Optical and Spectroscopic Study of a Submerged Arc Welding Cavern

A combination of high-speed imaging and spatially resolved spectroscopy at 5000 fps was performed on a submerged arc welding process using a thin-gauge steel tunnel

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ABSTRACT

For the first time, a combination of high-speed imaging and spatially resolved spectroscopy at 5000 fps was performed on a submerged arc welding process. This was achieved by inserting a thin-gauge steel tunnel into the flux and aligning the diagnostics accordingly. Four processes were observed; both direct current electrode positive (DCEP) and direct current electrode negative (DCEN), as well as alternating current (AC) at 600 A and DCEP with a higher current at 1000 A. The videos show an erratic droplet transfer with a lot of spatter that was caught by the cavern walls and directed into the weld pool. Additionally, flux was molten at the top of the cavern close to the electrode and merged into the droplet that was still attached to the wire. The cavern walls were a mixture of solid flux that was partially falling into the weld pool and molten flux, which created a smooth wall. The surface properties of the cavern wall behind the process was mostly smooth and merged with the weld pool, which created a solidifying layer of slag on top of the slowly cooling weld joint. The observed processes showed only a slight change in chemical composition of main alloying elements in the solidified weld joint, while the oxygen content varied significantly in the droplet stage and weld joint between the processes. The high-speed images indicated a correlation between droplet-flux interaction and oxygen content. The spatially resolved spectra showed intense self-reversed lines of Na, Ca, and Mn. Fe lines suggested that the arc was also dominated by metal vapor. Especially during the AC process, a fluctuating emission of Mn lines was observed, which correlated with the frequency of the shifting polarity.

KEYWORDS

• Submerged Arc Welding (SAW) • High-Speed Video • Metal Transfer • Cavern • Spectroscopy • Droplet • Flux • Oxygen Content

Introduction

Submerged arc welding (SAW) is a widely used joining process in a great variety of industries. This includes shipbuilding, construction, and the energy sector with the production of pipelines, wind towers, and offshore foundations. While the fundamentals of the process have not changed, there have been improvements in filler materials and power source technologies.

However, one basic characteristic of the process is the restricted observability of the wire, arc, and droplet behavior due to the flux covering the cavern and molten bath. This restricted observability affects the process from being well understood, compared to other arc welding processes [gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW)]. The complex chemical reactions leading to specified mechanical properties of the joint, which depend on the droplet transfer and parameters in SAW, have not yet been completely described.

The understanding of these mechanisms would support the development of more sophisticated process variations, as can be seen in other arc welding processes, because modern power sources are capable of a variety of different waveforms and current patterns.

In this work, the processes inside the SAW cavern have been recorded at 5000 frames/s (fps). There are only a few preceding papers on high-speed imaging in SAW. Two kinds of approaches to achieve these images can be found in literature. Tybus (Ref. 1) used two-quartz-borosilicat windows on both sides of the process. By welding between those windows, high-speed images could be analyzed from the side. This had a strong impact on the process, since it changed the shape of the cavern drastically. In addition, the images were of low quality due to the spatter and smoke residue adhering to the windows.

The second approach can be found in the dissertation from Franz (Ref. 2). He used a ceramic tube that he positioned in front of the weld path. By welding between those windows, high-speed images could be recorded to analyze the process from the side. This had a strong impact on the process, since it changed the shape of the cavern drastically. In addition, the images were of low quality due to the spatter and smoke residue adhering to the windows.

The second approach can be found in the dissertation from Franz (Ref. 2). He used a ceramic tube that he positioned in front of the weld path. By welding over it, he could observe the process with less disturbance. The material of the tube was chosen to match the flux. In addition, he compensated for the loss of pressure inside the cavern by adding a shielding gas. This also kept the tube and the attached window clear of debris. Within these investiga-
tions, the droplet behavior and material transfer were described as to their dependence on welding parameters and filler materials. Basic statements about arc behavior and electromagnetic blowing effects in SAW could be described. A more recent publication, which adapted this method, is from Mendez (Ref. 3). He used a tube made out of rolled steel sheets open at both ends. He found a droplet detachment frequency of approximately 9 Hz at 500-A DCEP, and 13 Hz at 500-A AC. At 1000-A DCEP, he found that a tapering electrode tip with a buried arc and a molten tail was ejected through a perforating electrode tip with a buried arc.

