FEEDBACK-BASED CONTROL OVER THE SPATIO-TEMPORAL DISTRIBUTION OF ARCS DURING VACUUM ARC REMELTING VIA EXTERNALLY APPLIED MAGNETIC FIELDS

Matt Cibula[1], Paul King[1], and Josh Motley[1]

[1]Chief Scientist, Ampere Scientific, 1546 SW Industrial Way, Albany, OR 97322

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Abstract

Ampere Scientific's *VARmetric*™ measurement system for Vacuum Arc Remelting (VAR) furnaces passively monitors the distribution of arcs over time during VAR in real time. The arc behavior is known to impact both product yield and quality and can pose potentially catastrophic operating conditions. Arc position sensing with *VARmetric*™ enables a new approach to control the heat input to the melt pool. Transverse external magnetic fields are applied to push the arcs via the Lorentz force using feedback of the arc location to control the arc. This has been tested on Ampere Scientific's small-scale laboratory arc furnace with electromagnets used for control for up to 60 seconds while monitoring the arc location with *VARmetric*™. The arc distributions are shown to be significantly different from the uncontrolled distributions with distinct thermal profiles at the melt pool. Alternatively, this type of control can be periodically applied to react to undesirable arc conditions.

Introduction

Vacuum Arc Remelting (VAR) furnaces are the workhorse for the manufacture of high value metals and alloys (Ni, Ti, Nb, Zr, Hf, etc.). During VAR, the input material (electrode) is lowered into a water-cooled copper crucible and heated under vacuum by an electric arc (50kW-5MW), the liquid metal drips into the crucible, and the molten pool solidifies into a homogeneous ingot. [1] The controllable parameters of the solidification process, including the input heat (current and voltage), crucible dimensions, materials, and cooling rate, are critical to the production of defect-free homogeneous materials. [2] These input parameters and boundary conditions control the properties of the molten pool, such as the pool depth, solidification angle, Rayleigh number, liquid velocity, and circulation time – all of which affect the persistence of defects, such as inclusions, freckles, white spots, etc., into the final ingot. [3] Despite the importance of producing defect-free ingots for safety-critical applications, including jet engines and medical implants, the VAR process has remained relatively unchanged since its introduction in the 1940s. Notable improvements in control include the addition of cameras to visually monitor the melt around the outside of the electrode, which have improved safety during the melting process by separating the operators from the furnace and helped to better understand the arc dynamics [4, 5], and the introduction of drip-short control over the vertical position of the electrode to fix the melt rate [6, 7]. While drip-short control may provide more consistent melting and heating over time, it does not affect direct control over the location of the arc and the spatial distribution of heat at the surface of the melt pool.

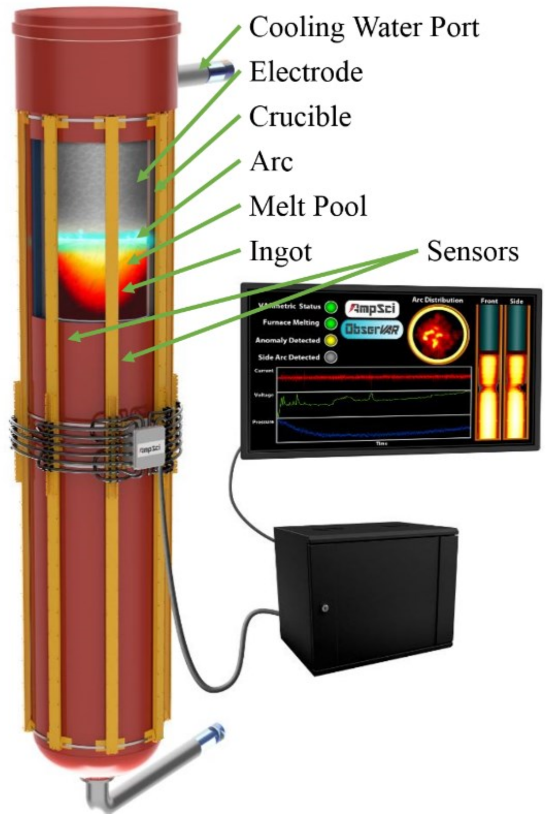

Figure 1 - VAR furnace with VARmetric™ sensors to monitor the distribution of arcs beneath the electrode.

