Behaviors of Cathode Spot in Alternative Current Helium TIG Welding of Aluminum

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Alternative current TIG welding is a common way to joint aluminum for the use of the oxide cleaning action by cathode spots. In order to improve the efficiency of the oxide cleaning through the control of the cathode spot, the cathode spot behaviors should be clarified in detail. For this purpose, an observation of the oxide cleaning action in helium TIG welding was carried out by a high-speed camera. Here, the behaviors of cathode spots were elucidated by tracking the movement of them in the observation. As a result, the new cathode spots were found to be generated only from the division of the old cathode spot. This division took place continuously around the radial distance of 3.5 mm from the center of weld pool. Most of the cathode spots generated there tended to move outward at average velocity decreasing from 200 m/s to 20 m/s with the radial distance. Arriving at the white zone, they suddenly decelerated around the radial distance of 5.5 mm to become gradually weak and then finally disappear. The probability of the generation of the cathode spot except for in the vicinity of the weld pool center was hence seen to be very low. Consequently, the general tendency of the life cycle of the cathode spot from the generation to the disappearance was clarified through the quantitative evaluation of the distribution and velocity of the cathode spot.

Key Words: Cathode spot, AC TIG welding, Aluminum, Helium

1. Introduction

In the arc welding field, it is not easy to achieve a high-quality joint of aluminum alloy due to several reasons. The coefficient of thermal conductivity of aluminum is six times larger than that of steel. Therefore, the heat source for welding aluminum needs to be further intense and concentrated than that for steel. Furthermore, the formation of oxide layer on the aluminum surface and its physical characteristics are also important reasons. The low electrical conductivity of the oxide layer prevents to maintain the arc current. Besides, the difference in melting points between aluminum (660 °C) and its oxide (2,060 °C) causes other problems; aluminum oxide - tenacious and rapid-forming oxide - hinders the heat transfer process and releasing process of dissolved gas in the weld pool. Due to these reasons, aluminum weld bead generally tends to have low penetration and contain fusion defects, oxide inclusions, and porosity.

At present, there are new welding processes developed to joint aluminum such as electron beam welding, laser welding and friction stir welding11. Each process has advantages and also limitations. The choice of the welding process depends on properties of the specific aluminum alloy, joint configuration, strength requirement, appearance, and cost. However, some conventional processes, such as Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) welding processes, are still in use widely because these are flexible and require a low capital cost. Moreover, TIG welding process has the ability to produce a higher quality joint than that of MIG welding process.

TIG welding is generally used in Direct Current Electrode Negative (DCEN) mode because this mode could provide a stable arc, large heat flux to the base metal leading to deep penetration, and high welding speeds. However, in case of aluminum welding, due to the need to clean the oxide on the aluminum surface, Alternating Current (AC) mode, which can utilize cathode spots to clean the oxide in Electrode Positive (EP) polarity, must be used. On the other hand, use of EP polarity of AC mode could result in the consumption of tungsten electrode and low penetration. The consumption of the electrode could reduce the lifetime of the electrode11. Therefore, in aluminum welding, there are still some issues needed to be resolved such as oxide cleaning, electrode consumption, and penetration. In AC mode, the EP polarity duration is generally adjusted around 30% of a cycle to balance these issues9. However, if the cleaning efficiency of the oxide is improved more, the EP polarity duration can be reduced to decrease the electrode consumption and increase penetration.

The commonly used shielding gas for the AC TIG welding of aluminum is argon. The oxide tends to be cleaned over a wide range during welding with argon9. Another advantage of using argon is that the arc ignites easily at polarity reversal in AC TIG welding. Another option of shielding gas in AC TIG welding

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process is helium. The penetration of weld bead is deeper in welding with helium than that with argon, because of the larger heat flux to the base metal in the helium arc\(^6\). An additional advantage of helium is a reduction of porosity\(^5\). However, helium arc provides less-effective oxide cleaning action than that of argon. Also, due to the high ionization potential of helium, the electrode is melted quickly by ion recombination heating in EP polarity to lead to electrode consumption. For these reasons, in aluminum AC TIG welding, pure helium is rarely used. Instead, a mixture such as 25 % helium and 75 % argon is used to take advantages of both gases\(^1\). At the first step, oxide clean action should be investigated in pure helium and argon arc to understand the essence of this phenomenon.