At 1000-A DCEP, he found that a tapering electrode tip with a buried arc and a molten tail was ejected through a perforating electrode tip with a buried arc. This was sufficient to play back the fast processes inside the cavern. In Fig. 1 ending under the flux. The material was steel foil with a very low amount of alloying elements (Table 1), and it had a thickness of 25 μm, which reduced the effect of additional material to a negligible amount. This tunnel was placed in two different ways.

One way is shown in Fig. 1, which gives a side view of the process. The second way was to put the tunnel along the welding direction. In this way, a front view of the process could be achieved. Similar to the setup in Franz (Ref. 2), a shielding gas was introduced into the tunnel. This helped to keep the cavern from collapsing due to the open channel, and to keep atmospheric gases outside. The additional tube brazed to the tunnel served as a gas inlet.

Second, a spatially resolved high-speed spectrometer system was added to the setup. It had to monitor the process from the same direction as the high-speed camera since the tunnel had a narrow angle of aperture. This was achieved by a 90-deg mirror that was placed in front of the lens at its blind spot — Fig. 1. This blind spot design was related to the internal mirror positions of the lens.

The mirror lens was a long-distance microscope from Questar Corp. called QM 1. In combination with a high-speed camera (HSC; MotionPro Y4-monochrome from Integrated Design Tools, Inc.) and an infrared filter, the images could be recorded at 5000 fps with only a slight disturbance caused by the arc. This was sufficient to play back the fast processes inside the cavern and give a visual overview of the processes concerning the metal transfer and flux behavior. The acquisition was synchronized with the second camera (MotionPro Y4-monochrome), recording the high-speed spectra from the 0.5-m monochromator (Princeton Instruments Acton SP2500). By doing so, it was possible to find the connection between high-speed camera images and the spectra.

The spectrometer was chosen due to several advantages. It has a high spectral resolution to determine which species are present inside the arc. Preliminary trials showed acquisitions with a mini spectrometer do not provide sufficient resolution to determine, and distinguish between, species present in the cavern. The spectrometer was equipped with three gratings with different groove densi-
In this setup, the welding head was positioned at ±1000 A. A constant current welding process was analyzed with an inverter power source (Lincoln AC/DC 8500 (EN 760 – S A FB 1)) with a maximum current of ±1000 A. A constant current welding characteristic was chosen.

In this paper, the single-wire SAW process was analyzed with four varying parameter settings. The four parameter changes that were observed with the diagnostics are given in Table 2. The materials were not altered. The wire was a Lincoln Electric L50M (EN ISO 14171 S3Si) with a diameter of 4 mm, and the base material was an EN 10025 S355 J2+N. The main chemical composition of the materials is listed in Table 1. The flux used was a Lincolnweld 8500 (EN 760 – S A FB 1) with a basicity index of 2.9 and a neutral chemical behavior. The flux composition is listed in Table 3. The welding and wire-feed speed was constant. The height of the pile of flux was kept constant as well. This was necessary to keep the basic conditions steady.

The pressure that the flux applied to the cavern was about 0.05 g/mm². The gas pressure that impinged on the cavern through the tunnel had to be finely tuned to the pressure inside the cavern. If the shielding gas pressure is too high, it will be injected into the cavern’s atmosphere and influence the process. In the case of argon (Ar), it would change the process to a spray transfer similar to the GMAW process. If the pressure is too low, the cavern will shrill, which is visible in the weld joint profile.

In addition, the tunnel tends to be clogged with debris. With a balanced setting of the gas pressure, the influence on the process is minimized and the view into the cavern is unobstructed. The best results were achieved by using Ar at an overpressure of 25 mbar. Carbon dioxide (CO₂) and Ar were investigated as applicable shielding gases. None of the gases in the preliminary trials changed the chemical composition of the weld deposit. Nonetheless, changes in the chemical compounds of the molten slag, investigated by x-ray fluorescence (XRF), were observed using CO₂ — Fig. 2. Furthermore, the measured short-circuit frequency changed from 3.6 Hz in the unaffected welding process to 4.2 Hz by injecting CO₂ as a shielding gas. Short-circuit frequency was constant while using the inert gas Ar. This indicated that the use of CO₂ as a shielding gas is more invasive to the process.
Results and Discussion

In the following subsection, some of the phenomenon observed with the high-speed camera is presented. In order to understand the still frames, the supporting online material is recommended (Ref. 16). This will help to enhance understanding on what each part in the frames represents, and it will facilitate identification of those parts. For a better understanding of the findings and explanations, Fig. 3 shows a snapshot of the clearly visible moment in the DCEP process.