The energy input for VAR is provided by a large (>5 kA) DC electrical current which bridges the gap between the electrode and the melt pool surface in the form of a vacuum arc. The current path through the furnace generates a magnetic field that changes over time as the arc moves around the electrode. Recently, methods utilizing measurements of the magnetic field to monitor the arc have been established to study the arc behavior. [8, 9] The Arc Position Sensing (APS) technology [10] was initially proven at the National Energy Technology Laboratory, Albany, OR, and developed into the *VARmetric*™ measurement system, which performs continuous, real-time measurements of the arc during VAR hundreds of times per second. [11] *VARmetric*™ combines an array of magnetic field sensors with simultaneous measurement of the furnace current and knowledge of the furnace's electrical geometry to calculate the centroid of the arc. [12] This measurement can be utilized to generate a detailed map of the spatial distribution of the heat input to the melt pool. These results have already shown that the heat distribution is not generally axisymmetric about the center of the furnace or constant throughout the melt, in contrast to the typical parameters used in modeling solidification. For example, some computational models have shown that changing the heat distribution from a Gaussian shape to a donut shape may alter the solidification angle near the sidewall, impacting sidewall yield and quality. [5, 2] Because most solidification models have assumed a static Gaussian, axisymmetric heat input, not much is known about the correlation of these new measurements to the final ingot yield and quality. The few papers that relax axisymmetric or Gaussian assumptions indicate that the real-time arc dynamics have a profound affect on solidification models that cannot be predicted with these assumptions in place. [13] For example, the Rayleigh number is used as an indicator of freckle formation, and transient models show a 300 times increase due to thermal perturbations provided by a rotating arc [14]. Mr. Motley further examines this problem with axisymmetric models in relation to the types of changes in arc distributions during melting that were observed by *VARmetric*™ on an industrial furnace. [15]

This paper reports on the development of the Vacuum Arc Control (VAC) technology, which couples feedback from APS through *VARmetric*™ with externally applied transverse magnetic fields to directly control the arc location, and thus provide a means of avoiding operational conditions leading to defects. Previous attempts to control the arc distribution in VAR with external transverse magnetic fields have only attempted to use a 'recipe' – such as a continuously rotating or switching magnetic field – to effect control over the arcs, but lacked information about the arc location and response to the fields. [16, 17] Axial magnetic fields applied to the furnace are often used as a process enhancement in VAR for certain alloys, but without regard to their impact on the arc distribution. [18] They are typically intended to stir the melt pool to improve homogeneity in Titanium melting, but very few studies exist on how these applied fields modify the arc distribution in VAR. The VAC work presented here represents the first time that the authors are aware of where external magnetic fields have been applied to control arcs with simultaneous magnetic-field based measurements of the arc.

Experimental Arc Furnace

The experimental VAR system was designed to emulate the physical and operational conditions of an industrial scale VAR at a research scale. Figure 2 shows the physical apparatus, including the vacuum chamber, vacuum pump, gas feed valve, horizontal adjustment feedthroughs, electrodes, electrical input and output feedthroughs, and a 15 kW (0-510 A, 0-80 V) power supply. This system was supplemented with *VARmetric*™ to monitor the arc location in real time at 150 Hz; synchronized video cameras to visually confirm the arc location measurements; and, a pressure transducer to monitor pressure swings. The system is configured with a fixed lower electrode and a movable upper electrode to draw the arc to a fixed gap size of 0-3 cm. The electrodes are copper (upper) and stainless steel (lower) cylinders with 5.08 cm diameter surfaces, although for longer duration tests the lower electrode was extended to include a 7.62 cm diameter drip cup to contain liquid metal. This scale was chosen to keep the density of arcs on the electrode surface similar to industrial conditions. Assuming 70A/arc, the experimental furnace provides an arc density of 0.044-0.088 arcs/cm^2, while industrial furnace may melt up to 100 cm diameter electrodes with 5kA to 50kA, resulting in a typical density between 0.0091-0.36 arcs/cm^2. Therefore, in terms of spacing between arcs, the experimental arc furnace is within the industrial operating regime for VAR.