The oxide layer can be cleaned during the EP polarity by a large number of cathode spots occurring on the surface of the base metal to be cathode \(^6,7\). The cathode spot is known to have greatly high current density and also travel randomly on the surface at very large velocity. These characteristics are thought to be strongly linked to the efficiency of the cleaning.

The diameter of each cathode spot is estimated to be in order of 10–100 μm from the size of the crater formed on the surface\(^8\); the current in order of 10 A can be conducted from the arc to the base metal through the cathode spot with a high current density exceeding 10\(^9\) A/m\(^2\) \(^6,9\). The high current density of the cathode spot leads to the cathode materials and also the oxide to be evaporated easily due to intensive joule heating and strong ion bombardment. This evaporation could be one of the dominant mechanisms of the oxide cleaning action by the cathode spot. From the above, the current density is found to depend on the size and the current of each spot and considered significantly to affect the power used for the oxide cleaning action by each cathode spot.

The movement of the cathode spot was also investigated by experimental observations, because the cathode spot is a historical topic in the electrical arc discharge, as mentioned in review papers\(^8,10,11\). Unfortunately, most of the experimental observations were carried out in vacuum condition. Whereas, in welding application, the arc is produced in atmospheric-pressure inert gas. Because the characteristics and pressure of the gas largely different from those in vacuum are considered to affect the behaviors of the cathode spot\(^12,13\), the observation of cathode spot in the welding arc is also necessary. However, at present, the movement of the cathode spot in the welding arc has still little experimental evidence.

Observations of the cathode spot were carried out in AC TIG welding on aluminum by several research groups. Ushio et al. observed the cathode spot movement by the high-speed camera with a frame rate of 8,000 fps\(^14\). In that observation, the cathode spots were generated at first in the weld pool, and then extended radially to the oxide-cleaning zone with the elapsed time. The number, diameter and velocity of cathode spots were roughly obtained and found to be affected by alloy elements in several kinds of aluminum alloys. Sarrafi et al. also observed AC TIG welding on aluminum with a high-speed camera at a frame rate of 2,000 fps\(^15\). The cathode spots were randomly formed on different locations on the surface at the beginning of an EP period. Then, especially a part of strong cathode spots formed near the arc center and expanded outward. However, the observation with the above frame rates just showed the general tendency of cathode spot movement\(^14,15\). Tashiro et al. performed the observation of the cathode spot with a frame rate of 500,000 fps\(^16\). The average velocity of cathode spots reached an order of 100 m/s in the weld pool area and 10 m/s in the oxide layer area.

The velocity of 100 m/s means that the distance of the cathode spot movement within one frame reaches 10 cm when the frame rate of 1,000 fps is used. It implies that the frame rates used in the previous studies\(^14,15\) were not enough for understanding the behavior of the cathode spot. Yuji et al. also observed the cathode spots in AC TIG welding on an aluminum plate with helium shielding gas\(^17\). In this experiment, the absence of cathode spot in the center of the weld pool was found. They explained that the absence was considered to be caused by the difference in degree of oxidation of the surface between the center and the edge of the weld pool. However, these studies still lack the detailed information on the cathode spot behavior enough for giving us deep understandings.

The behaviors of the cathode spot are thought to vary complicatedly depending on many factors such as cathode material, shielding gas, surface condition, to make the physical nature of the cathode spot difficult to be understood clearly. Therefore, at present, control of cathode spots to improve the efficiency of the oxide cleaning is still not yet achieved.

In order to realize the control of the cathode spot, their behaviors should be clarified in detail. Therefore, in this study, behaviors of the cathode spot are further investigated in AC TIG welding process with helium shielding gas by using the high-speed camera which has the maximum frame rate of 1,000,000 fps. The increase of the DCEP duration is known to enlarge the clean zone\(^18\). It means the cathode spot has enough time to move far toward the oxide layer in that condition. Therefore, the observation is performed near the end of EP polarity aiming to discuss the cathode spot behavior on the oxide layer as well as that on the weld pool. The base metal of pure aluminum A1050P is used to ignore the influence of alloy elements on the behaviors of the cathode spot for simplicity. The distribution and velocity of the cathode spot are quantitatively measured from the observation to discuss formation and movement of the cathode spot.
2. Experimental setup

Fig. 1 shows a schematic illustration of the experimental setup. The electrode is stationary to the base metal with a gap of 3mm. The arc duration is 3.1 s. The distance from the camera lens to the center of the weld pool surface is 200 mm. The tilt angle between the optical axis of the camera and the surface of the base metal is 30 degrees. A lens (Macro-NIKKOR 12 f/6.3) is utilized to adjust the magnification of images. The other setting parameters are shown in Table 1. The clamp meter measures the current waveform and send it to the data logger with the acquisition frequency of 0.5MHz. At the same time, the voltage waveform is also measured directly by the data logger. These measurements are carried out with a delay time of 3 seconds from the beginning of the arc by delay timer and Welding Current Relay (WCR). The observation time is synchronized with arc by trigger line from the data logger to the camera.

