A Measurement System for Determining the Positions of Arcs During Vacuum Arc Remelting

C. Rigel Woodside[1] and Paul E. King[1]

[1]National Energy Technology Laboratory
U.S. Department of Energy
Albany, OR, USA
Rigel.Woodside@netl.doe.gov

***Abstract*— It is has previously been shown that arcs can constrict during Vacuum arc remelting (VAR), and this constriction can lead to undesired defects in the material. This paper describes a novel measurement system capable of locating arcs in an existing industrial VAR furnace. The system is based on non-invasive magnetic field measurements and VAR specific forms of the Biot-Savart law which relate the measurements to the positions of arcs. Electromagnetic finite element modeling assists the analysis. The measurement system is applied to a commercial VAR furnace, and data are taken during production of titanium alloy. It is shown there exists arc distribution differences during this VAR operation and these differences are not apparent in the existing measurements used to control the furnace. It is also shown that there is more than one arc at an instant, and likely more arcs present at an instant than can be resolved with the number of sensors applied. Still, the described methodology can be extended to locating additional arcs by adding additional sensors.**

Keywords- arcs; magentic; sensing; Biot-Savart; VAR; titanium

I. INTRODUCTION

Vacuum arc remelting (VAR) is a widely used metallurgical casting process that improves a material's chemical and physical homogeneity. The input material, commonly referred to as the electrode, is generally cylindrical in shape. Electrical power heats this electrode by means of a metal vapor plasma arc and gravity works to transport droplets of the electrode into a water cooled copper crucible. The output material, which is also cylindrical, is called the ingot. Fig. 1 shows the cross section of a typical coaxial VAR furnace.

An arc strikes between the electrode and the forming ingot over a distance referred to as the electrode gap. Generally, gap lengths are less than a few centimeters for the VAR process. The physical layout of the VAR furnace does not allow for direct viewing of this region, and arcs are free to move about. It is important to realize that arc position is not directly controlled in the process. Instead, control of the process is achieved by controlling the system current, and the system voltage by moving the electrode up or down. In some cases externally mounted magnetic stirring coils are also used.

Much of the knowledge of VAR arc behavior comes from studies that utilize specially designed furnaces that allow for direct cross section viewing of the electrode gap region for short durations.

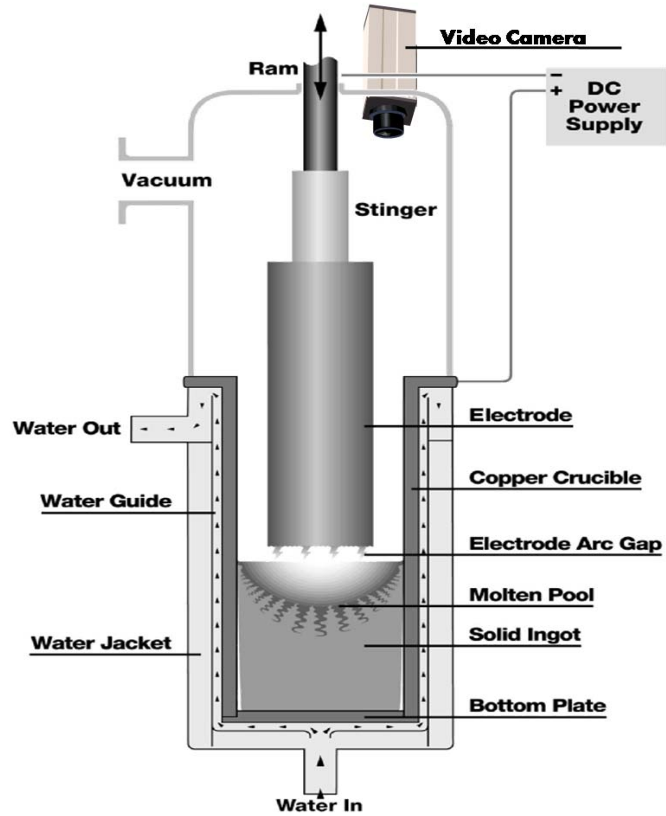

Figure 1. Cross Section of a typical industrial VAR furnace. Sketch is courtesy of ATI-Allvac, with a modification to show the video camera's location during the experiments.