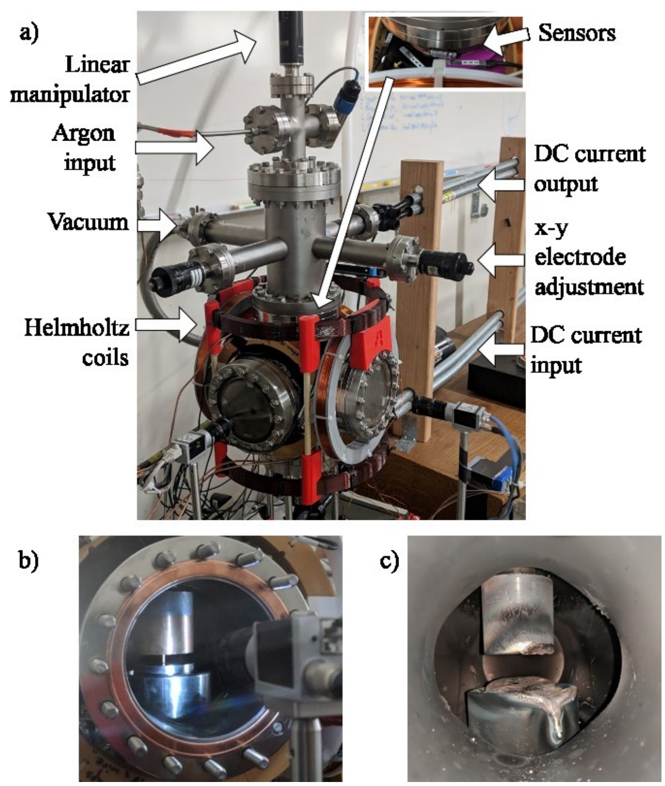

Figure 2 – a) Arc furnace arrangement including 3-axis Helmholtz coils, with the inset showing VARmetric™ sensor locations. b) Copper and steel electrodes configured with a copper bridge to calibrate sensors. c) electrodes upon completion of a test.

Arcs within the furnace can typically be defined as diffuse, constricted, or semi-constricted. A spatially diffuse arc is shown in Figure 3a – over the exposure time, 6 ms, there appears to be a single dim arc column, whose width nearly

