Effect of Current on Metal Transfer in SAW
Part 2: AC

Most detachments occur during the electrode positive cycle of alternating current

BY V. SENGUPTA AND P. F. MENDEZ

ABSTRACT

The effect of current on metal transfer in submerged arc welding (SAW) between 500 and 1000 A for alternating current (AC) polarity was directly captured in videos at 10,000 frames/s by inserting a thin-sheet steel tunnel perpendicular to the welding path. Analysis of the videos showed many similar features as observed for direct current electrode positive (DCEP) and were discussed in Part 1 of this paper. The key feature in AC is the electrode negative (EN) cycle with mobile cathode area on the droplet surface. Droplet detachment is much affected by current and polarity. The detachment frequency increased with increasing current and was found to be higher than corresponding DCEP experiments at lower currents. The detachment frequency increased from 28 Hz at 500 A to 76 Hz at 1000 A. The detachment frequency for both DCEP and AC converged at higher current. The detachment morphology was often different in EP and EN cycles. At 500 A, analysis of the videos showed the detachment in the EP cycle takes place without forming a molten metal tail. Between 600 and 1000 A, the detachment in the EP cycle was based on electromagnetic kink instability giving it a "whipping tail" kind of detachment. In the EN cycle, the detachment took place through explosions. Most of the detachments (approximately 72%) were in the EP cycle. Analysis of weld cross sections showed similar features before, during, and after the tunnel. The weld pool flows were found to be consistent with previous experiments done with radioactive tracer techniques.

KEYWORDS

- Electrode Positive Cycle
- Electrode Negative Cycle
- Electromagnetic Kink Instability
- Explosions

Introduction

The physical phenomena in submerged arc welding (SAW) takes place under a flux bed and is not visible directly. Alternating current (AC) polarity has limited use in gas metal arc welding (GMAW) but is commonly used in the case of SAW. Modern hardware to produce square waveforms and AC in SAW is also capable of producing more sophisticated waveforms. However, due to lack of understanding of the metal transfer in SAW, this capability is seldom used.

In literature, very limited work has been reported on metal transfer in AC polarity in SAW. Part 1 of this paper (Ref. 1) discussed all the relevant literature available related to this topic. Among all the researchers, only Adrichem (Ref. 2), Mendez et al. (Ref. 3), and Gött et al. (Ref. 4) have reported carrying out metal transfer studies in AC SAW. Adrichem used a 3.2-mm (0.125-in.) wire and studied the metal transfer between 300 and 600 A with AC polarity. The work reports the observations of metal transfer in SAW but nothing specific was mentioned related to AC SAW. Mendez used a 3.2-mm (0.125-in.) wire and reported that for 500 A, the metal transfer in AC is similar to DCEP. Mobile cathode spots were observed on the droplet surface in the EN cycle. Gött et al. (Ref. 4) did experiments at 600 A, AC and reported movement of cathode spots all over the droplet surface during the EN cycle.

The present work explores the effect of current on the metal transfer mode in SAW between 500 and 1000 A with the use of high-speed videos captured at 10000 frames/s for a 3.2-mm (0.125-in.) wire in AC polarity. The cross sections before, during, and after the tunnel were compared for all currents. The electrical signal was analyzed for an experiment.

Experimental Setup

The experimental setup, camera setting, and consumables were explained in Part 1 of the paper. All experiments were made by program 59 (CC Square Wave Steel 0.125 in.) with a frequency of 60 Hz and balance of 50% electrode positive (EP) and 50% electrode negative (EN) cycle. The offset was kept at 0% to maintain the same current during the EP and the EN polarities. Data acquisition was carried similar to that in Part 1 of this paper.

The welding parameters are listed in Table 1. The voltage was varied with the intention of keeping a constant average visible arc length of 4.85 mm (0.19 in.) [corresponding to an average electrode...
extension of 26.90 mm (1.06 in.). The frames used to measure the visible arc length are reported in Table A1. Travel speed was also increased with the aim to keep a relatively uniform nominal heat input of 51.45 kJ/in. (2.03 kJ/mm) on average. The important variation between welds is in the welding current varying between 500 and 1000 A in 100-A intervals. The travel speed was directly recorded from the gantry display. The procedure to estimate all the related errors has been explained in Part 1 (Ref. 1).