The position of the cathode spot is determined by tracing the luminous zone in the observed image. Because the observation surface is inclined to the optical axis, a spatial distortion has to be taken into account, considering the difference of calibration scales between the width (x-axis) and the height (y-axis) of observation image. An image resolution of 320 × 260 pixels (width × height) is used to capture a real dimension of 15.36 mm × 21.84 mm. Therefore, the calibration scales in x-axis and y-axis are 0.048 and 0.084 mm/pixel, respectively. The velocity of each cathode spot is calculated by the changing distance between two consecutive frames. The position of center (C) is calculated from the position of three points on the edge of the weld pool. The center of weld pool (x_c, y_c) and the radial distance between the cathode spot and the center (C) are used for calculation of the radial position (R) of the cathode spot as in Fig. 3.

3. Experimental results

The waveforms of voltage and current are shown in Fig. 4. The difference in voltage in EP polarity and EN polarity is clearly

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Table 1  Setting parameters.

|                  | OC (DC) Daishen DA300P | AC, 200A, 70Hz | 30%  | W+ 2% La2O3, ø3.2mm | He 20l/min | A1050P |
|------------------|------------------------|----------------|------|----------------------|------------|--------|
| Welding parameters | Ultra-high-speed camera Shimadzu HPV 1 | 500 000 fps | 312 × 260 | 1 μs |
| Camera setting   |                         |                |      |                      |            |        |

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Fig. 1  Schematic illustration of the experimental setup.

Fig. 2  Specific moment of observation.

Fig. 3  Schematic of position calculation.

Fig. 4  Voltage and current waveform.
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seen. The voltage value in EP polarity tended to increase from about 24.5 V to 28.0 V with a slight oscillation, except a peak value at the start of EP polarity. Meanwhile, it changed steadily from -11.0 V to -13.0 V in EN polarity. The value of voltage in the EP polarity was more than double comparing with that in the EN polarity. At the time of observation, the average voltages in EP and EN polarity were 28.2 V and approximately 12 V, respectively.

Fig. 5 shows the appearance of the weld pool during EP polarity and after the welding arc stopped with the same position of base metal. The dark area appearing in the center of Fig. 5(b) corresponds to the region where the weld pool existed. With the welding parameter of this experiment, the radius of the weld pool after welding was approximately 4.3 mm. The weld pool was seen to be surrounded by a white zone which was the oxide-cleaning zone on the solid surface. The average width of this white zone was about 1.4 mm. In Fig. 5(a), cathode spots are found to exist as small and bright area in both of the weld pool and the white zone.

Fig. 6 shows time-sequential images of the movement of cathode spots. From these images, some characteristics of the cathode spot can be seen. There were many cathode spots moved in the weld pool with the radius of 4.3 mm. It indicates that the distances between them were small. The division and movement of spots occurred consecutively within interval times between two frames of 2 μs as in the square 1. The new cathode spot inside the weld pool was found to be formed only by this division. Moreover, the cathode spot outside the weld pool did not spontaneously appear; it moved outward from the weld pool as in the square 2. After arriving at the white zone, it gradually became slow and weak before disappearing. So it is implied that with the observation of several thousand fps, the formation, movement and disappearance of cathode spots couldn’t be determined correctly.

Fig. 7 shows the average number of cathode spots according to their radial position to the center of the weld pool. This data was created from 3 videos. Here, the cathode spots were picked up from 5 frames of each video. The time between two selected frames was 20 μs. The number of the cathode spots according to the radial position were hence averaged from totally 15 frames.

It could be seen that the total number of cathode spots was 15 ± 2 in each frame. Furthermore, the average number varied greatly depending on the radial position. The spot is seen to be concentrated around 5.5 mm from the center, on the white zone. Moreover, the non-existence at the position of 6.5 mm means that the spots were hard to reach the oxide zone at the observation moment. On the other hand, the spots did not exist in the center of the weld pool. The reason was that when cathode spots moved to the radial position of 2 mm, some of them disappeared, others...
divided and moved outward from the center of the weld pool.