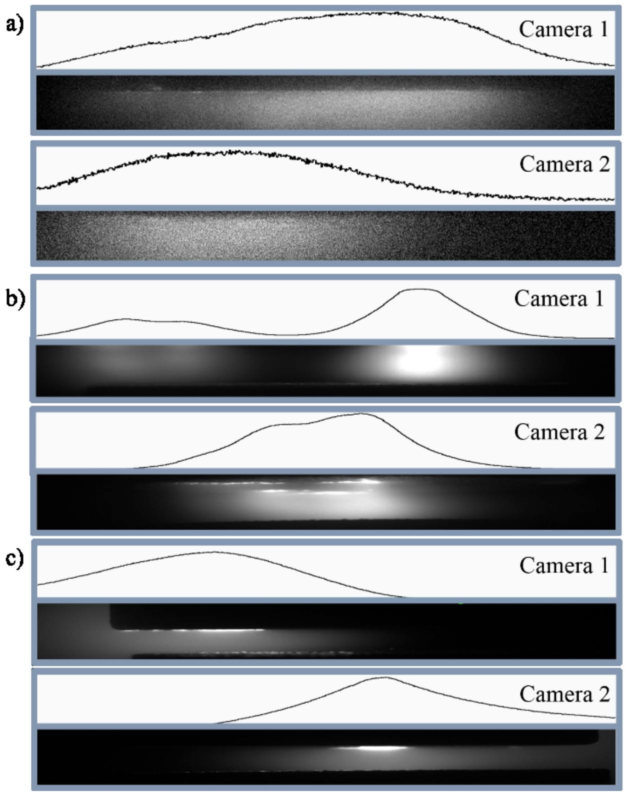

Figure 3 - (a) Diffuse, (b) semi-constricted, and (c) constricted arcs over 5.08 cm diameter electrodes with a 1 cm gap. Images taken with a 6 ms exposure time.

covers the entire electrode. The centroid measured on this type of arc appears as a slowly varying, confined spot near the center of the electrode. Alternatively, a semi-constricted arc distribution is composed of a few constricted columns, approximately 1 cm in diameter, during an exposure, Figures 3b and 3c. The cathode spots and their plasma columns move rapidly across the surface of the electrode, typically moving out from the center and travelling up the side of the electrode before extinguishing. Finally, for a constricted arc, all of the arc columns are focused to a tight (1-2 cm) region on the electrode for an extended period of time (>5 seconds).

The location of the arcs in this furnace can be measured by analyzing the video images independently of the installed *VARmetric*™. The 'single-arc' method of APS applies the Biot-Savart law to calculate the arc centroid from electromagnetic measurements of the furnace [9]. For example, and as the only nonunique case, a completely random distribution of many arc columns over the surface of the electrode, a homogeneous glow discharge, and a centered constricted arc would all result in a measurement of the centroid of the arcs at the center of the electrode and are only distinguishable by higher order statistical measurements. Similarly, video images are analyzed by measuring the center of mass of the light intensity distribution emitted by the plasma beneath the electrode (Figure 4a). For tests ranging from 10-60 seconds, with 1500-9,000 measurements, the correlation coefficient between the two measurements was >0.95, indicating good agreement between the two measurements. Figure 4b provides a comparison of the measured arc distributions over time for each method with the furnace at 250 Amps. The distribution plots are generated by treating the arc as a Gaussian distribution of current around the centroid location, with a full width at half max diameter of 1 cm. At 500 A (Figure 4c), the distribution is concentrated to the center of the electrode – the increased number of arcs tends to average out the arc locations towards the center of the furnace.

Vacuum Arc Control

In order to push the arcs with an external magnetic field, the 3-axis Helmholtz coil system was designed to apply uniform fields (-40 to 40 Gauss, >92% uniformity) in any direction in a 5.08 cm diameter sphere around the center of the furnace. This is approximately the same order of magnitude as the stirring coils used on some industrial furnaces, which are known to affect the distribution of arcs beneath the electrode, as well as apply forces to stir the melt pool. The fields

