_{loc} , may be calculated to be $g_{loc}\rho_{col}/A_{loc} \approx 0.01$ ohm. Assuming that this value is typical of all locally conducting regions in the arc and that there are 64 such regions in a 6,400 A arc, the average total arc column resistance, R_{col} , due to these parallel arcs is calculated to be $\sim 1.5 \times 10^{-4}$ ohm. It should be noted that this total column resistance is much smaller than the total arc resistance derived by dividing the circuit voltage by the melting current. This is because the circuit voltage includes V_0 .

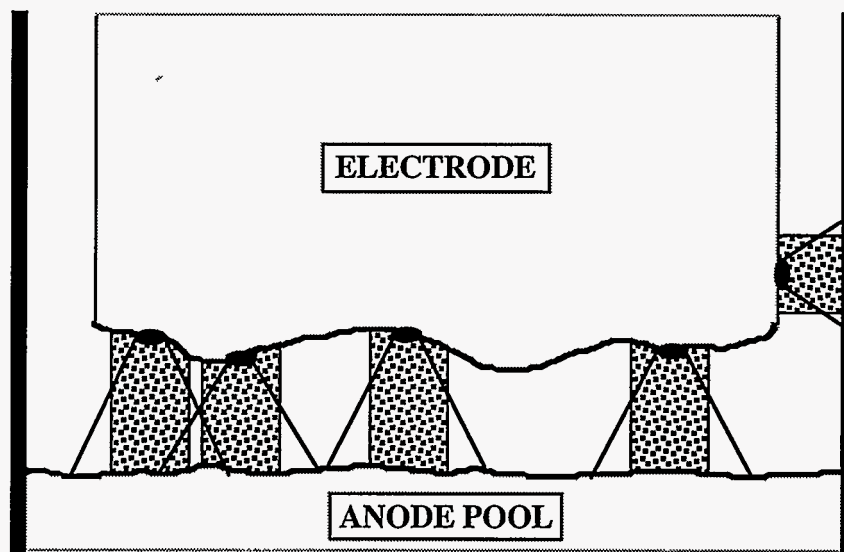


Figure 3 - A depiction of the idealized multiple arc columns model. Cathode spot clusters give rise to independent, cylindrical plasma columns of uniform density.

Arc Behavior During Drip-Shorts And At Zero Gap

It is of interest to investigate the effect on the total arc resistance of setting the local column resistance associated with a single cathode spot cluster to zero. This occurs when a spot cluster resides on the tip of a molten protuberance hanging from the cathode with the protuberance tip in very close proximity to the anode pool surface. This situation is commonly encountered during drip-shorts as described above. If the local arc conduction zones are viewed as a set of parallel resistors situated between the electrode faces (Figure 3), the total arc resistance is given by the well known formula

$$R_T = \frac{1}{\sum_n \frac{1}{R_n}} \quad (2)$$

Now, suppose that there are 64 local arc columns active between the electrode surfaces, each carrying 100 A of current and that g_e is 0.01 m. A typical arc voltage under these conditions is -23 V (see Fig. 2). The average value of the local arc resistance is, therefore, V_{arc}/I_{loc} or 0.23 ohm. Suppose further that all of these columns have this average resistance except for one which has a value of 0.22 ohm, the average value less the 0.01 ohm contribution due to the local arc column, R_{loc} , as estimated above. This is the value of the local arc resistance when the local column resistance approaches zero as occurs when a cathode spot cluster resides on a protuberance tip that is in very close proximity to the anode pool surface. From Eq. 2, $R_T=3.59 \times 10^{-3}$ ohm under these conditions, virtually the same as that calculated assuming a uniform gap of 0.01 m. Thus, the effect of a single local arc column resistance going to zero on the overall arc voltage is negligible. This is because 1) the local arc column resistance is only a small fraction of the local arc resistance and 2) the other local arc columns act independently, maintaining their normal resistance values at their respective local gaps. This is in agreement with observation.[3] If all of the parallel resistances are set to 0.22 ohm, a zero-gap arc resistance of 3.44×10^{-3} ohm is obtained. This represents the resistance across the cathode sheath and in other parts of the circuit. Multiplying by -6,400 A gives an estimated zero-gap arc voltage of -22.0 V.

The above estimates may be compared with data acquired from SMPC sponsored experiments at Cytemp Specialty Steel in Titusville, Pennsylvania,[1] and at INCO Alloys International in Huntington, West Virginia[2]. Both experiments were carried out during VAR of Alloy 718 under conditions similar to those used for the model estimates. The empirically determined parameters used in Eq. 1 to describe the voltage response at small gaps are listed in Table 1. The experimentally determined zero-gap resistances and average total arc column resistances are given in the table for comparison with the estimated values. These values are in good agreement with the model estimates indicating that the estimated individual arc column resistivity (10^{-4} ohm-m) is consistent with available data.

Table I. Experimental values for arc response function constants (Eq. 1). Values for R_{ave} and V_{ZG} are also tabulated.

	Cytemp Exp't	INCO Exp't	Model Estimates
V_0	-21.3	-21.1	--
c_1	-0.0129	-0.0113	--
c_2	0	0	--
c_3	-0.0155	-0.0174	--
$R_{col}(10^{-3} \text{ ohm})$	0.13	0.11	0.15
$V_{ZG}(\text{volt})$	-21.9	-21.8	-22

Local Arc Resistivity And Pressure

The local arc column resistivity may be used to estimate the local column pressure. Assuming that ~90% of the current is carried across the electrode gap by conduction electrons [8], an average electron density may be calculated in the region of a cathode spot conduction column simply by dividing the electron current by the average electron charge flux:

$$n_e = \frac{0.9I_{loc}}{A_{loc}e v_D} \quad (3)$$

e in this equation is the electron charge. Given the same estimates of I_{loc} and A_{loc} as used above, and taking the electron drift velocity, v_D , to be $\sim 10^5$ m/s [9], n_e is estimated to be $\sim 6 \times 10^{19} \text{ m}^{-3}$.