Analysis of High-Speed Videos in AC Polarity

Six high-speed videos of metal transfer in SAW were uploaded as supporting online material (SOM) (Ref. 5). The uploaded videos were rendered at 25 frames/s, which corresponds to a factor of 400 in the time dimension. Many more experiments were conducted but failed as falling flux blocked the camera view. Droplet detachment was much affected by current and polarity. At 500 A, the metal transfer was through the formation of a chaotic, irregular-shaped droplet. At 600 A and above, the detachment morphology was often different in the EP and EN cycles. The metal transfer in the EP cycle was based on electromagnetic kink insta-

Table 1 — Parameters Corresponding to AC-SAW experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Video</th>
<th>Polarity</th>
<th>RMS Current A</th>
<th>RMS Voltage V</th>
<th>Average WFS m/min</th>
<th>Travel Speed m/min</th>
<th>in./min</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>SOM9</td>
<td>AC</td>
<td>530.50 ± 0.364</td>
<td>30.13 ± 0.020</td>
<td>2.04 ± 0.002</td>
<td>0.457</td>
<td>18</td>
</tr>
<tr>
<td>66</td>
<td>SOM10</td>
<td>AC</td>
<td>622.29 ± 0.462</td>
<td>32.83 ± 0.020</td>
<td>2.66 ± 0.002</td>
<td>0.604</td>
<td>23.76</td>
</tr>
<tr>
<td>55</td>
<td>SOM11</td>
<td>AC</td>
<td>720.19 ± 0.347</td>
<td>36.02 ± 0.023</td>
<td>3.19 ± 0.001</td>
<td>0.762</td>
<td>30</td>
</tr>
<tr>
<td>67</td>
<td>SOM12</td>
<td>AC</td>
<td>813.50 ± 0.418</td>
<td>37.80 ± 0.024</td>
<td>3.63 ± 0.001</td>
<td>0.914</td>
<td>36</td>
</tr>
<tr>
<td>57</td>
<td>SOM13</td>
<td>AC</td>
<td>920.53 ± 0.770</td>
<td>39.11 ± 0.031</td>
<td>4.19 ± 0.004</td>
<td>1.092</td>
<td>43</td>
</tr>
<tr>
<td>64</td>
<td>SOM14</td>
<td>AC</td>
<td>1011.60 ± 0.882</td>
<td>41.89 ± 0.033</td>
<td>4.82 ± 0.005</td>
<td>1.280</td>
<td>50.4</td>
</tr>
</tbody>
</table>
bility giving it a “whipping tail” kind of detachment. In the EN cycle, the metal transfer typically takes place through explosions. An instance of the effect of polarity on droplet detachment can be seen in video SOM12 (800 A, AC). Frames 4520 to 4580 of Video SOM12 show an EP cycle with a detachment event based on electromagnetic kink instability taking place between frames 4550 and 4565. Frames 4430 to 4490 of video SOM12 show an EN cycle with a detachment event based on explosions taking place between frames 4460 and 4475. A lot of spatter is generated in the EN cycle. The frames corresponding to the visual identification of droplet detachment for each experiment are listed in Appendix B.

The average detachment frequency increased with current. Most detachments (approximately 72%) took place in the EP cycle. The average detachment frequency based on the frames was calculated and shown in Fig. 1. The average droplet size based on detachment frequency, wire diameter, and average wire feed speed is represented in Fig. 2. The calculation of average droplet diameter with associated error is explained in Part 1 of this paper (Ref. 1). Table D1 summarizes the detachment frequency and droplet diameter for all currents. Up to 800 A, the weld pool meniscus is no longer seen in the videos; beyond this the weld pool is below the original plate surface and not visible.

Fig. 4 — The effect of current on bead width in AC polarity. A slightly wider bead is observed during the tunnel except for cases when the solidifying molten tail ended inside the tunnel.

Fig. 5 — The effect of current on penetration. A gradual increase in penetration is observed, and between 800- and 900-A molten metal meniscus is no longer seen in the videos, consistent with a change in penetration mode from recirculating flows to gouging penetration.

