SAND99-0025C

ESR Process Instabilities while Melting Pipe Electrodes

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Abstract

With the demonstration of the viability of using the electroslag remelting process for the decontamination of radionucleides, interest has increased in examining the unique aspects associated with melting steel pipe electrodes. These electrodes consist of several nested pipes, welded concentrically to a top plate. Since these electrodes can be half as dense as a solid electrode, they present unique challenges to the standard algorithms used in controlling the melting process. Naturally the electrode must be driven down at a dramatically increased speed. However, since the heat transfer is greatly influenced and enhanced with the increased area to volume ratio, considerable variation in the melting rate of the pipes has been found. Standard control methods can become unstable as a result of the variation at increased speeds, particularly at shallow immersion depths. The key to good control lies in the understanding of the melting process. Several experiments were conducted to observe the characteristics of the melting using two different control modes. By using a pressure transducer to monitor the pressure inside the pipes, the venting of the air trapped inside the electrode was observed. The measurements reveal that for a considerable amount of time the pipes are not completely immersed in the slag, allowing the gas inside to escape without the formation of bubbles. This result has implications for the voltage swing as well as for the decontamination reactions.

This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000. Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Introduction

The Electroslag Remelting (ESR) process has long been utilized to refine metals and produce fully dense ingots because it provides controlled solidification and the slag can be effectively used to control the chemistry of the resulting ingot.[1] ESR is used both as an intermediate and as the final stage in the production of a wide range of alloys including stainless steels and premium grade superalloys. The remelting in an ESR furnace, as shown in Figure 1, essentially takes place by immersing a consumable metal electrode into a molten slag bath that is resistively heated usually with AC current to a temperature above the melting point of the metal. The electrode gradually melts, coalescing into metal droplets. Since the metal is considerably more dense than the molten slag, the droplets eventually fall through the slag and collect in a pool below the slag. The remelting is all contained inside a water cooled copper mold. The mold removes heat, causing the molten metal to solidify. The controlled remelting of the electrode eliminates the voids and pipe that often occur in cast electrodes. The slag used for a particular application must provide the appropriate electrical properties for the heating as well as the required chemical reactions to yield the desired ingot composition.[2]

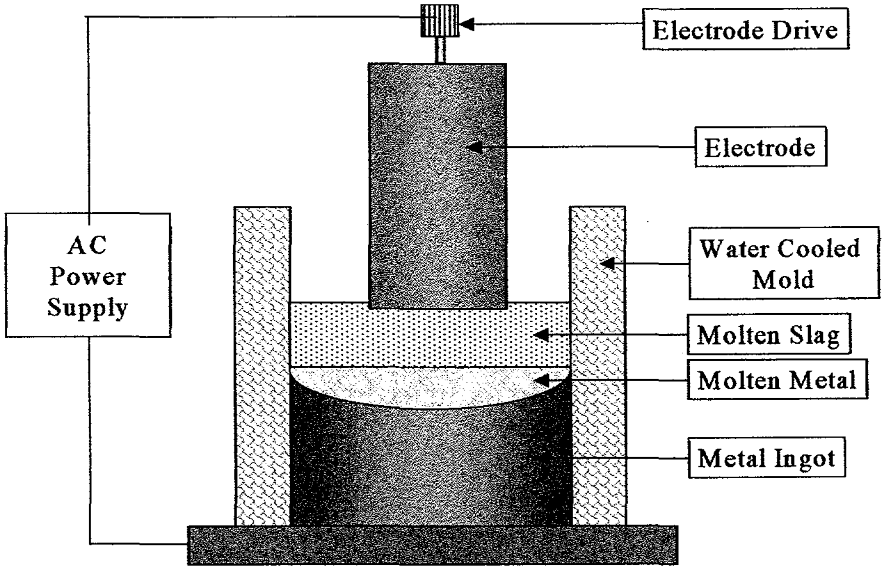

Figure 1: ESR Furnace Schematic

The unique capability in ESR for changing the chemistry of the electrode has led to the evaluation of the process for the removal of radioactive contaminates from scrap metal. In the decontamination of radionucleids, the reactions can take place at three locations: at the electrode tip, as the droplet moves through the slag and at the molten pool. Buckentin investigated the removal of non-radioactive rare earth elements from 304L stainless steel.[3] Various slag compositions with different percentages of CaF_2, Al_2O_3 and CaO were used and analyzed according to melting efficiency, ingot surface quality, slag entrapment, partitioning of the surrogates in the slag cap and slag skin, and the resulting ingot chemistry. The analysis showed the removal of the contaminates below the detection limit of 1 ppm regardless of the slag composition used. However there was wide variation in the other important properties including ingot surface quality, slag entrapment, slag skin thickness and the partitioning of the surrogates.