It is helpful to keep in mind from what perspective the process was observed. In this case, it was from a low angle just above the surface of the base material. The tunnel was the outer limiting part of each image, and moving parts like the droplets, flux grains, weld pool surface, and the wire were visible. The only light source was the arc itself, except for the hot surfaces that represented a very small part of the total emission. Therefore, particles in front of the arc are seen as shadows. Particles next to or behind the arc are illuminated and can be seen as bright spots. The surface of the liquid metal has a low emissivity. Therefore, it has a high reflectivity. It was perceived as a reflecting surface similar to mercury at room temperature.

**High-speed images of the DCEP process with 600 A.** The videos showed different effects. In Fig. 5, the DCEP process, with its SAW basic parameters, is shown in a front view, and in the following section the general findings are presented and discussed. Later on, the characteristics of the other parameter sets are discussed in comparison to the DCEP process. The front view of the DCEP process showed a stable arc behavior the entire recorded time. The droplet transfer was turbulent and changed randomly between short circuiting dropping, exploding, and repelling — Fig. 4 and Ref. 16, SOM1.

Most of the time, flux grains, and small metal and slag droplets, were splattering through the cavern area. The analyzed videos show more or less turbulent processes inside the cavern, although the SAW process is known for a high grade of stability and smooth weld joints. These are probably a consequence of the slow solidification of the molten weld pool and the smoothing effect of the freezing slag. The reaction between flux and metal happens preferably at the contact point between molten droplet and cavern wall in the welding direction, where flux is continuously molten and absorbed by the droplet.

This reaction is clearly visible in Ref. 16 (SOM2) as a front view, where the absorbed molten flux also leads to a change of emissivity in the metal droplet. This is probably the place and state in the welding process where the most intensive chemical slag metal reactions take place due to the spherical droplet shape (positive ratio of absorbing-surface area to volume), the high reaction temperatures, and the constant flux supply. In the lower part of the frame, the base material with some flux and metal droplets can be seen. Obscured by the base material surface is a settling, which builds the weld pool, respectively the emerging weld joint — Figs. 5 and 6. It is created by the arc pressure onto the liquid weld pool. In the upper left corner of Fig. 5, parts of the melting tunnel are visible.

Other effects take place behind the wire. One is the kinking of the unduloid, a mathematical term used to describe the geometry of the long molten metal droplet that is still attached to the upper electrode. Magnetic forces drive the kinking and throw molten metal to the back. This effect can also be seen in GMAW processes with high currents (Ref. 16, SOM3).

The cavern was stable the entire observed time, with just a few flux grains falling from the walls. This means the minimum internal cavern pressure was equal to the pressure applied by the flux on top of the cavern. The cavern had a half-ovoloid shape with a minimum width of 12 mm based on the given scale and visible wire diameter. Figure 6 (SOM4) shows the rear part of the cavern where different effects appear compared to the front part. The view is mostly obscured by the debris coming from the falling flux. On the left side of this image, the sloping surface of the weld pool can be seen. In the center of the frame a part of the wire is visible, and left of the wire the molten cavern ceiling appears. It merges into the weld pool, visible on the left end of the frame. This part is where the cavern surface in this area is mostly molten and migrates toward the metal surface.