Fig. 6 — Cross sections before, during, and after the tunnel of the welds done with AC. For reference of scale, average thickness of the substrate was 9.65 mm (0.38 in.) (single plate) and 19.32 mm (0.76 in.) (two plates).
Video SOM9 corresponds to Experiment 60 (500 A, AC). It was run with similar conditions to Experiment 71 (500 A, DC) (Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the electrode positive (EP) cycle lasted approximately 85 frames (3.4 s in rendered video) and the electrode negative (EN) cycle lasts approximately 80 frames (3.2 s in rendered video). The light from the arc dimmed out during the polarity switch. Frame 3464 showed the start of the EN cycle. The droplet is observed to be irregular in shape due to the erratic movement of the cathode area (bright area on the droplet). The EN cycle lasted until frame 3545 and then the EP cycle started. Frame 3678 captured a moving cathode area at the left surface of the droplet and then moved to the center by frame 3686. Explosions observed were similar to DCEP experiments.

Video SOM10 corresponds to Experiment 66 (600 A, AC). It was run in similar conditions to Experiment 68 (600 A, DC) (Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the EP cycle lasted for approximately 78 frames (3.1 s in rendered video) and the EN cycle lasted for approximately 78 frames (3.1 s in rendered video). The switch between the EP and the EN cycles can be seen similar to Experiment 60 except when the weld pool blocks the view. Frame 4470 captured a cathode area in the right corner of the droplet that then moved to the center by frame 4480 and then to the left by frame 4489. It is mobile until the cycle ends at frame 4533 and gives the molten metal an irregular shape. Frames 5875 to 5901 show the tapering of the electrode and then detachment similar to one observed for Experiment 68 (600 A, DC). The molten metal exploded into fine drops in the EN cycle that spread randomly in all directions. One such explosion can be seen in frame 6339.

Video SOM11 corresponds to Experiment 55 (700 A, AC). It was run with similar conditions to Experiment 47 (700 A, DC) (Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the EP cycle lasted approximately 85 frames (3.4 s in rendered video) and the EN cycle lasted approximately 79 frames (3.2 s in rendered video). Frame 1947 (in the EN cycle) captured a cathode area that is at the bottom of the molten metal and moves to the left by frame 1953 and then to the right by frame 1957. Between frames 3590 and 3601, a detachment event took place; the molten metal detached forming a characteristic "whipping tail." It should be noted that the "whipping tail" kind of detachment takes place only in the EP cycle and is different from that observed in the EN cycle. The molten metal in the EN cycle was observed to be irregular in shape. Frames 4982 to 6605 show the electrode surrounded by the flux grains falling from the top giving a good representation of the process under fluxes. The detachment frequency was found to be higher than that observed with the DC experiment done with the same parameters. Gases produced from the fluxes, similar to all the previous experiments, can be seen throughout the video.

Video SOM12 corresponds to Experiment 67 (800 A, AC). It was run with similar conditions to Experiment 61 (800 A, DC) (Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the EP cycle lasted for approximately 80 frames (3.2 s in rendered video) and the EN cycle lasted for approximately 80 frames (3.2 s in the rendered video). Frames 4552 to 4559 show the formation of a kink in the molten tail and then detachment. At frame 4569 (in the EN cycle) a cathode area appears on the bottom left of the droplet. It is mobile throughout the cycle giving the molten metal an irregular shape. The cathode area is moving too fast, and it is difficult to quantify its location.

From frame 2267 onward, flux grains can be seen falling from the top. The flux grains falling near the wire were pushed to the side by the erratic arc in the EN cycle. Frames 6994 to 9192 capture the molten pool behind the arc (toward left of welding direction in the video), thus giving a good representation of molten pool phenomena in SAW as reported by Mori and Horii (Ref. 6).

Video SOM13 corresponds to Experiment 57 (900 A, AC). It was run with...
similar conditions to Experiment 58 (900 A, DC)(Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the EP cycle lasted for approximately 86 frames (3.4 s in rendered video) and the EN cycle lasted for approximately 82 frames (3.3 s in rendered video). From the first frame of the video, a tapered electrode was observed ejecting a molten tail. Detachments seem faster when compared to previously conducted experiments with AC at lower currents. Many of the similar features observed in Experiment 58 are present. Frames 1004 to 1031 show the formation of a tapered electrode finally ejecting a molten tail. The ejected molten metal flies sideways, where it may meet the flux and moves down into the weld pool.