In this paper, the unique aspects of melting pipe are discussed. First the theoretical control instabilities are outlined from the electrical and thermal perspectives. Then the two different control methods used in this investigation are summarized. Finally the experimental results using two common slag compositions are presented. The discussion focuses on the issues concerning voltage swing and the entrapped air with special consideration given to the aspects that could impact decontamination.

Instabilities in Melting Pipe Electrodes

Since much of the contaminated scrap metal is in the form of stainless steel pipes, the effort of this research is to evaluate the control strategies available as they pertain to the melting of pipes. This discussion will relate to a pipe electrode, which is made from six different readily available sizes of pipe with inside and outside diameters shown in Table 1. The pipes are nested and welded to a top plate to form the electrode. The average gap between the pipes is shown in the last column.

Inside Diameter (m)	Outside Diameter (m)	Pipe Thickness (m)	Gap (m)
0.025	0.032	0.006	0.006
0.038	0.048	0.010	0.002
0.050	0.060	0.010	0.016
0.076	0.089	0.013	0.013
0.102	0.114	0.012	0.013
0.127	0.143	0.016	

Table 1: Pipe Sizes

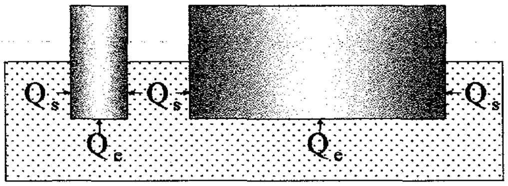

Figure 2: Side and End Heat Transfer Ratios

In pipe electrodes, the heat transfer to the electrode will happen very differently since the ratio of the area on the side to the area on bottom, in contact with the slag is considerably different. At a typical immersion depth of 0.005 m, this ratio for a solid electrode with a diameter of 0.143 m is 0.14.[4] For the pipe electrode described above, the ratio for all the pipes combined is an order of magnitude greater at 1.6. With different side-to-bottom ratios as illustrated in Figure 2, the primary direction of the heat transfer changes from Q_e for solid electrode, to Q_s for the pipes. At shallow immersions, this heating will produce rounded ends on each individual pipe. If the immersions are deep, the melting on the sides can happen fast enough that a pinching effect will occur and very rapid changes in the immersion depth will result. The relationship between the voltage and immersion depth generally follows the relationship given by

$$V = (I d) / (A k) \tag{1}$$

where V is the voltage, I is the current, d is the distance between the electrode and the molten metal pool, A is the area of the electrode in contact with the slag and k is the slag conductivity. The voltage in the furnace with the pipe electrode will be considerably more sensitive to changes in immersion, since these changes will effect all twelve sides of the nested pipes. This increased sensitivity has implications for the control algorithms. However, it is difficult to precisely define the changes because of the rounding of the ends and the impact of the entrapped air.

The entrapped air will impact both the heat transfer and the resistance of the system as it affects the effective area of the electrode in contact with the slag. The pressure inside the electrode will rise as the electrode melts and gets shorter, forcing the slag out of the pipe. Consequently less of the pipe will be in contact with the molten slag. The lower temperature and the poorer heat transfer properties of the air should reduce the heating on all the inside pipes and will impose an asymmetric heat profile on the outside pipe, reducing the melting from the inside out. In addition, the decrease in the effective area will increase the electrical resistance, raising the voltage and causing the controller to drive the electrode deeper. However, when the pressure finally reaches a high enough value to cause some of the air to bubble out of the pipe, the situation is quickly reversed. This continually reversing situation could lead to instability in controls as well as nonuniform melting.