The recorded electrode gap videos from one of these studies showed that the arcs can become constricted, which means they exist on one side of the furnace for an extended amount of time. It was shown that these arc constrictions were more likely to result in material defects [1]. Thus, a non-invasive measurment system that can detect such constictions is desired.

If arcs shift to one side of the furnace in a constriction, then some net magnetic field should exist on the outside of the furnace in accordance to the relation of electrical current and magnetic field as stated in Maxwell's equations. Previously, magnetic flux density sensors were placed outside of the crucible in a VAR furnace, and it was shown that there may be an ensemble rotation to the arcs [2]. This analysis was based on

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an observed pattern in the magnetic field measurements. The ultimate goal of such measurements is to quantify arc positions.

Arc position data are necessary information for quantification of the current density into the ingot per unit area and per unit time. This spatial and temporal pattern of energy into the ingot affects the solidification process, and thus the quality of the product. A method utilizing magnetic field measurements to determine the position of a single arc and characterize this information in terms of an arc distribution and an arc motion was recently presented by the authors [3]. This paper builds on the approach to include finding multiple arcs, and arc distribution differences during VAR are highlighted.

A. *Vacuum Arcs*

A vacuum arc refers to an electrical discharge between a cathode and an anode at pressures low enough that the conduction path is sustained by vaporization and ionization of the electrode rather than the ambient gas. In a VAR furnace, the most important feature of the arc is the cathode spot. A cathode spot is a small zone having an extremely high current density resulting in melting, vaporization, and ionization of the electrode material via Joule heating. Empirical observations in laboratory settings have shown that a given cathode spot can only hold a certain amount of current before splitting into multiple spots. For example, it has been reported that a titanium cathode spot can carry up to 70 Amps [4]. It also has been reported that spots cluster together. For Titanium cathode spots in an experimental VAR furnace it was estimated that a cluster of spots would carry 380 Amps, and have a diameter of 3mm. [5]. However, there is some evidence that the number of spots in a cluster may not be stable. From observations of VAR furnace electrode gap videos it was reported that cathode spots tend to move around in ill-defined clusters, separating and coalescing with retrograde motion [6]. The term retrograde motion refers to the tendency of cathode spots to move in the opposite direction of the Lorentz force. So in the absence of an externally applied magnetic field, retrograde motion can yield an expanding ring of cathode spots which can be observed by examining small craters left behind by the cathode spots [7].

II. METHODOLOGY

For purposes of this paper the term arc will be used to refer to a region in the electrode gap having a locally axisymmetric electrical discharge consisting of multiple cathode spots that is clearly separated spatially from other such discharges. In practice, this differentiation of arcs will be determined by the resolution and uncertainty associated with the measurement system.

A. *Experimental Set-up*

Eight 3-axis hall effect sensors having a measuring range of +/- 50 mT and a bandwidth of 20kHz were utilized. The axis' are orthogonally oriented and closely spaced so that a magnetic flux density vector can be determined for each sensor. The sensors were placed on the outside of a commercial VAR furnace at ATI-Allvac's Albany facility in two planes of four sensors each. During a melt the electrode gap moves up the axis of the furnace as the ingot length grows, so there ends up being two times during a melt where the gap was coincident with a plane containing four sensors. The sensors were arranged symmetrically about the circumference.

In addition to the magnetic measurements, the furnace voltage, current, and stirring coil current were acquired. This data were sampled and recorded at 3.7kHz. Data were taken during a variety of titanium melts. The exact operation parameters of each run are propriety, but it can be said that for final melts furnace current was greater than 30kA, voltage 30 to 50 Volts, and stirring coil operation low with moderate reversal times. The magnetic field at a sensor due to the stirring coil current was negated from the measurements by running the coil prior to striking an arc and determining an offset as a function of coil current.

ATI-Allvac provided internally acquired electrode weight data, ram position data, vacuum pressure, and melt view video. The electrode ram position data and the electrode weight data along with the electrode's density and dimensions were used to calculate the ingot length during the melt.