Video SOM14 corresponds to Experiment 64 (1000 A, AC). It was run with similar conditions to Experiment 62 (1000 A, DC)(Ref. 1) but with AC polarity. For the balance, frequency, and video parameters used, the EP cycle lasted for approximately 77 frames (3.1 s in rendered videos) and the EN cycle lasted for approximately 81 frames (3.2 s in rendered videos). The EP cycle showed similar detachments as seen in Experiment 62. Frames 450 to 475 show a tapered electrode ejecting a molten tail by a mechanism of electromagnetic kink instability. Frames 1738 to 1773 show the formation of a molten tail that does not detach. A possible reason for this can be insufficient electromagnetic force necessary for detachment. After the experiment, the tunnel top surface on the right side of the welding direction showed a hole that was made by the spatter because of explosions; this shows the importance of the flux in this welding, especially at high currents.

Analysis of Weld Cross Sections

For all the welds discussed here, cross sections were analyzed before, during, and after the tunnel. Figures 4 and 5 display the effect of current on the bead width and penetration, respectively. Figure 6 shows the cross sections of welds, and Table C1 lists the measurements of the cross sections before, during, and after the tunnel for all welds. For most of the cases, the bead width was found to increase gradually with the current. Table C1 shows the reinforcement did not change much with increasing current. These measurements show the tunnel has a small effect on the shape of the bead, with the welds being slightly wider and taller under the tunnel, but with less penetration.

A possible explanation for the differences in cross sections inside and outside the tunnel is the stray arcs shift the energy balance toward the electrode, increasing the amount of electrode melted (thus the larger cross section), but reduce the amount of energy going to the plate (thus the lower penetration). As the stray arcs alternate with arcs to the plate, to maintain the same average voltage the arc to the plate is longer (thus the wider beads). Synchronized videos and data acquisition are needed to support or reject this hypothesis and are the focus of ongoing work.

An analysis of cross sections before and during the tunnel indicates the cross section during the tunnel is on average 62% larger than before the tunnel. A similar analysis of cross sections (Ref. 3) results in increases of 107%. The cross sections of Experiments 57 and 64 were not included in this measurement as the molten tail ended inside the tunnel, thus affecting the measurements. The fact that the difference in cross sections before and after the tunnel decreases with thinner steel for the tunnel is consistent with the explanation suggested.

The increase in the penetration with current is consistent with the observation of gouging penetration, observed clearly at 700 A and above despite constant heat input. The undercut observed for Experiment 64 (1000 A, AC) is due to the very fast travel speed chosen to maintain a constant nominal heat input for that current. The thickness of the plate was measured with a micrometer with 0.001-mm resolution and reinforcement, depth, and width were measured counting pixels in images of 300 pixels per inch resolution giving an accuracy of measurements of the order of 0.1 mm.

Figure 6 shows some artifacts resulting from the experimental setup. For Experiment 67 (800 A, AC), the tunnel did not get cut in a straight line, resulting in a bead with an irregular-shaped reinforcement for the during-tunnel cross section. In experiments at 900 and 1000 A, the molten tail of the weld pool became very long and the weld was stopped before the whole tunnel exited the tunnel (approximately 60 mm or 5 s) after the arc exited the tunnel, while the trailing tail of the weld pool was still under the tunnel, affecting the measurements of cross sections during and after the tunnel because they did not reach steady state before they solidified. The flat top observed for the during- and after-tunnel welds for 900 and 1000 A is due to the trailing tail of the weld pool ending inside the tunnel.

The cross sections of the weld for Experiment 60 (500 A, AC) show an increase of 1.8 mm (0.07 in.) in bead width between before and during the tunnel. An increase of 0.8 mm (0.03 in.) in reinforcement was observed during the tunnel compared to before the tunnel. The difference in penetration was small, with a variation of 0.48 mm (0.02 in.) before and during the tunnel.

The cross sections of the weld for Experiment 66 (600 A, AC) show the penetration is approximately 1.5 mm (0.06 in.) less during the tunnel compared to before the tunnel. The bead was approximately 6 mm (0.24 in.) wider during the tunnel than before the tunnel. The reinforcement during...
the tunnel was 1.5 mm (0.06 in.) lower than that before the tunnel.

The cross sections of the weld for Experiment 55 (700 A, AC) show an increase in penetration compared to previous AC experiments; this is consistent with the gouging region penetration mechanism. The penetration during the tunnel was approximately 2 mm (0.08 in.) less than that before the tunnel. The bead width was approximately 2 mm (0.08 in.) more during the tunnel than before the tunnel. The reinforcement was approximately 5.5 mm (0.22 in.) more during the tunnel than before it.