In addition to the thermal environment and the instabilities caused by the entrapped air, the fill ratio for the pipe electrode is also considerably different. For a fully dense electrode 0.143 m in diameter melted into a 0.203 m mold, the fill ratio is about 2. However since the pipe electrode is 46% void, the fill ratio increases to approximately 3.6. To achieve the melting rate needed for good surface quality, a fairly high average electrode drive speed will be required, adding yet another complication to the control algorithm.

Control Methods

To produce high quality, homogeneous ESR ingots, both the melting rate and electrode immersion depth into the slag need to be controlled. The melting rate used depends on the required solidification grain structure of the ingot, the ingot surface quality, the elimination of defects and the economics for the manufacturer. While maintaining the melting rate is an important part of modern controller, this paper will concentrate on the second aspect of control, the immersion depth, since it presents a greater challenge when melting pipe electrodes. The depth needs to be held to a constant shallow level, or the surface quality of the ingot will be degraded. However, at shallow immersion depths the process is less stable and without proper care, arcing between the electrode and the slag can occur, producing deleterious reactions. Two distinct approaches for controlling ESR are available: the typical Voltage Error (VE) mode and the Constant Voltage (CV) mode.

Basically the VE mode maintains the immersion depth by varying the electrode speed and controls the melting rate by changing the current. Since no technique exists to measure the immersion depth directly, the depth must be inferred from measurable quantities. Based on (1), it might appear that the proper immersion depth could be achieved simply by moving the electrode up or down to match a particular voltage level or set point. However because the slag conductivity varies between melts and even within a single melt with temperature changes, and as slag reactions take place, the relationship is not adequate to define the immersion depth.[5] Consequently, modern algorithms use voltage swing instead as a measure of immersion depth. The swing is a value characterizing the voltage variation (typically the standard deviation) over a prescribed length of time. It results from variation in the melting process and the electrode movement. To control the depth, the electrode is driven up and down in the slag at a speed linearly proportional to the difference between the actual voltage and a voltage set point, causing additional voltage variation. For a more detailed explanation of VE controls see the reference below.[6]

Alternatively, the CV mode maintains the immersion depth by varying the current and sets the melting rate with the electrode drive speed. This method also uses a voltage set point as the initial predictor for the depth. This set point is sent directly to the power supply, which is configured to hold the voltage constant by changing the current. At a constant electrode speed, the current changes will alter the instantaneous melting rate, thereby controlling the depth. This type of immersion control is more responsive, since actual changes in the electrode speeds are relatively slow compared to the speed that the power supply can vary the current. Voltage swing is also used as the metric for the immersion depth, however its variation will be smaller, since the power supply is configured to hold it constant. As discussed by Schlienger, this method is theoretically more stable than the VE mode.[7] Consequently, because of the additional instabilities involved in melting pipe, the CV mode is of considerable interest in this study.

Experimental Results

The investigation into the melting of pipe electrodes as listed in Table 1 was conducted in a series of six experiments shown in Table 2. The first four melts used steel pipe with $33^1/_3$% CaF_2, $33^1/_3$% CaO and $33^1/_3$% Al_2O_3 slag and the last two used stainless steel pipe with 60% CaF_2, 20% CaO and 20% Al_2O_3 slag. The melting rate for the last two was lower because of the less resistive slag. The first two melts were vented by drilling a hole through all the pipes, while the third melt had no venting. The inside pressure was monitored on the final three melts. A pressure equalization hole drilled between all the inside pipes to eliminate the complicating factors that could result as air moved between the pipes on the inside. Then a hole was drilled through the top plate into the gap between the outer two pipes. A pressure transducer was then connected to this hole so the internal pressure could be monitored. Both VE and CV modes of control were employed in these melts. The voltage set point was held constant during the periods when the CV mode was being used.

	Control Mode	Electrode	Slag	Voltage	Melting Rate	Vented
Melt 1	Voltage Error	Steel Pipe	33/33/33	45 volts$^+$	2.5 kg/min	Yes
Melt 2	Constant Voltage	Steel Pipe	33/33/33	45 volts	2.7 kg/min	Yes
Melt 3	Constant Voltage	Steel Pipe	33/33/33	45 volts	2.7 kg/min	No
Melt 4	Constant Voltage	Steel Pipe	33/33/33	45 volts	2.7 kg/min	Inside
Melt 5	Constant Voltage	Stainless Pipe	60/20/20	37 volts	1.9 kg/min	Inside
Melt 6	Both	Stainless Pipe	60/20/20	37 volts$^+$	1.8 kg/min	Inside