**Fig. 8** shows an example of traces of the cathode spot movement. It was seen that cathode spots moved in both of the weld pool and the white zone. The division and disappearance of the cathode spot (as in square 1 of **Fig. 6**) always happen continuously in the inside of the weld pool, especially around the radial position of 3.5 mm. The motion of each spot was hence random with direction always changed. The cathode spot moving toward the center tended to divide with high probability. Then, the newly created spot was seen to move outward. This movement presents the trace like sample 1. Other spots generally move toward the white zone. Their movement, corresponding to the cathode spot in square 2 of **Fig. 6**, was traced as sample 2.

The velocity of two cathode spots (sample 1 and sample 2 in **Fig. 8**) is shown in **Fig. 9**. Sample 1 moved inward inside the weld pool, and sample 2 moved from the inside of the weld pool to the white zone. The average velocity of sample 1 was higher than that of sample 2. The result shows that the cathode spot accelerates when it moves inward and, conversely, it decelerates when it moves outward. The velocities oscillated in the range of 140 m/s in case of sample 1 and around 100 m/s in case of sample 2. The oscillation of the velocity is considered to be caused by the temporal and spatial variations of the properties of the arc plasma covering the surface such as temperature or metal vapor concentration.

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**Fig. 10** shows the correlation between the average velocities and position of the cathode spot relative to the center of the weld pool. As a result, it can be seen that the average velocities tended to decrease as the radial position increased. The difference in average velocities was over 100 m/s between in the weld pool and the oxide zone. The large standard deviation could be caused by the essence of the cathode spots as well as the measurement error. The essence of cathode spot was expressed through the oscillation of its velocity as in **Fig. 9**. Moreover, the accuracy to determine the position of the cathode spot depends on the brightness of the cathode spot. It is possible to lead to the error in calculating the velocity.

**Fig. 11** shows the quarter of the weld pool which was taken by the optical microscopy after arc stopped. Here, areas of the white zone were selected to see the craters formed by cathode spots.
In the area near the edge of the weld pool, there were several big holes with diameters of about 0.1-0.3 mm as in square 1. Inside these big holes, there were several craters with the diameter of around 15 μm. Outside the big holes, the craters had an average diameter of and the distance between them around 10 μm as in square 2. The craters are considered to be formed by the cathode spots.

4. Discussion

Following the experimental results in the previous section, the behaviors of the cathode spot in the final stage of EP polarity are herein discussed. Especially, these behaviors include velocity, distribution and current density of the cathode spot as well as arc voltage. In this experiment, cathode spots existed on both of liquid and solid surface and under atmospheric pressure helium shielding gas.

Firstly, the velocity of cathode spots in Fig. 10 is discussed. The average velocity on the weld pool surface was the same order of 100 m/s with it in a previous study. Inside the weld pool, the cathode spot moved freely on the liquid surface and the average velocity can reach 200 m/s at the maximum. It means that cathode spots moved by an average distance of about 0.4 mm within interval time between two frames of 2 μs. Whereas, on the surface of the white zone to be almost solid, the average velocity was approximately 20 m/s. This value was found to be slightly higher than those in the vacuum, which were reported to range from some tenths of a meter per second up to meters per second. The decrease of average velocity on the white zone is explained referring Fig. 12. This decrease depends on the position of the cathode spot because the surface of the white zone was not completely solid. The big holes in Fig. 11 show that the surface locally melted near the edge of the weld pool. When cathode spots moved from weld pool to white zone, a part of them could be trapped in the big holes. In that case, the movement of the cathode spot was limited by the size of these holes. Therefore, the diameters of 0.1-0.3 mm was synonymous with the velocities of cathode spots from 50 m/s to 150 m/s. The magnitude of the velocity reduction is thought to be proportional to the number of cathode spot stayed on the solid surface.

Secondly, the distribution of cathode spots in Fig. 7 is explained. This study confirmed that the cathode spot did not exist in the center of the weld pool in helium shielding gas as reported in reference. During the observation, when cathode spots moved to the radial position of 2 mm from the outside, a part of them disappeared and the others split to move outward from the center of the weld pool. Therefore, in the center of the weld pool, the cathode spot did not exist. On the other hand, when cathode spots moved from the inside to arrive at the white zone, the velocity of them decreased, like sample 2 in Fig. 9, because they were trapped in the big holes on the white zone near the edge of weld pool. Therefore, the number of cathode spots around the radial position of 5.0 and 5.5 mm was high; conversely the probability to find the cathode spot outside this position was low.