B. *Arc Position Determination*

The data were processed with a 25 Hz low pass filter. In general, electrical processes up to 60Hz can be described using magentostatic formulations without introducing much error [8]. The furnace power is well rectified direct current, but there is still the possibility that the arcs might change positions fast enough to violate a magentostatic formulation. In this paper, we only attempt to determine the positions of stationary or slowly moving arcs.

The voltage drop across the furnace is primarily due to the electrode arc gap, thus arc position changes will have the largest influence on changing current paths in the furnace. In accordance with the Maxwell-Ampere law, electric current generates a magnetic field which can be measured at a distance. To quantify the relation of the external magnetic fields to different arc positions, an electromagnetic finite element model (FEM) of the furnace was generated. COMSOL Multiphysics, an off the shelf commercial FEM software program, was utilized. This package already contains the appropriate magentostatic formulations, so the details of this will not be discussed. The approach was basically to simulate various arc positions for a geometry representing the actual VAR operation, and then outputting the resulting magnetic fields at locations corresponding to sensor locations.

It was previously shown that the relation of arc positions to external magnetic fields predicted by the FEM could be approximated with a continuous set of arc finding equations without introducing much error [9]. The formulated equations are essentially furnace specific forms of the Biot-Savart law which relate electric line sources to the magnetic field at a point. The equations are based on principles of superposition, thus they can be extended to multiple arcs if it is assumed that the arcs are collinear. In a coaxial furnace, as utilized in these experiments, further simplification can be made. The term coaxial refers to the aspect that the overall current flow in the crucible is in the opposite direction of the current flow in the electrode. Thus, a centered arc produces zero net magnetic field outside of the furnace. These aspects, along with the axsymmtery in the furnace's geometry yield the arc finding equations (1) and (2) in a polar coordinate system.

$$B_t = m_t I \left(\sum_{i=1}^{n} \frac{\mathrm{f_i} \sin\theta_i}{d_i} - \frac{1}{r_s} \right) \quad (1)$$

$$B_r = m_r I \left(\sum_{i=1}^{n} \frac{-\mathrm{f_i} \cos\theta_i}{d_i} \right) \quad (2)$$

B_t and B_r are the magnetic flux densities (T) at a sensor in an orientation as indicated in Fig. 2, θ is the angle from the sensor to the arc, d is the distance from the sensor to the arc (m), r_s is the distance from the sensor to the center of the furnace (m), I is the total circuit current (Amps), f is the fraction of the total current associated with the arc, and n is the number of arcs present. The terms m_t, m_r, are determined from the FEM data in the same manner as previously reported [9] and the units are the same as that for magnetic permeability (N/A^2). Each sensor will have an equation (1) and (2), and for a circle of sensors m_t, m_r, f_i, r_s, n and I will be the same for each. One approach to solving the system of equations is to assume that each arc carries equal current. Given that current amounts in arcs are thought to be multiples of a material dependent discreet amount, this might be an effective approach if large numbers of sensors are available. For these experiments, it was expected that the number of arcs present exceed the number of sensors (4), thus the problem is underdetermined. Still, gross movements of arcs from one side of the furnace to the other should be apparent. To quantify this, a single arc formulation was used. The single arc version of equations (1) and (2) can be inverted to give an exact arc position from a single sensor using equations (3) and (4).

$$d = \frac{I m_r m_t}{\sqrt{\frac{I^2 m_r{}^2 m_t{}^2}{r_s{}^2} + \frac{2 I B_t m_t m_r{}^2}{r_s} + B_r{}^2 m_t{}^2 + B_t{}^2 m_r{}^2}} \quad (3)$$

$$\theta = \cos^{-1}\left(\frac{-B_r d}{m_r I} \right) \quad (4)$$

Fig. 2 shows the set-up. Br is pointed toward the center, such that theta is always between 0 and 180 degrees. I, total system current, is positive and pointed out of the page. Although a single arc is located, an identical result will be found if there are multiple arcs with local axisymmetry about the found point. Thus, we can expect that the single arc formulation yields position data for something that might be called the center of the arcs. For the data presented, the found arc positions using equations (3) and (4) for each sensor were averaged to give a final position result. This is the single arc method.