$^+$ indicates several Voltage Set Points

Table 2: ESR Pipe Electrode Melts

The instabilities in melting pipe using the conventional VE mode in the first melt led to unacceptably large voltage oscillations. The typical VE algorithm uses a symmetrical response to a positive or negative voltage error with no offset. To bring the process under control, an offset needed to be added. The large fill ratio precludes the possibility of melting in a controlled fashion without an offset. At the desirable melting rate, the maximum speed of the electrode drive is insufficient to keep up with the required average speed without having to oscillate between the maximum and some nominal value. Since the speed would be zero when the voltage matched the set point but the electrode would be melting at a rate as fast as 30 to 40 mm/min, the actual voltage would be consistently above the voltage set point which in itself would be more unstable. In addition, the mechanical and process delays in response to these large changes in the commanded speed lead to a very unstable situation for control. The natural solution is to use the average speed as the offset. Due to the rapid changes in the process with the pipes, a relatively short time average proved best.

However even with the offset, the control of the immersion depth proved to be inadequate and the large oscillations persisted. Since the first electrode was vented, the oscillations were not being caused by the air inside the pipes but were the result of the rapid, uneven melting of the pipes. The large heat flux into the sides of the pipes periodically caused rapidly decreasing immersion depths. The magnitude of the decrease requires the controller to respond to process changes with fast electrode drive speeds. However, the inherent delays in the drive response and in monitoring and determining the state of the ESR process prevent the controller from responding in a timely fashion. Actually these delays in ESR control are at least partially responsible for the drive generating the voltage swing when melting solid electrodes. However because the pipe electrode drive response is larger than the response required for solid electrodes, the electrode in this melt was driven considerably above and below the appropriate voltage level in an effort to maintain the immersion depth. By reducing the magnitude of the upward response, the oscillation was damped. Note the transition of the voltage shown by Figure 3 from a symmetric response during 12:12 to 12:15 where the peaks often approached open circuit levels, to the signal after 12:15 when the downward response was four times greater than the upward response. The effective voltage for the immersion depth however was not affected by this change. Once these changes were implemented, the VE control mode proved to be stable, even at shallow immersion depths.