As soon as the cavern surface gets in contact with the still molten weld joint, the cooling process starts because there is no heat input any more. Once the molten flux is cooled, it will peel off the weld joint as slag. This contributes to the high weld quality, since the cooling is slowed down and the atmospheric gases are held back during this process. In contrast to the smooth surface of the slag, once cooled, it can be said that most parts of the cavern wall are not as smooth.
The inner cavern surface consists of solid flux grains, molten slag, and solid particles merging into a molten stage (Ref. 16, SOM5). Within a short time of exposure to the heat source, the surface of the flux grains starts melting with visible outgassing or even boiling on the surface. The over-exposed region at the center is the arc with the hot wire tip. The emitted light illuminates the whole cavern. The arc contains mostly metal vapor and nonmetallic elements, like calcium (Ca), according to the recorded spectra. On the right-hand side in each frame, the front wall can be seen because this is a side view of the process. Flux grains in different sizes are falling through the cavern or along the cavern wall. These grains with a melting surface appear in the rear part of the cavern relative to welding direction as well, which is supposed to be the coldest part because of its maximum distance to the burning arc.

The flux used was agglomerated and fluoride-basic. These fluxes typically start melting at around 1200°C–1400°C depending on chemical composition and the relation of mineral constituents (Refs. 17–19). There is the possibility of reactions and forming of different compounds or crystal phases before melting of the flux grains. One has to be aware that these compounds have different, usually lower, melting and solidification points compared to the separate components listed in Table 3 (Ref. 17).

For a first approximation of the internal cavern temperature close to the surface, these effects were disregarded. Since the fusing process of the flux grains is visible in the high-speed images, the cavern surface must rapidly exceed the melting temperature of the flux. This is possible due to the temperatures of the arc and the liquid.

<table>
<thead>
<tr>
<th>Chem. Comp.</th>
<th>SiO₂</th>
<th>MnO</th>
<th>MgO</th>
<th>CaF₂</th>
<th>Na₂O</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>Metal Alloys</th>
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<tr>
<td>CONCN in %</td>
<td>13</td>
<td>1</td>
<td>30</td>
<td>24</td>
<td>19</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1855</td>
<td></td>
</tr>
<tr>
<td>T_melt in °C</td>
<td>1713</td>
<td>1650</td>
<td>2852</td>
<td>1423</td>
<td>1275</td>
<td>2050</td>
<td>2575 ± 5</td>
<td>2575 ± 5</td>
<td>1855</td>
<td></td>
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weld pool. Since the arc is metal-vapor dominated (see section on high-speed spectroscopy), it might have a core temperature of approximately 7000–10,000 K as other research suggests (Ref. 20).

In addition, between 10 and 20% of the electrical energy put into the process is converted into radiative energy in arc welding processes (Ref. 21). This radiative energy from the arc plus the heat from the weld pool, which is all trapped inside the cavern, leads to a heat accumulation. Therefore, a quick heating of the flux is to be expected. To verify these statements further, more precise investigations have to be conducted.

High-speed images of the DCEN process with 600 A. In the direct current process with electrode negative polarity (DCEN), as shown in Fig. 8 and Ref. 16 (SOM6), the arc is much shorter than in the DCEP process and almost not visible. The droplet transfer happens beneath the surface of the base metal in a weld pool depression. Therefore, it is not visible. The flickering and fast drifting of regions, with high emissivity on the droplet, indicates a less stable arc behavior. This could be explained by the high amount of CaF₂ in the flux, which is well known for destabilizing the arc. Cathode spots appeared all over the droplet, mainly in the upper region near the solid wire. This can be explained with lower temperatures and lower electrical resistance. The cavern showed less volume compared to the DCEP process, which is probably a result of lower internal pressure due to lower temperatures and a smaller amount of metal vapor. This is a result of a less concentrated arc on the wire, which is a typical feature of a DCEN process (Ref. 11).

High-speed images of the DCEP process with 1000 A. While the cavern walls were largely covered with flux grains in the DCEP process with 600 A, more flux was molten in the DCEP process with 1000 A. This makes the observation more difficult due to high-viscosity slag moving in the visual field. This can be seen in Ref. 16 (SOM8) as a front view. Here the breakup of the cavern wall, consisting of high-viscosity molten slag, is clearly visible as well. The concentrated arc attachment on the droplet shows a stable behavior with a higher emissivity compared to the lower current in DCEP. The material transfer mainly takes place in a streaming way. Due to the high amount of completely molten slag, the interior temperature of the cavern is supposed to be significantly higher than a DCEP process with 600 A. From this we can deduce that there was a higher amount of vaporized metal and elements from the flux in the cavern atmosphere.