It is important to realize these formulations are for the electrode side of the gap. This is because some of the current leaving the end of the electrode does not enter the ingot, but rather is transferred directly to the crucible via the metal vapor plasma associated with an arc. It is not known what percentage of the total measured circuit current is entering the ingot. Placement of electrodes on the side of the crucible has indicated that only 67% of the total current entered the ingot during titanium alloy VAR melting [10]. The current transfer in the plasma is more diffuse than the discharge from the cathode spot, though the plasma is generated by the spot. Correct accounting for the plasma is certainly relevant to arc position determination. However, the error arising from neglecting the current paths in the plasma may be minimal because the shrinkage of the ingot tends to lead to most of the current exiting the ingot near the top surface.

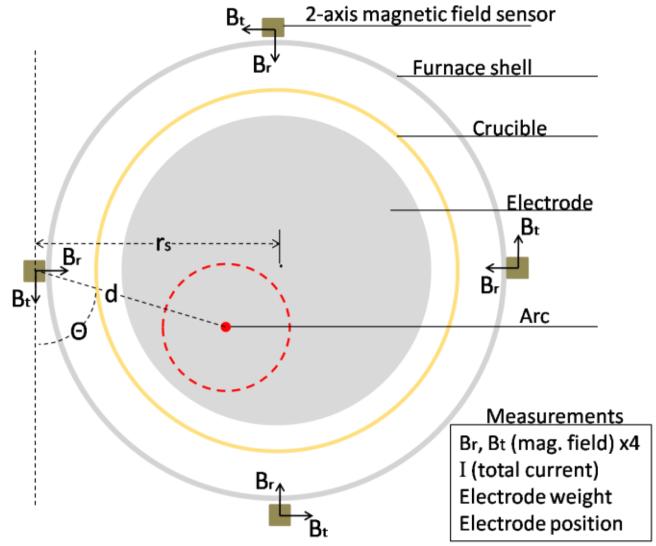

Figure 2. Overhead view of the experimental set-up. The red dotted line is to show that the found arc location with the single arc method could actually be a locally axisymmetric region of arcs (center of the arcs).

The equations are imperfect approximations of the FEM, but the error between the FEM data and the equations can be quantified. For the single arc method the difference between the simulated single arc radial positions in the FEM and the found arc radial positions using the equations can be seen in Fig. 3. There is negligible (less than 1mm) error in the azimuthal direction. Since the radial error is systematic and known, it can be corrected for if increased accuracy is desired. Additionally, this error does not significantly change when using a constant mr, and mt, over an ingot length change of about 15cm when the gap is near alignment with the sensors.

III. Results and Discussion

A total of 9 different melts were analyzed. Of particular interest were final melts. Final melts, as the name suggests, represent the last solidification step for the material. For the

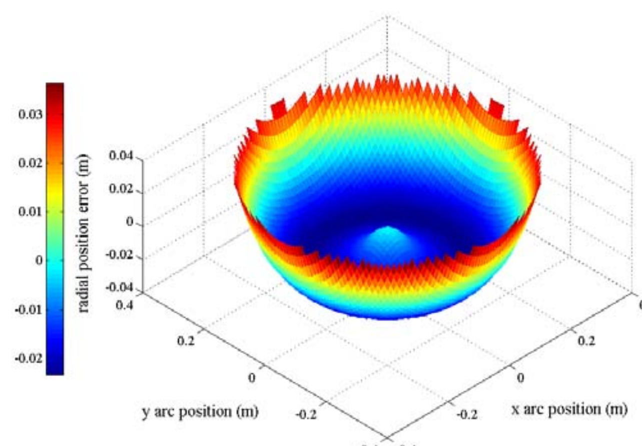

Figure 3. The radial position difference (error) between FEM arc locations and calculated arc locations using the single arc method.

final melts examined, the electrodes had previously been melted at least once. Fig. 4 shows a waveform for some of the data during a final melt. The highest signal to noise ratio can be found when the electrode gap is in line with the sensors. As the electrode gap moves away from the stationary sensors, the signal decreases and part of the magnetic field emanating from the arcs moves to the z-axis. B_z was measured, but it is not utilized in this paper.