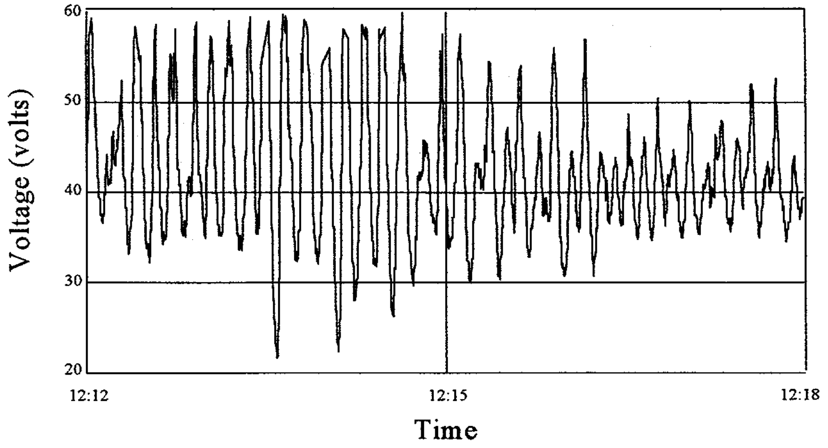

Figure 3: Voltage Swing change with Asymmetric Response in Melt 1

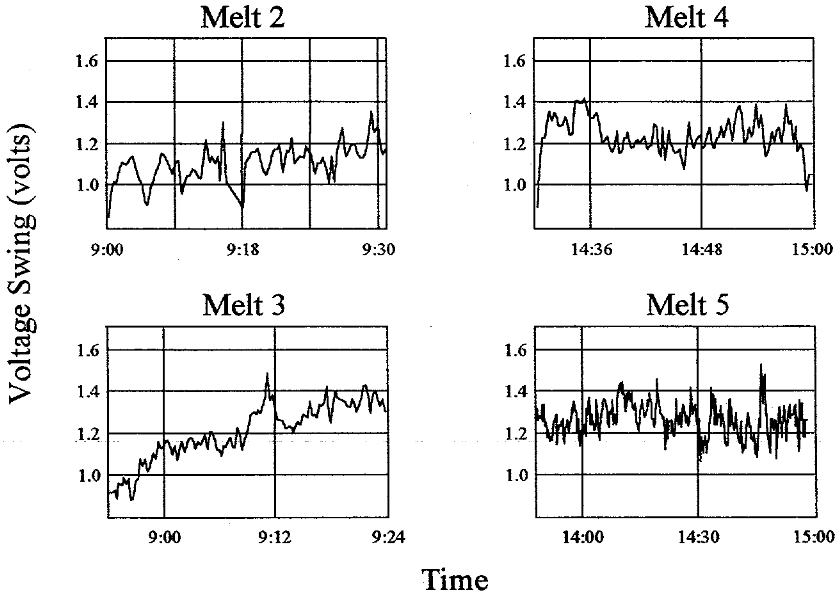

Figure 4: Voltage Swing for Melts 2,3,4 and 5

The next four melts clearly demonstrated the inherent stability advantages of the CV control mode. They were all completed in a stable fashion without any modifications to the algorithm. By changing the venting, they also provided insight into the mechanism of melting pipe. As shown in Figure 4, the voltage swing increased during both melts 2 and 3. Keep in mind that the electrode drive speed in this control mode is held constant. For these melts, the speed was set at 35 mm/min. So the swing was not being generated by moving the electrode up and down in the slag but rather was a consequence of the melting itself. Since the voltage set point was fixed, and electrode was vented, the rise in swing can be attributed to changes in the process (e.g. slag conductivity or temperature). In the next melt with no vent hole in the electrode, the increase in the swing was somewhat greater. However, the pattern and magnitude was similar enough that no definite conclusions could be drawn about the impact of the air inside the pipe.

Melts 4 and 5 were then conducted to further investigate the impact of the entrapped air. For these melts, the swing over the course of the melts was relatively similar and flat (see Figure 4), even though the melt rates and slags were considerably different. The air was still trapped inside the electrode since the outside pipe was not vented, however no bubbling between the inside pipes took place because of the internal pressure equalization hole. Figure 5 shows the correlation between the inside pressure and the impedance during Melt 4. When the impedance dropped below a certain level, the pressure rose rapidly, indicating that the end of the outside pipe was completely submerged in the slag, sealing the end from the atmosphere outside the pipe. But the pressure did not stay high for very long before it rapidly dropped. However, it does not appear that these drops were purely the result of bubbles since the pressure remained low for a considerable amount of time after the drop before starting to rise. These long periods indicate that the electrode was not making complete contact with the slag for a majority of the time. Portions of the pipe were melting completely out of the slag, allowing the air to vent without bubbling, even though the electrode was being driven down at the constant speed of 35 mm/min. Because the pressure remains low for such long periods of time, it seems likely that the venting location shifts to different area on the pipe rather than being the result of a single melt back. Consequently, estimating the amount of melt back at particular locations is difficult. However, since the electrode is effectively vented to the atmosphere for such long periods, the air is not a significant factor in the swing.