The cross sections of the weld for Experiment 67 (800 A, AC) show the bead width during the tunnel was 4 mm (0.16 in.) more than that before the tunnel. The reinforcement during the tunnel was 2 mm (0.08 in.) more than that before the tunnel. Figure 6 shows a different reinforcement shape during and before the tunnel.

The cross sections of the weld for Experiment 57 (900 A, AC) show an increase in penetration compared to lower currents. The bead width during the tunnel was approximately 2 mm (0.08 in.) more than that before the tunnel. The penetration during the tunnel was approximately 3.55 mm (0.14 in.) lower than before the tunnel. The reinforcement was similar during and before the tunnel.

The cross sections of the weld for Experiment 64 (1000 A, AC) show an increase of bead width by 3.46 mm (0.14 in.) between before and during the tunnel. The reinforcement during the tunnel was 2.19 mm (0.09 in.) lower during the tunnel than before the tunnel. The penetration was similar during the tunnel than before.

Discussion

The metal transfer observed with this technique was found to be consistent with works of previous researchers and has been discussed in depth in Part 1 of this paper (Ref. 1). The key feature of the AC is the EN cycle and movement of the cathode area; this mobility of the cathode area is in accord with Ref. 7.

The detachment frequency at 500 A, AC was found to be higher than that in DCEP. One possible reason for the higher detachment frequency for 500 A, AC compared to DCEP experiments is the mechanical perturbations (Ref. 1) introduced by electromagnetic forces while switching polarity from EN to EP. The detachment frequency in this range (28 Hz) is of comparable order to the switching polarity (60 Hz). For the currents 600 and 700 A, the higher detachment frequencies observed for AC compared to DCEP for an approximate constant droplet size indicates a similar magnitude of capillary forces for both AC and DCEP, so the higher detachment frequencies are due to the higher amount of wire melted in AC. For example, the ratio of the detachment frequencies for 700 A for AC and DCEP is approximately 1.3 and the ratio of WFS is 1.24, almost the same magnitude. At higher currents (800 to 1000 A), the detachments are governed by the electromagnetic forces, possibly causing the similar detachment frequencies in both AC and DCEP.

The weld pool flows observed in video SOM12 for Experiment 67 (800 A, AC) are consistent with previous nondisruptive experiments using radioactive tracers by Mori and Horii (Ref. 6), shown in Fig. 7. The secondary pool is seen to be lifted above the original substrate surface and is in accord with Ref. 6. The color contrast of the weld pool is the same as that of the molten metal at the tip of the wire, thus confirming it is the molten pool and not molten slag. Researchers interested in this field are encouraged to analyze video SOM12.

The small differences in weld width, reinforcement, and penetration under the tunnel are thought to be because the strays arc shifts the energy balance toward the electrode, increasing the amount of electrode melted (thus the larger cross section), but reduce the amount of energy going to the plate (thus the lower penetration). As the strays arc alternate with arcs to the plate, to maintain the same average voltage, the arc to the plate is longer (thus the wider beads). Synchronized data acquisition is required to check this hypothesis. The reason for the complete penetration observed for the before-tunnel cross section of Experiment 57 (900 A, AC) and after tunnel cross section of Experiment 55 (700 A, AC) is not known.

Conclusions

The effect of current on metal transfer in AC-SAW was captured in high-speed videos. Lincolnweld L-50 wire, 3.2 mm (0.125 in.) diameter, and Lincolnweld 980 flux, basicity index of 0.6, were used for the experiments. Many features observed in AC were similar to DCEP. The key feature for AC is the electrode negative (EN) cycle in which a very irregular-shaped droplet was observed. A moving cathode area was seen on the droplet surface.

Droplet detachment was affected by current and polarity. The detachment frequency increased from 28 Hz at 500 A to 76 Hz at 1000 A. Most detachments (approximately 72%) were in the EP cycle. The detachment morphology was often different in the EP and EN cycles. At 500 A, the detachment in the EP cycle took place without forming a tail. Between 600 and 1000 A, the detachment in the EP cycle was based on the electromagnetic kink instability. The electromagnetic kink instability resulted in a “whipping tail” kind of detachment of the molten metal as observed in the videos. In the EN cycle, the detachment took place through explosions.