A. *Arc Position Validation*

The arc position determinations were compared to melt view video. The camera looks down the axis of the furnace, as shown in Fig.1, and can see the melt pool surface that is in view between the electrode and crucible. The video is not part of the automated control system, but rather gives an operator indication that the electrode is centered in the furnace and there is no side-arcing. Gross movement of arcs can be observed, such as when they gather together on one side of the electrode. A video frame with a determined arc position superimposed can be seen in Fig.5. Arc position was determined with the single arc method.

B. *On the Number of Arcs*

Perhaps the most significant challenge to the measurement system is that the number of arcs present at an instant is unknown. Although unknown, we can learn something about the number of arcs from the data. Consider the case where the arcs are centered about the middle axis of the furnace. If there were a single arc, or if there were hundreds of arcs, than the result would tend to be the same: all sensor elements would read zero field and the single arc calculations from the different sensors would agree that the arc location was in the exact middle of the furnace. Helping this evaluation is that many systematic errors, such as those associated with the current measurement, tend to be negligible when the arcs are centered. Centered arc sensor agreement can be seen in the data. However, what is far more prevalent is disagreement in arc position amongst sensors on the order of 0.05 to 0.1m and these distances change during short time scales.

In the FEM, different fixed numbers of arcs can randomly

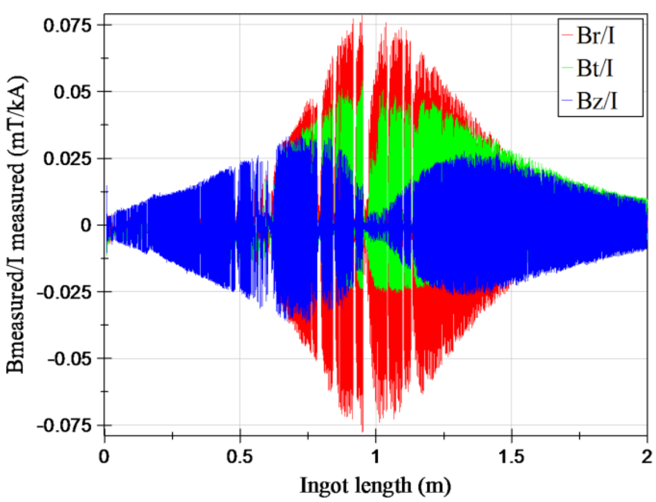

Figure 5. Waveform showing some of the measurements during a melt. The sensor was located at a position corresponding to an ingot length of about 1m.

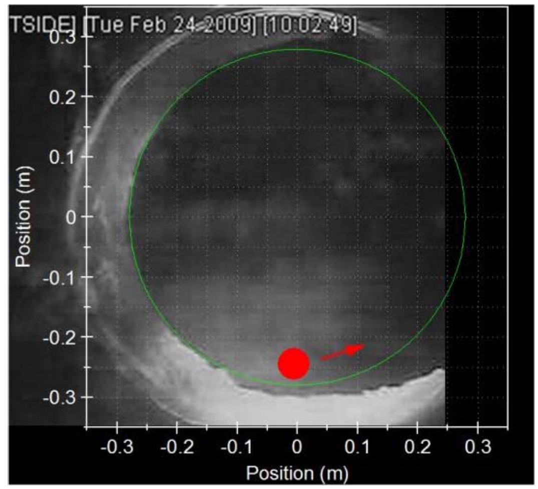

Figure 4. Determined arc position superimposed on top of a video frame at an instant. The arrow indicates the direction of arc motion, as observed in both the video and the arc postion data.

be moved about, and the effect on the single arc location data can be observed. This analysis showed that the number of arcs likely exceeded 4 at an instant. However, it does appear that the number of arcs is low enough to warrant continued development of the described approach to locate arcs.

We can also compare solutions when solving for different numbers of arcs. A single arc was solved for with the inverse solution. Two and four arcs were solved for as a forward problem assuming equal current in each arc and forcing the resulting found arc positions to be geometrically balanced around the single arc method's predicted arc position. Using the single arc method in this way makes the computation quicker, and reduces position errors that can result from unequal weighting of the closest sensor when the arcs gather on one side of the furnace. Fig. 6 shows some root sum of squares (RSS) data for solutions with the indicated fixed numbers of arcs. As noted, this does not reflect solutions that strictly show a minimum in the RSS. The point is that going from a single arc to a multiple arc method does significantly reduce the RSS. Still, the single arc method can detect gross movements of the arcs and thus has use as a real time diagnostic.