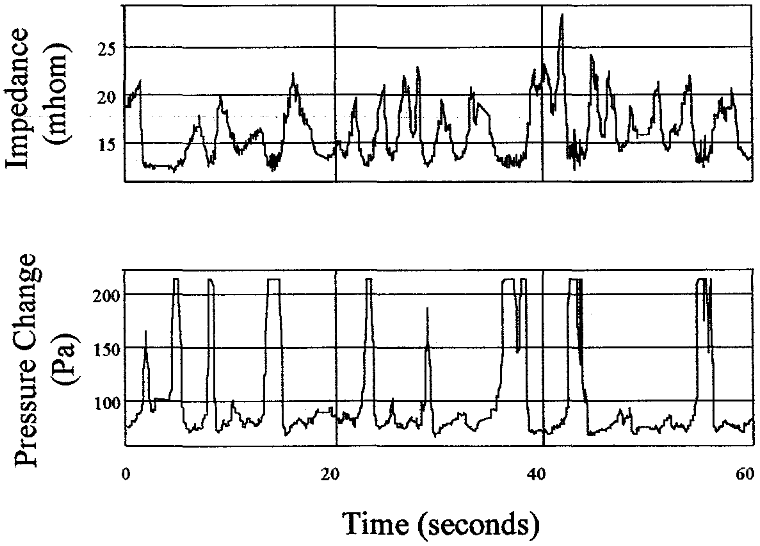

Figure 5: Impedance and Pressure for Melt 4

The final melt dealt with some of the remaining issues associated with venting. Since the VE mode changes the drive speed, the amount of venting with the changing speed needed to be investigated. With the movement of the electrode, the sealing and unsealing of the pipe with the slag could be affected. The pressure signals when using the VE mode however did not appear significantly different from the signals measured during the CV mode. The formation of bubbles and the melting back apparently occur much faster than the electrode drive can respond.

Figure 6 shows the period of the last melt under CV mode where the voltage level was being changed. The pressure signatures indicative of bubbling occurred at a voltage level of approximately 26 volts. The pressure gradually built up as the electrode melted over the period of approximately 3 seconds. The air then bubbled out, causing an immediate rapid pressure drop of around 124 Pa. The bubbles were visible on the slag surface. Considering the density of the molten slag, this change in pressure represents about a 1 mm change in immersion depth. This depth is to be expected since the bubbles developed about every 3 seconds, and the drive speed was 23 mm/min. Immediately after the bubble, the pressure began building again. The transition to the state where the electrode was melting out of the slag, occurred at about 27 volts. At that level, longer periods of low pressure occur. For controlling in a stable fashion close to the surface, the voltage was set at about 34 volts. At 26 volts, the swing was about 1/3 the swing at 34 volts. A large portion of this difference occurred in the change from 26 to 27 volts when the voltage swing almost doubled, indicating the large impact that the melting back with loss of contact has on the swing.

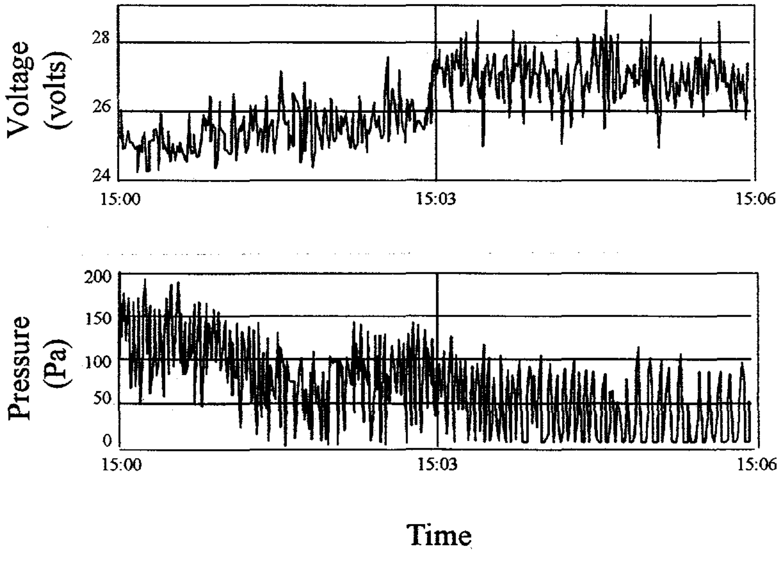

Figure 6: Pressure and Voltage for Melt 6

As noted by Buckentin, surface quality and slag skin thickness are very important in the area of decontamination.[8] The ingot surface quality for all the melts for both slags was generally very good and the slag skin thickness were relatively thin. The only change occurred when the voltage set point was lowered to 26 volts in Melt 5. This voltage is much lower than would typically be used in the melting of pipes. The surface quality at this level was only slightly worse but the slag skin was about 50% thicker. Also the heat transfer to the mold was reduced. The difference between the inlet and outlet water temperatures dropped by almost 25%.