The high-speed videos showed penetration mode changes gradually from recirculating to gouging region penetration; this behavior is consistent with results of previous nondisruptive experiments using radioactive tracers. Analysis of the cross sections showed penetration increased with current. The presence of the tunnel had a small but measurable effect on the weld cross sections, resulting in wider and shallower beads under the tunnel.

No streaming or rotating spray-type transfer as in gas metal arc welding (GMAW) was observed; however, it cannot be discarded for wires and fluxes different than those used in this report.

Acknowledgments

The authors would like to thank Lincoln Electric for the power supply, welding consumables, and invaluable technical advice; Praxair for donating carbon dioxide gas; Wilkinson Steel for donating steel plates; Goetz Dapp for help with editing videos; Cory McIntosh and Nairn Barnes for assistance.
with experiments; Adam Ostashek for the metallographic analysis; and Gentry Wood for insightful discussion.

References


5. https://ualberta.ca/~ccwj/Publications/WJ_ECMT_ACSAW/SOM1: ccwj_000035.008.mp4
   SOM2: ccwj_000035.013.mp4
   SOM3: ccwj_000035.003.mp4
   SOM4: ccwj_000035.014.mp4
   SOM5: ccwj_000035.019.xlsx.


Appendix A. Frames corresponding to visible arc length measurements used to calculate electrode extension.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Frames used to measure visible arc length</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 (500 A, AC)</td>
<td>2266, 2591, 2801, 3073</td>
</tr>
<tr>
<td>66 (600 A, AC)</td>
<td>4556, 4670, 6264, 6548, 6722</td>
</tr>
<tr>
<td>55 (700 A, AC)</td>
<td>2259, 2654, 2913, 3659, 4248</td>
</tr>
<tr>
<td>67 (800 A, AC)</td>
<td>3124, 3517, 3691, 3933, 5594</td>
</tr>
<tr>
<td>57 (900 A, AC)</td>
<td>372, 529, 751, 2302, 2526</td>
</tr>
<tr>
<td>64 (1000 A, AC)</td>
<td>214, 280, 480, 878, 1118</td>
</tr>
</tbody>
</table>