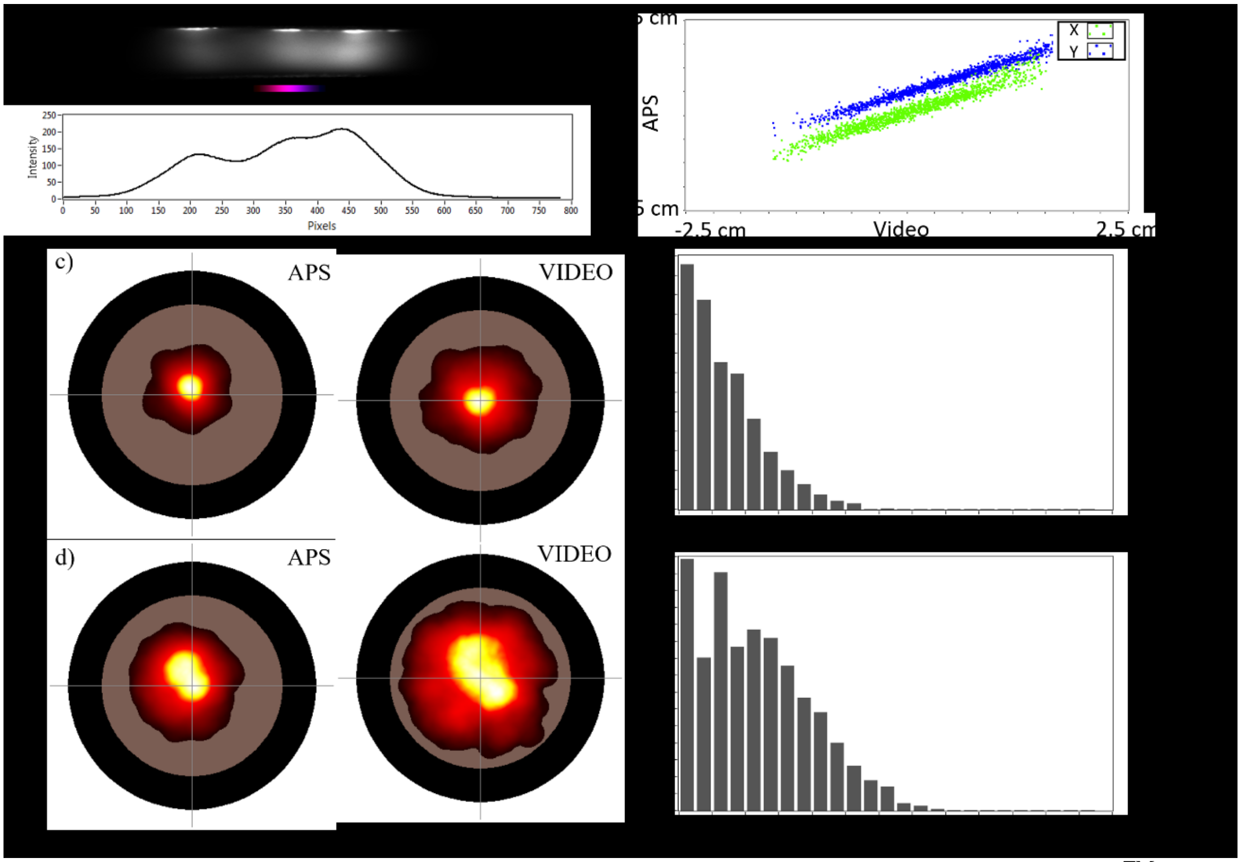

Figure 4 - Comparison between measurements of the arc centroid taken by VARmetric™ and by image processing. a) Image taken by one of the cameras and the arc luminosity measured within the gap, showing the centroid measurement overlaid on the image. b) Correlation between APS and luminosity centroid measurements over 20 seconds of arc location measurements. c) and d) compare the arc distributions and centroid measurements for an uncontrolled arc at 500 Amps and 250 Amps. The black ring extends to the 7.62 cm diameter drip cup, while the copper ring extends to the 5.08 cm diameter electrode surfaces.

were generated with a set of switching DC power supplies, which were able to reverse the direction of the field within 0.1 seconds.

Figure 5 shows the effect of a transversely oriented magnetic field on the distribution of arcs over 10 seconds compared to an uncontrolled arc. Prior to activating the translational control of the arc, the camera images also show a semi-constricted arc with 1-3 columns that moves across the parallel surfaces. Meanwhile, the arc distribution is nearly centered and spread out, and covers most of the electrode surface. Histograms of the arc radius and angle measurements show a broad distribution, indicating that the arc is moving freely about the electrode as might be expected. After applying the control field, the arc moves predictably in response to the Lorentz force, F_L, to one side of the electrode and remains focused at that location. Arc radius and angle are commensurately constricted as indicated in the histograms. This action was verified with at least 30 tests at varying control field strengths and directions. At higher field strengths, it was possible to extinguish the arc by pushing the arc to the edge of the electrode, while at lower levels the average arc radius was