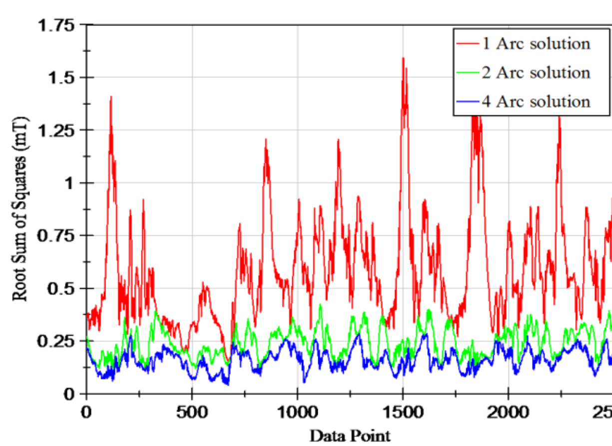

Figure 6. The RSS for the difference between the measured magnetic fields and the calculated magnetic fields for the best found arc positions when solving for the indicated number of arcs.

C. Arc Distribution and Motion

Arc position data using the single arc method were processed with a 2-d histogram having a bin size of 1cm x 1cm. This distribution data were taken over an ingot length change of about 15cm, and typical results are shown in Fig.7. Patterns A, B, and C are taken from final titanium melt operations. The pattern for A is consistent with that which would arise from a diffuse collection of arcs providing a centered distribution of energy into the ingot, whereas pattern B indicates that more energy is entering the ingot near the side wall (with the crucible). Pattern C was observed less often than the other two. Pattern D is typical for results seen during primary melt operations, where the crucible size is smaller and the melting current only about half of what is seen during final melts. Thus pattern D may yield a simlar distibution of energy into the melt pool as pattern A, but the pattern could appear different because there are not as many arcs present or becasue the diameter of a cluster of arcs is smaller.

The arc motion in terms of rotations for A, B, and C are shown in Fig. 8. The rotation pattern in B and C appear to relate to the externally mounted stirring coil. The stirring coil generates a z-direction (axial direction) field inside the furnace which is thought to help confine arcs to the gap as to prevent side-arcing (arc from electrode to crucible). The stirring coil can also have an effect on molten pool motion. For these experiments, the stirring coil current was DC current and the polarity of the coil was switched at regular intervals. This polarity switch leads to the arc rotation direction changes seen in B and C. For B the arc rotates around the center of the furnace at a near constant speed before switching, whereas in C the arc makes only half a rotation with each switch. This rocking back and forth leads to the "winged" pattern as seen in Fig. 7. The stirring coil is on during A, but the switch of the coil does not usually have an effect on rotations. It is also interesting that there is consistently some net rotation about the furnace axis. It is not clear what might cause these net rotations, or whether this has significance to the melt.

Changes in arc distribution and motion, for example from pattern A to pattern B, have also been observed during a melt. A given melt does seem to result in one distribution pattern being more prevalent than another. It is believed this has more to do with differences in the processing of the electrode pre-VAR, as opposed to differences in the VAR operation parameters. Indeed, patterns A, B, and C can be found for the same alloy having the exact same VAR operation control parameters. This indicates that the measurement system is providing new information. This information could potentially be used to achieve the desired distribution pattern during melting.

IV. CONCLUSIONS

This paper describes a technique to determine positions of arcs inside a vacuum arc remelting furnace. The non-invasive measurement system was successfully applied to an industrial VAR furnace during production of titanium alloy. Refinement of the system remains a work in progress. The following conclusions can be made.