The mean collision time, τ , may be calculated from simple kinetic theory to be

$$1/\tau = \sqrt{2} Q_{e-a} v_D n_a \quad (4)$$

where Q_{e-a} , the electron-metal atom collision cross-section, is estimated to be $\sim 5 \times 10^{-19} \text{ m}^2$ assuming that the electron temperature is in the range of one-to-four electron volts. [10] n_a in Eq. 4 is the heavy particle (ion and atom) density. The resistivity is related to τ by [11]

$$\rho = \frac{m_e}{n_e e^2 \tau} \quad (5)$$

where m_e is the electron mass. Substituting in the appropriate values and making use of Eq. 4 gives for the local column resistivity

$$\rho_{loc} \approx 4.2 \times 10^{-26} n_a. \quad (6)$$

Substituting in the model estimate of 10^4 for ρ_{loc} gives $2 \times 10^{21} \text{ m}^{-3}$ for n_a . Typical of relatively low current density vacuum arcs is that the heavy particle temperature in the arc column is low, $\sim 500 \text{ K}$. [12] This corresponds to a pressure of $\sim 20 \text{ Pa}$ in a local arc column, considerably higher, though not unreasonably so, than the ambient pressure ($< 1 \text{ Pa}$) in the furnace head. As demonstrated by Schellekens [13], pressure in a high current density arc on the verge of anode spot formation can be as high as 10^4 Pa in the immediate vicinity of the cathode. Note that the arc column plasma (electron) temperature is considerably higher than the heavy particle kinetic temperature, the former usually estimated to be $6,000\text{-}15,000 \text{ K}$.¹⁴ This temperature range is corroborated by spectroscopic measurements which yield electronic Boltzmann distribution temperatures in this range for both atoms and ions. [15] However, at these pressures, the relatively low electron-heavy particle collision frequency makes it impossible to effectively transfer kinetic energy from the electron gas to the heavy particle gas and bring the system into thermodynamic equilibrium. This is supported by the result obtained above that $n_e \ll n_a$ which indicates that the plasma is weakly ionized. This would not be true if the heavy particle kinetic temperature were equal to the plasma temperature.

Non-Linearities In The Arc Voltage Response

The idealized multiple arc columns model is very useful in accounting for the gross (linear) features of the mean arc voltage response as well as for estimating arc column resistivity and pressure. However, in reality the arc is somewhat more complicated and this gives rise to deviations from Ohm's law behavior. For example, increasing melting current causes the plasma to be more confined beneath the electrode tip due to magnetic field effects and, because of the increase in energy input to the surfaces, also causes an increase in the amount of electrode material injected into the arcing region through vaporization. Thus, the scattering center density is expected to increase with increasing current at constant electrode gap. The qualitative effects of this on column resistance may be seen by considering the following equation, derived from Eq.'s 3-5 above:

$$R_{loc} \propto \frac{g_{loc} n_a v_D^2}{I_{loc}} \quad (7)$$

An increase in melting current is accommodated by an increase in the total number of spot clusters operating on the cathode tip [16] while the local current or current per cluster, I_{loc} , remains constant. Thus, as current is increased at constant electrode gap, Eq. 7 predicts an average increase in total arc column resistance due to the increase in n_a . Because of the increase in voltage with current, the electron drift velocity may also increase. However, this will be partially offset due to increased scattering. The result is that arc column resistance increases as melting current increases at constant g_e ; therefore, the slope of the voltage response becomes steeper as current is increased. If melting current is held constant, a similar effect may be

deduced for the voltage response as a function of g_e at large gap (>0.030 m). If I_{loc} and v_D are assumed constant, R_{loc} increases linearly as the average local gap increases provided there is no change in n_a . However, as the gap is opened, the partitioning of current between the crucible wall and anode pool changes in favor of collection by the wall, thereby decreasing power deposition on the pool. This serves to decrease vaporization of pool material. Also, the gap volume increases as the gap is opened. The combination of decreased vaporization and increased volume leads to an inverse relationship between g_e and n_a . The result is that the change in local gap is partially offset by a decrease in the density of scatters and the slope of the voltage response to changes in melting current decreases as the g_e is increased.

Summary

A simple, multiple arc columns model has been developed and used to account for the response of the arc voltage to changes in melting current and electrode gap during VAR. Though the model was developed assuming sizes and conditions typical of low current melting of nickel-base alloys, these assumptions were for illustrative purposes only. The model is expected to be applicable to VAR in general. For the conditions considered, the model predicts a local column resistivity of $\sim 10^{-4}$ ohm-m. This indicates that the plasma is weakly ionized ($n_a \gg n_e$) and that pressures in the localized arc columns exceed the ambient pressure measured at the furnace exhaust by a least an order of magnitude. The model was also used to explain why arc voltage is unaffected just prior to and just after a drip-short when the anode and cathode are in very close proximity. Non-linearities in the arc voltage response to changes in melting current and electrode gap were related to changes in arc column resistivity due to changes in heavy particle density.

Acknowledgments

A portion of this work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy. Additional support was supplied by the Specialty Metals Processing Consortium. Special thanks to Cytemp Specialty Steel and INCO Alloys International for hosting experiments.

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