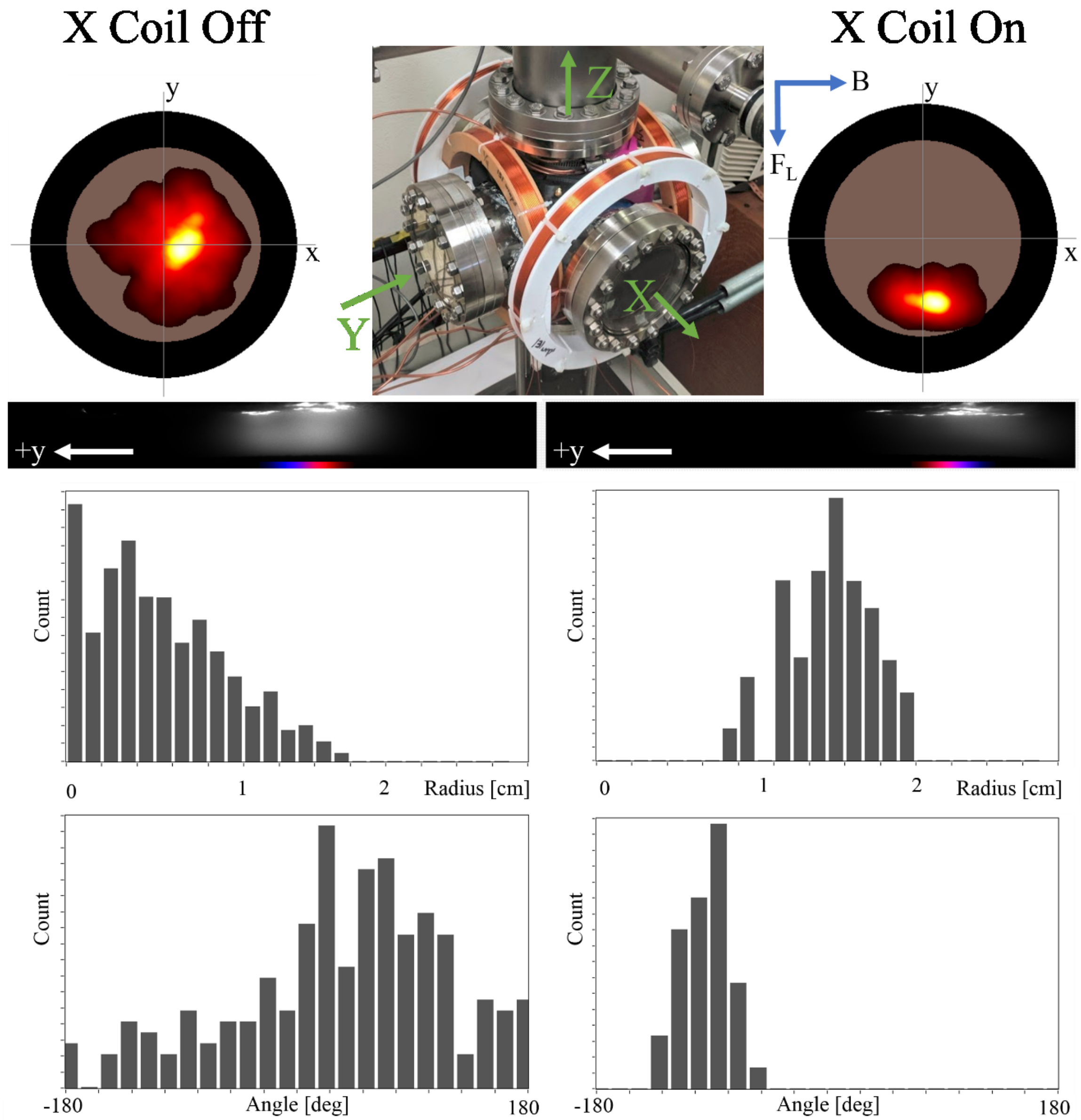

Figure 5 - Arc distribution before (left) and after (right) applying a uniform, transverse magnetic field to the arc gap in the x-direction. Initially the arc is free to roam about the 5.08 cm diameter electrodes, but after the control is applied the arc moves in the direction of the Lorentz force. For the duration of these tests, the arc remained pinned to that side of the electrode until the control field was changed.

reduced. It should be noted that unlike a VAR, this arc furnace does not have sidewalls that could conduct the arc beyond the edge of the electrode, so it might be expected that this behavior could push the arc from the melt pool to the sidewall or vice versa.

Using the transverse magnetic field controller, the distribution of the arc over time was continuously controlled by switching the orientation of the magnetic field every second between 8 different directions over 180 degrees. The results for each control step are provided in Figure 6a, while b) shows how the total controlled arc distribution over 8 seconds compares to an