Thirdly, the electrical characteristics of the cathode spot are mentioned. In this experiment, the total arc current of 200 A and the total number of cathode spots of 15 (Fig. 7) mean the current per a spot was averagely 13.3 A. However, the total number is known to increase with the gas pressure. As a result, the value of current per a spot was lower than 21.6 A in the experiment conducted in vacuum. If the diameter of all spots is assumed to be 10 μm which is the averaged crater diameter on the solid surface, the average current density of the cathode spots was approximately $16.9 \times 10^{10}$ A/m². This current density is found to be higher than the value of $5 \times 10^{10}$ A/m² on aluminum with the high arc current of 20,000 A. Because the average number of cathode spots increases in proportion to the total arc current, the current per spot is hence less dependent on the total arc current. However, the measurements of each cathode spot diameter were different, the current density could vary in a large range.

![Fig. 11](image1.png) Appearance of weld pool surface by microscopy.

![Fig. 12](image2.png) Schematic illustration of the change in cathode spot velocity.
As in Fig. 4, the difference in the cathode materials in EN and EP polarity is thought to affect the characteristics of the arc. In EN polarity, the cathode was tungsten to be a refractory material. In contrast, it was the aluminum to be a non-refractory material in EP polarity. In the latter case, it becomes the cold cathode on which the cathode spot has high current density. It leads the metal inside a spot evaporated and ionized strongly, and the vapor density of the arc hence increases in EP polarity. The metal vapor and ions are considered to cause the voltage in EP polarity higher than that in EN polarity. It could also explain why the cathode spot was locally brighter than the overall arc.

To explain the above behaviors, the nature of the cathode spot should be described in detail. The cathode spot is an electron emission process with a lifetime in the order of nanoseconds. During the observation with the temporal resolution of microseconds, the continuous repetition of the appearance of new spot and the disappearance of previous one is recognized as the motion of the cathode spot as in Fig. 13. The division of the cathode spot is correlated to the initiation of several new spots from the old one. The mechanism of the initiation of the new spot was supposed to be the impact of positive metal ions flux from the old one. The positive metal ions from the cathode spot could include Al, Al2+, Al3+ 23). The highly ionized ions increase electric field above the cathode surface to enhance the electron emission process. The new cathode spot is considered to be created by the division of the old cathode spot in a narrow area (Fig. 6).

Because of the high ionization energy of helium, the ionization of helium hardly occur until arc temperature exceeds 20,000 K4). Therefore, the arc outside the cathode spot with diameter of around 10 μm is considered not to have sufficient energy density for the ionization. The new cathode spot hence cannot spontaneously appear without the initiation from the old one. In the center of arc, due to higher temperature, the ionization state of the metal vapor is easy to be maintained. The energy flux can transfer far away from old spot inside the weld pool zone. The frequency of division is hence higher than that outside the weld pool. Outside the weld pool, the collisions of the fast metal ions with the slow gas ions will transfer energy to the gas. It causes the decline of the positive ions flux. Therefore, on the solid surface, the new cathode spot could hardly be initiated far away from the old one. Therefore, the velocity of the cathode spot is thought to become slower on the solid surface.

In this paper, the experiments were carried out in one set of the welding parameter. However, since the behaviors of the cathode spot are considered to depend on many factors such as base metal composition, shielding gas composition, the presence of metal vapor and so on, further research is planned to investigate the influence of the above factors to the cathode spot.

5. Conclusions

In this work, AC TIG welding was observed at the end of EP polarity by high-speed camera. The formation and movement of cathode spots were investigated in order to improve the efficiency of the oxide cleaning through the control of the cathode spot. As a result, the new cathode spots were found to be generated only from the division of the old cathode spot. This division took place continuously around the radial distance of 3.5mm from the center of weld pool. Most of the cathode spots generated there tended to move outward at average velocity decreasing from 200 m/s to 20 m/s with the radial distance. Arriving at the white zone, they suddenly decelerated around the radial distance of 5.5 mm to become gradually weak and then finally disappear. The probability of the generation of the cathode spot except for in the vicinity of the weld pool center was hence seen to be very low. Consequently, the general tendency of the life cycle of the cathode spot from the generation to the disappearance was
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