High-speed spectroscopy. In this part, the results of the spectroscopic measurements are presented. The aim of these measurements was to find a suitable spectral range to analyze the arc atmosphere and to identify significant changes within the process. This could help to enhance the understanding of the chemistry and mechanics in the cavern.

Similar to the high-speed videos, the spectra were recorded from a low angle. The setup allowed a correlation between the spectra (Fig. 9) and the images (Fig. 10). The spectra were recorded along a vertical line across
the tunnel (Fig. 1). The upper part in the spectra represents the upper region in the middle of the images and the lower part in the spectrum, which is the lower part in the middle of the image. Figure 10 shows frames from Ref. 16 (SOM9). The images show both high-speed images of the process and synchronized spectra in combination. The recorded spectra were dominated by iron (Fe), calcium (Ca), self-reversed sodium (Na) lines, and manganese (Mn) (compare to Fig. 9).

Noticeable is the pair of Na lines at the center with around 589 nm, which appear as one dark stripe because they are strongly self-reversed. Most lines below 580 nm are from Fe vapor. Both the line groups between 610 and 620 nm, and 643 and 652 nm, and with three lines each are from Ca. In the center image of Fig. 10 there is another set of spectral lines visible at around 601–602 nm, which are missing in the frames before and after (see left and right image in Fig. 10). These lines originate from Mn (601.4, 601.7, and 602.2 nm), and are only detectable during the phase around current zero. This phase obviously has a lower arc temperature, and the composition of the plasma allows these lines to be emitted. Just before the positive phase at higher currents, there are many more Fe lines visible and the Na line is also more intense. A similar situation is visible in the negative phase. It might be because of the low boiling temperature of Mn that its lines are visible at all.

Otherwise, the spectra show an Fe-dominated arc. This is consistent with the earlier presented observation made by the high-speed imaging. Both suggest that the main current path is situated below the droplet that is still attached to the wire. Therefore, the droplet transfer in SAW has similarities to a CO₂ GMAW process, although its atmosphere is different. In CO₂, the main current path exits at the wire tip in contrast to the Ar-dominated GMAW processes where it exits the wire above the liquid part of the wire. This mechanism is necessary in certain GMAW processes to achieve globular and spray transfer (Ref. 21). The same effect was stimulated in SAW when the shielding gas introduced into the tunnel was set to an excessively high pressure and Ar entered the cavern. Under these circumstances, the droplet transfer changed to a constricted spray transfer without any short circuits. This had to be avoided to maintain a diagnostic method with as little influence as possible.

Chemical Analysis. The weld joints were analyzed by OES. The samples for the OES of the weld metal were collected from bead-on-plate welds with eight layers to avoid dilution with the base material. Only a few changes were found in the chemical composition of the main alloying elements within the varying processes (Table 1). This can be attributed to the chemically neutral character of the flux and the low amount of alloying elements in the wire. As can be observed, slight changes occur by varying polarity with most melting loss of alloying elements in DCEN and AC processes. This is especially the case for alloying elements with a high affinity to oxygen like carbon, aluminum, and titanium.

Oxygen is an important element in welding metallurgy and can act both positively and negatively on microstructure formation. In a balanced, low amount, oxygen plays an important role in nucleation and can support a fine-grained microstructure formation with improved toughness and tensile strength. In interaction with titanium, boron, or other microalloying elements, this effect is enhanced (Ref. 12). In contrast, a high amount of oxygen in the weld joint leads to embrittlement and porosity. Therefore, optimized oxygen content is ideal for adequate mechanical properties. In sub-
merged arc welding, the main sources of oxygen are the decomposed flux constituents, which contaminate the droplet (Ref. 23).

In the determination of oxygen contents, significant changes were detected between the observed processes in droplet and weld joint. The highest variations were measured between different settings of polarity (DCEP, DCEN, and AC). Figure 11 shows the transient amount of oxygen in the wire, droplet, and solid-weld joint stage within varying processes.

As can be seen, the amount of oxygen rises in the droplet in all specimens. The value of oxygen content depends mainly on the polarity but also on the current. It is highest in DCEP compared to DCEN, and slightly increases with higher currents. After passing over into the weld pool and solidifying, the oxygen content drops to a lower level in all investigated processes. This can be explained by two separate effects.