As mentioned previously, it is difficult to determine from the pressure and electrical information how far the electrode melts back. So, for Melts 4 and 5, the power was turned off before the electrodes were completely melted. By examining the ends of these electrodes, indications of the melting back are readily available. The ends of all the pipes for Melt 4 were generally round, except for one location about 20 mm long on the outer pipe which had melted back further by approximately 2 mm. The end was concave, with the center melted in about 5 mm more than the outer edge. This shape indicates that the air was not a significant factor in reducing the heat transfer to the inner pipes. In fact the heat transfer in the center was greater. However, as shown in Figure 7, the end of the electrode for Melt 5 was very irregular. The outer pipe has spots on the upper left and right edges (marked A) where the metal had melted back about 3 mm. The center pipe had melted back about 5 mm more than the outer edge. In addition, there were areas (marked B) which had melted back an additional 5 mm. The inside pipes on the left (marked C) show the expected round ends as the pipes melted, but this shape was on a much smaller fraction of the surface than on the previous melt. Many of the other pipes, (e.g. the front edge of outer two pipes marked D), had sections, where the melting was clearly from the inside out. This type of melting may lead to the melt backs since as the pipe gets thinner, it will reach a point where the remainder of the pipe will rapidly melt. Melt 5 was run at a lower voltage set point than Melt 4, so the irregularities seen on its cap may be attributed to the pinching effect described earlier.

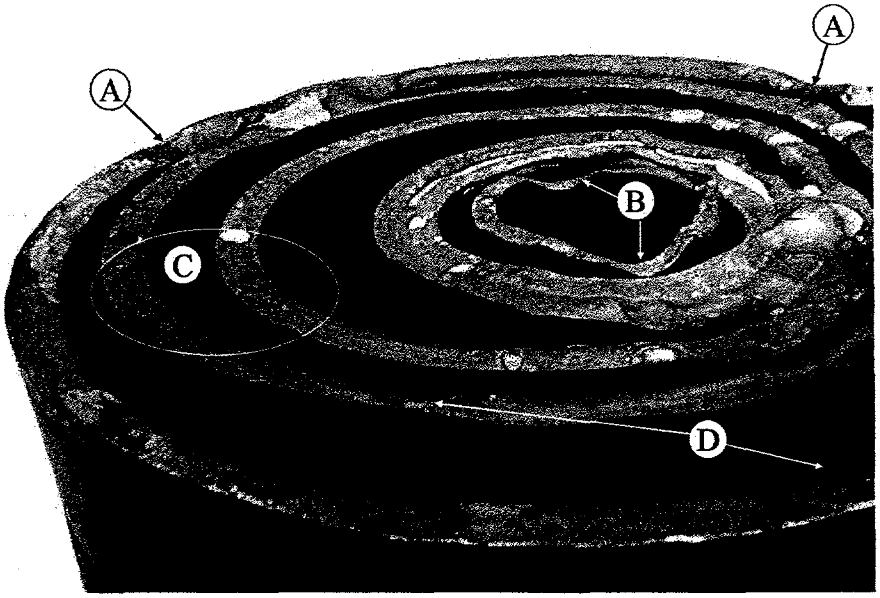

Figure 7: Pipe Electrode Cap for Melt 5

Conclusions

As expected, the melting of pipe electrodes in ESR is less stable than the melting of solid electrodes. The unique thermal transfer properties cause uneven melting of the electrode. The standard CV mode of operation proved stable enough to control the melting of pipe electrode. With some modifications to the standard algorithm, the VE mode proved to be stable as well. Neither mode proved to be significantly superior in terms of stability or in the resulting ingot quality. The CV melts revealed aspects of the melting mechanism. The nonvented pipe showed an increased swing over the vented pipe, but not enough to demonstrate a difference. The reason was discovered in the last melts. These melts revealed the strong tendency for the pipes to melt out of the slags. When this event occurs, the effect of the air in the pipe is significantly reduced.

To achieve the state where bubbling occurred, the voltage set point had to be significantly reduced. However, because of the increased slag skin thickness, decreased cooling, and greater irregularities on the electrode tip which occur at that voltage level, higher voltage levels are recommended for melting pipe electrodes. However with higher voltages, as already mentioned, sections of the electrode melt out of the slag. When this happens, it has some implications for the decontamination reactions. The potential reaction sites noted earlier are at the electrode tip, between the molten drops and the slag, and between the slag and the molten pool. For surface contaminates, the period when the electrode is in contact with the slag is optimal, because the ratio of volumes of the slag to the molten metal is much more favorable for the desired reactions. However, if the pipe melts out of the slag, the surface of the electrode does not come in contact with the slag, eliminating this reaction site.

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