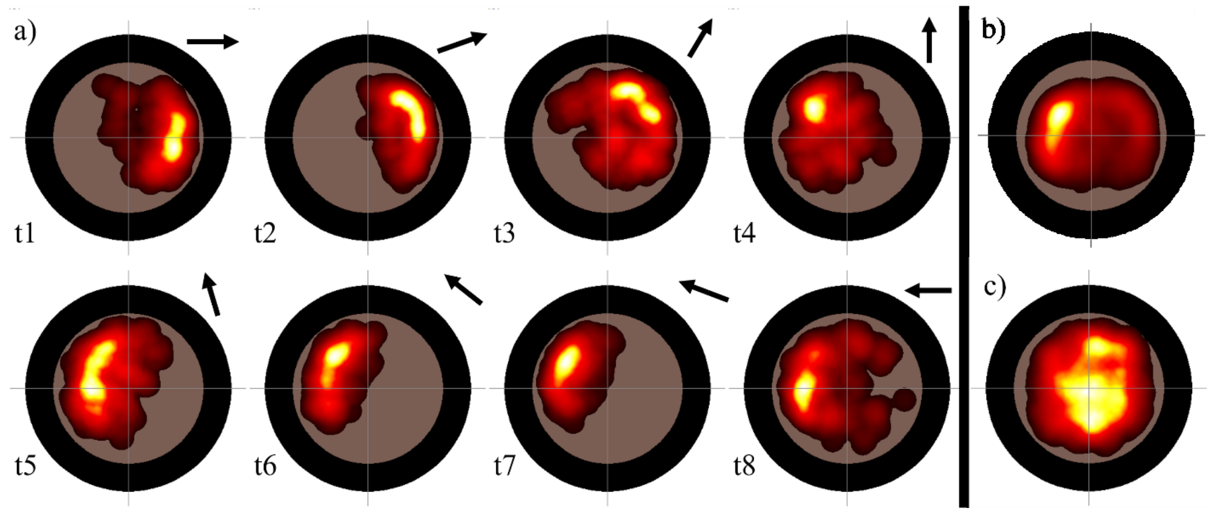

Figure 6 – a) Arc distributions, each of which shows 1 second of measurements, over a total of 8 seconds for a controlled arc as the control field is rotated around 180 degrees. The direction of the Lorentz force is indicated by the overlaid arrow for each time step. The total arc distribution over the 8 second control, b), shows that the arc spends more time near the edge of the electrode than an uncontrolled arc distribution over the same time period, c).

uncontrolled distribution, c), over the same time frame in the same melt. While the uncontrolled arc forms a Gaussian distribution around the center of the electrode, the control fields focus the arc off-center to about 2/3 of the electrode radius and pushes the arc around the electrode. Similar arc distributions have been measured by *VARmetric*™ on industrial titanium alloy VAR furnaces, for example. However, in this case the arc distribution is controlled, and the arcs move in the direction expected by the Lorentz force for each field direction.