Appendix B. Detachment frames corresponding to the high-speed videos of the AC-SAW experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detachment frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 (500 A, AC)</td>
<td>1935, 2166 (EN), 2783 (EN), 3043, 3143, 3420, 4083 (EN)</td>
</tr>
<tr>
<td>66 (600 A, AC)</td>
<td>2073, 2563, 2770, 3356 (EN), 3600, 3884 (EN), 3988, 4191, 4455, 4634, 4822, 5030 (EN), 5052, 5279, 5481 (EN), 5718, 5793, 5902, 6015, 6200</td>
</tr>
<tr>
<td>55 (700 A, AC)</td>
<td>107, 249, 426, 589, 773, 1054 (EN), 1095, 1121 (EN), 1575, 2213, 2543, 2585, 2898, 3383, 3600, 3761, 4015 (EN), 4205, 4237, 4448, 4616</td>
</tr>
<tr>
<td>67 (800 A, AC)</td>
<td>2674, 2750, 3086, 3282 (EN), 3462 (EN), 3664, 3960 (EN), 4133 (EN), 4241, 4472 (EN), 4560, 4737, 4937, 4967 (EN), 5289 (EN), 5494</td>
</tr>
<tr>
<td>57 (900 A, AC)</td>
<td>353, 402, 528, 568, 681, 717, 736, 773 (EN), 852, 993 (EN), 1031, 1218, 1389, 1513, 1531, 1584, 1791 (EN), 1928, 2128 (EN), 2289 (EN), 2420, 2611 (EN), 2783 (EN), 2895, 3177, 3456 (EN), 3613 (EN)</td>
</tr>
<tr>
<td>64 (1000 A, AC)</td>
<td>88, 377 (EN), 476, 597, 692 (EN), 846, 974, 1089, 1175, 1382, 1429, 1504, 1595, 1888 (EN), 1952, 2198 (EN), 2261, 2402 (EN), 2434, 2523 (EN), 2717 (EN), 2886 (EN), 2972</td>
</tr>
</tbody>
</table>
Appendix C. Measurements of cross sections for AC-SAW welds.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location relative to tunnel</th>
<th>Thickness of plate (mm)</th>
<th>Bead width (mm)</th>
<th>Penetration (mm)</th>
<th>Reinforcement (mm)</th>
<th>Cross section (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 (500 A, AC)</td>
<td>before</td>
<td>9.657</td>
<td>17.13</td>
<td>4.11</td>
<td>3.28</td>
<td>40.77</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>9.648</td>
<td>18.93</td>
<td>4.59</td>
<td>4.17</td>
<td>54.21</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>9.622</td>
<td>14.73</td>
<td>4.86</td>
<td>3.32</td>
<td>33.76</td>
</tr>
<tr>
<td>66 (600 A, AC)</td>
<td>before</td>
<td>9.678</td>
<td>14.37</td>
<td>5.81</td>
<td>4.04</td>
<td>40.82</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>9.674</td>
<td>20.78</td>
<td>4.48</td>
<td>2.45</td>
<td>41.13</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>9.698</td>
<td>13.02</td>
<td>7.57</td>
<td>1.62</td>
<td>16.08</td>
</tr>
<tr>
<td>55 (700 A, AC)</td>
<td>before</td>
<td>9.720</td>
<td>15.45</td>
<td>7.48</td>
<td>3.91</td>
<td>42.05</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>9.665</td>
<td>21.18</td>
<td>5.23</td>
<td>5.78</td>
<td>83.05</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>9.689</td>
<td>13.64</td>
<td>10.04</td>
<td>2.15</td>
<td>21.27</td>
</tr>
<tr>
<td>67 (800 A, AC)</td>
<td>before</td>
<td>9.636</td>
<td>13.29</td>
<td>8.36</td>
<td>4.32</td>
<td>40.51</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>9.709</td>
<td>17.49</td>
<td>6.67</td>
<td>6.10</td>
<td>87.94</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>9.652</td>
<td>12.62</td>
<td>8.78</td>
<td>2.90</td>
<td>22.91</td>
</tr>
<tr>
<td>57 (900 A, AC)</td>
<td>before</td>
<td>9.559</td>
<td>12.92</td>
<td>9.52</td>
<td>3.93</td>
<td>35.78</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>9.543</td>
<td>15.36</td>
<td>5.97</td>
<td>3.34</td>
<td>44.41</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>9.555</td>
<td>12.83</td>
<td>8.22</td>
<td>1.76</td>
<td>18.30</td>
</tr>
<tr>
<td>64 (1000 A, AC)</td>
<td>before</td>
<td>19.321</td>
<td>12.59</td>
<td>10.07</td>
<td>5.57</td>
<td>57.46</td>
</tr>
<tr>
<td></td>
<td>during</td>
<td>19.334</td>
<td>16.05</td>
<td>9.79</td>
<td>3.88</td>
<td>58.16</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>19.311</td>
<td>13.96</td>
<td>10.44</td>
<td>2.33</td>
<td>28.55</td>
</tr>
</tbody>
</table>

Appendix D. Detachment frequency and droplet diameter for all AC-SAW experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Average detachment frequency (Hz)</th>
<th>Average droplet diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 (500 A, AC)</td>
<td>27.93 ± 15.29</td>
<td>2.65 ± 0.48</td>
</tr>
<tr>
<td>66 (600 A, AC)</td>
<td>46.04 ± 13.12</td>
<td>2.46 ± 0.23</td>
</tr>
<tr>
<td>55 (700 A, AC)</td>
<td>44.36 ± 14.24</td>
<td>2.67 ± 0.29</td>
</tr>
<tr>
<td>67 (800 A, AC)</td>
<td>53.19 ± 13.44</td>
<td>2.60 ± 0.22</td>
</tr>
<tr>
<td>57 (900 A, AC)</td>
<td>75.23 ± 19.04</td>
<td>2.53 ± 0.20</td>
</tr>
<tr>
<td>64 (1000 A, AC)</td>
<td>76.28 ± 18.64</td>
<td>2.52 ± 0.41</td>
</tr>
</tbody>
</table>

VIVEK SENGUPTA (vsengupt@ualberta.ca) is with Lincoln Electric Company of Canada, Toronto, ON, Canada. PATRICIO F. MENDEZ (pmendez@ualberta.ca) is with the Canadian Centre for Welding and Joining, University of Alberta, Edmonton, AB, Canada.