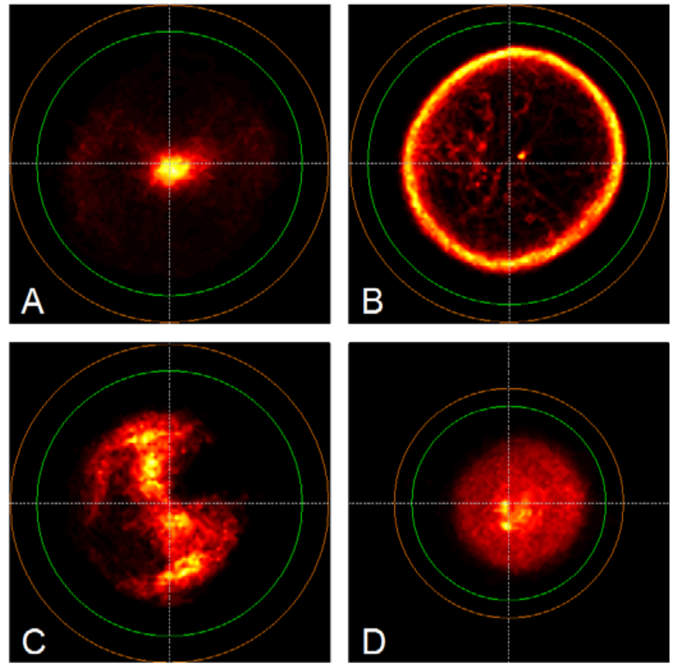

Figure 7. Four types of arc distribution patterns observed during Ti. VAR melting. Color intensity (hot color map) corresponds to the number of insistences the center of the arcs were found at the corresponding position. The inner circle represents the electrode and the outer circle the crucible. The view is looking down the axis of the furnace.

There is significant arc position information in external magnetic field measurements at frequencies below 25Hz during industrial VAR titanium alloy production employing a stirring coil. The data were consistent with the presence of multiple arcs at an instant. The application of 4 sensors could not conclusively locate all the arcs present, which is not surprising, but the results were consistent with a finite number of arcs that could be located if additional sensors were applied. By applying a large number of sensors, the described approach could be used to construct an electric current density tomogram at the electrode side of the gap. This would likely require assumptions on the diameter of the arcs. Construction of a tomogram on the ingot side of the gap cannot rely on the total

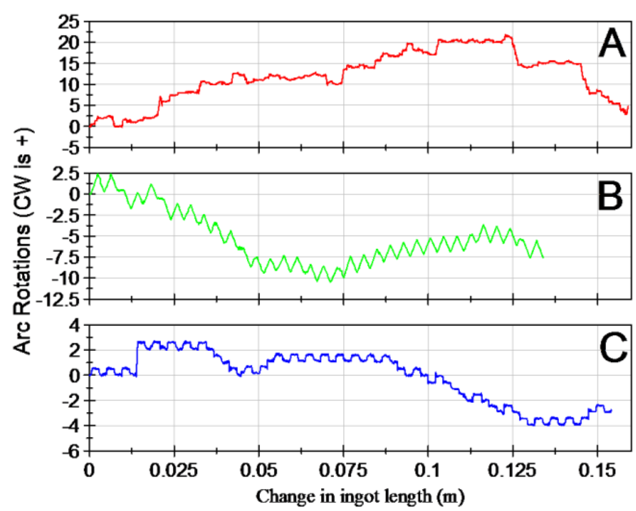

Figure 8. Arc rotation about the axis of the furnace when viewed from above where 1 rotation is 2π radians. The letters correspond to those in Fig. 7.

circuit current measured, and so a modification to the described approach would be needed. An ingot side electric current density tomogram would allow for prediction of the flow pattern in the melt pool due to the magneto hydrodynamics, in addition to quantifying the spatial and temporal distribution of energy into the melt pool.

A single arc method was used to identify 3 different arc distribution patterns during final titanium alloy melting. It is proposed that the observed patterns represent different types of arc distribution modes. The single arc method utilized is simple, cost effective, and can be retrofitted on existing furnaces. It is already capable of real time monitoring.

There does not appear to be any overall correlation between VAR operation parameters and the prevalent arc distribution mode present. This indicates that the measurement system is providing new information. With feedback from the measurement system, gap length or stirring coil current could be modified in order to achieve the desired arc distribution. Identification and avoidance of defect favoring arc distribution modes during melting could lead to lower incidences of rejected ingots, and improved quality control.

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