First, the droplet and the oxygen it contains are “dissolved” in the weld pool. Second, the thermochemical de-oxidation effects in the weld pool reduce the oxygen content of the weld metal further. This happens through the oxidation of alloying elements with a high affinity to oxygen, like silicon or aluminum. These oxidized compounds are transferred from the weld metal through the slag-metal interface into the slag. However, the level of the final oxygen content in the solid weld joint seems to be determined by the oxygen content in the droplet stage.

It is known that a lower oxygen content in weldments can be achieved by DCEN polarity due to electrochemical reactions (Refs. 13–15). Supposedly, this is one of the main reasons for the final amount of oxygen in SAW. Other investigations show that the final oxygen content depends on the weld solidification time as well (Ref. 23).

Referring to the high-speed images, the oxygen content also seems to be influenced by the droplet-flux interaction and arc length, which are determined by the chosen polarity. As can be seen in Ref. 16 (SOM1) (DCEP) and described in an earlier subsection, the flux merges directly into the droplet. The molten droplet is situated in the upper part of the cavern and in direct contact with the cavern wall, respectively, with the flux. At this point, the flux, consisting of a wide range of oxides, raises the oxygen content of the droplet due to its absorption.

Within the DCEN process (Ref. 16, SOM6), the arc is much shorter and the droplet is closer to the weld pool. Therefore, the droplet transfer is not clearly visible most of the observed time. There is only a slight droplet-flux interaction visible, as opposed to the DCEP process. This could lead to a lower amount of oxygen in the droplet due to less absorption of flux with its oxidic compounds.

The AC process shows characteristics of both DCEP and DCEN in the high-speed images (Ref. 16, SOM8). It has a medium oxygen content in droplet and solid weld joint, which is between the DCEP and DCEN processes.

The highest amount of oxygen was detected in the DCEP process with high current ($I = 1000$ A). Referring to the high-speed images (Ref. 16, SOM7) and the explanations in an earlier subsection, the flux is completely molten because of the high energy input and heat in the cavern. This leads to an increased reactivity of flux compounds, and most likely an increased oxygen range in the cavern. These reactions could result in a higher oxygen content in the droplet.

**Conclusion**

In the presented investigations, a combined and synchronized method for high-speed imaging and spatial-resolved spectroscopy in submerged arc welding (SAW) was introduced. It was shown that there is a minimum invasive influence on the process achieved by using this method. Based on the high-speed images, detailed descriptions of the process were made concerning the nature, behavior, and size of cavern, droplet, and arc in different polarities (DCEN, DCEP, and AC) and welding currents (600 and 1000 A) in submerged arc single-wire welding.

Through observation of the physical state of the flux and slag inside the cavern, estimations of cavern temperatures could be made. Based on this and in combination with the results of the spectroscopy, the main components of the cavern atmosphere are
likely iron vapor and dissociated flux components. With varying polarities, DCEN welding shows the lowest cavern temperatures, and the DCEP process shows the highest, founded on the condition of the flux and slag inside the cavern. As expected, at the same time, cavern temperature rises with increasing welding current, which is visible by the completely molten flux around the cavern.

The oxygen contents were determined in the wire, droplets, and weld joints with varying polarities and welding currents. It was found that in all investigated process varieties, the oxygen content rises in droplet stage and drops in molten bath, respectively, in the weld joint. The final oxygen content seems to be determined by welding polarity in a wide range. Lowest oxygen contents were achieved with a maximum percentage of cathode burning time on the electrode (DCEN and AC). This can be explained by electrochemical reactions and in consideration of the high-speed images by droplet-flux interaction and arc length, which are determined by the chosen polarity. It was shown that high-speed imaging can help explain fundamental activities and reactions in the SAW cavern. Additional spectra may allow us to draw conclusions about the mechanisms behind these effects.

In future investigations, high-speed images will be correlated with electrical characteristics (current and voltage) of the process, which describes recurring patterns in process behavior by means of current-voltage courses. Furthermore, different welding parameters, positions, SAW multiwire processes, and materials (e.g., austenites) are to be examined.

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