Conclusions

This paper presents results of utilizing a synchronized measurement system to control arc locations, and more importantly arc distributions, as a function of time. A purpose-built experimental vacuum arc remelting furnace was constructed to accommodate both the Arc Position Sensing Technology, *VARmetric*™ as well as the vacuum arc control mechanism to exacting laboratory standards for accuracy in measurements. The VAC comprised a series of orthogonally positioned Helmholtz coils designed to provide a uniform field in a specified direction at the center of the VAR and across the electrode area. By actuating the different fields individually, the resultant control force vector is completely tailorable with response characteristics in the millisecond time frame. Through varying the application of the coil current, arbitrary control vectors in the x-y plane are achievable as a continuous function of time.

While the type of control demonstrated here did not utilize active feedback from the APS, further developments in the hardware and software for the test furnace enabled longer melting (up to 90 seconds at 500 Amps) and real time control over the applied field. The user interface for the controller software allowed the user to choose the direction of the desired Lorentz force with the mouse and hence provide a corresponding field from the Helmoltz coils to accommodate the desired force. This controller interface was provided side-by-side with a real-time arc distribution plot so that the user could act in response to changes in the arc distribution. The tests proved that this type of control enabled the user to 'push' the arc out of constrictions and apply more even heating to the surface of the unmelted electrode, while uncontrolled arcs typically stuck to one side of the electrode and rapidly melted the surface in that region.

Ampere Scientific continues the development of the *VARmetric*+VAC on an industrial furnace under funding provided by the National Science Foundation. Implementation of the industrial trials are to begin in late 2019 where feedback from *VARmetric*™ will be integrated with the VAC to control arc distributions, and consequently the heat flux for segregation prone alloys. In parallel, solidification modeling is being used to predict pool shape as a function of heat flux towards development of an integrated tool able to measure, predict, and control solidification as a function of heat flux where, for example, the instantaneous arc distributions over time (Figure 7) are used to provide feedback for the control algorithm.

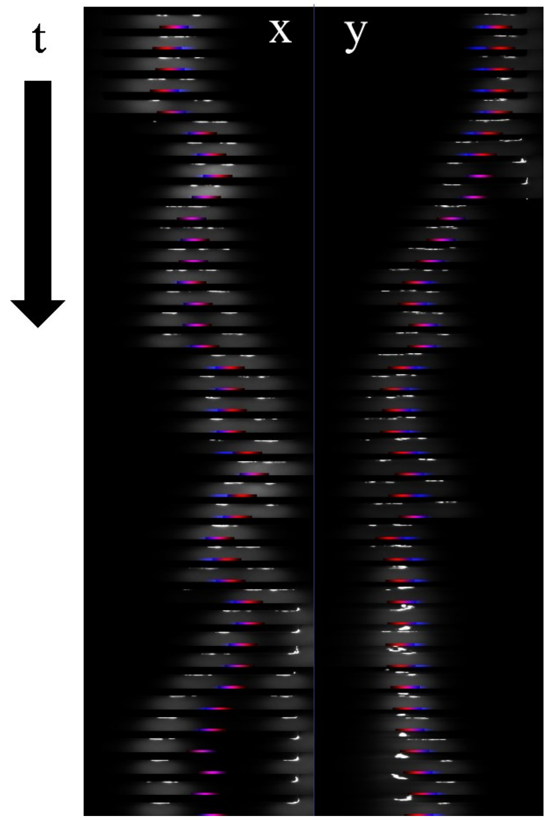

Figure 7 – x-y plots of instantaneous arc distributions as a function of longitudinal axis of the ingot providing a vector centroid and distribution standard deviation as feedback for control, including tracking lines from video and VARmetric™.

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