Alternating Current Tungsten Inert Gas (AC TIG) welding and Gas Metal Arc (GMA) welding are popular welding processes for various materials such as steel and aluminum. In these processes, the base metal to be non-refractory material is used as a cathode during electrode positive (EP) polarity. In EP polarity, the arc is operated as the cathode spot type, in which the spot decisively governs the heat input and surface-oxide cleaning on the surface as well as electromagnetic force in the arc and weld pool, thus affecting the weld penetration. Furthermore, in GMA welding, the cathode spot distribution is thought to be also related to droplet detachment process. Therefore, the study of cathode spot is indispensable for improving welding quality and productivity.

A cold cathode using low boiling temperature materials such as steel, aluminum or copper mainly makes the arc to become a spot type in which a large number of current attachments with very high current density form on the cathode surface simultaneously. Those show futures such as mobile, small (micrometer dimensions) and luminous and are called as cathode spots. The formation and movement of cathode spot are suggested to relate to the intensive evaporation flux of cathode metal. Under the presence of a background gas in welding field, although the behavior of cathode spot was affected by the pressure and characteristics of gas, metal vapor flux from the surfaces is thought to be still essentially important. From the above, the discussion on separate influence of background gas and metal vapor on the formation, movement of cathode spot is necessary for welding application, because the condition of welding arc has some differences with the vacuum arc in characteristics of the atmospheric-pressure gas and cathode surface condition.

The cathode spot behavior is expected to vary complicatedly depending on various welding conditions selected according to the requirement for application especially such as material composition. Magnesium is one of the major elements of aluminum alloy for industrial use, since it is able to greatly improve the strength of aluminum. Most studies on cathode spots in AC TIG welding focused on the oxide cleaning action on the aluminum surface by using a high-speed video camera (HSVC) with various frame rates. Ushio et al. observed the AC TIG welding on several kinds of aluminum alloy by a HSVC with a frame rate of 500,000 fps. The number of CS in A5052 case was larger than that in A1050, leading to the smaller average current per spot of 6.9 A comparing with 16.7 A in A1050. The larger current per spot is considered to cause the CS higher velocity. The average velocity of CS on liquid surface of A5052 was 110 ± 37 m/s far lower than that in A1050 case. The central area, where the CS did not exist, had a radius of 2.0 mm and expanded over EP time. The existence of magnesium in A5052 led to the increase in the cathode spot number inside the weld pool. The predicted mechanism could be the more easy evaporation of magnesium than that of aluminum.

Key Words: Cathode spot, Weld pool temperature, Helium, TIG welding, Aluminum, Magnesium, High-speed video camera observation
the thermionic electron emission from the surface. From this, the cathode spots high-likely stayed on the oxide layer. Recently, several studies were carried out through observation of the TIG welding arc with a frame rate of 500,000 fps\(^{12-14}\). It was found that the first cathode spot appeared on the oxide layer. Then it moved inward the weld pool where the oxide was almost cleaned\(^{14}\). Therefore, the work function is thought to be not the unique factor affecting the cathode spot behavior.

In this study, the cathode spot behavior in AC TIG welding of aluminum is further investigated by using the HSVC which has the maximum frame rate of 500,000 fps. The influence of the base metal composition is mainly discussed by using the base metal of aluminum alloy A5052 containing magnesium as the main alloy element, in comparison with the cathode spot behavior on A1050\(^{15}\). The observation is performed in EP polarity, aiming to discuss the temporal variation in cathode spot behavior such as the distribution and velocity of cathode spots.

2. Experimental method

Fig. 1 (a) shows a schematic illustration of the experimental setup for observing cathode spot behavior in stationary AC TIG welding.

A TIG welding power source (OTC Daihen, DA300P) establishes an AC arc between a tungsten electrode and an aluminum base metal (A5052). The distance from the electrode tip to the base metal is 3 mm. The main difference in the alloy composition of A5052 from that of A1050 is a larger amount of magnesium content as in Table 1. The observation is carried out from the up-side direction by a HSVC (SHIMADZU, HPV-1) equipped with an optical lens (Macro-NIKKOR 12 1:6.3), whose distance from the center of weld pool surface is 200 mm. The line of sight of the camera is set at 30 degrees from the surface of base metal. Table 2 shows the other setting parameters. The current waveform is measured with the clamp meter (HIOKI, 3285) to send it to the data logger (KEYENCE, NR-500/NR-HV04). In addition, the data logger directly measures voltage waveform. The sampling rate of data logger is 0.5 MHz. The low pass filter is not used. The data logger starts to record after a delay time from the beginning of the arc ignition counted by using a delay timer and a Welding Current Relay (WCR). The delay times are 3 s similarly with\(^{15}\). Therefore, all the observations is taken at 3 s after arc started. The observation time of cathode spot is synchronized with the current waveform by using a trigger line between the data logger and the camera.

Fig. 1 (b) shows the observation time overwritten on the current waveform in the EP polarity. When the current reaches a threshold value of 100 A in EP polarity, the data logger transmits the trigger signal to the camera. Because the maximum frame number of each video is limited to 100 frames due to the size of camera memory, the observations are made at three different times (100 frames per each observation). In the constant current phase, the high-speed

![Figure 1](image)

**Figure 1** Schematic illustration of (a) observation system and (b) observation time.

| Weight %   | Cu | Fe | Mg | Mn | Si | Al |
|------------|----|----|----|----|----|----|
| A1050      | 0.64 | 0.35 | 0.02 | 0.03 | 0.09 | Bal |
| A5052      | 0.02 | 0.25 | 2.03 | 0.61 | 0.07 | Bal |

| Welding parameters | Setting parameters |
|--------------------|---------------------|
| Welding power source | DA300P, OTC Daihen |
| Current            | AC 290A, 70Hz |
| EP ratio           | 30% |
| Electrode          | W+2%La2O3, ϕ3.2mm |
| Shielding gas      | He, 20l/min |
| Arc duration       | 3 s |
| Base metal         | A5052 |
| Cathode spot       | HSVC |
| observation setting | HPV-1, SHIMADZU |
| Frame rate         | 500,000 fps |
| Expose time        | 1 μs |
observations (500,000 fps) are carried out at (A) 1 ms, (B) 2 ms and (C) 3 ms after receiving the trigger signal. The cathode spot behavior is quantitatively analyzed from the recorded videos after completing the observation.

The position of the cathode spot is determined by tracing the luminous zones in the observed image. The real dimension is calculated from the number of pixels in the image through the calibration scales. The real dimensions per pixel in x-direction and y-direction are 0.049 and 0.082 mm/pixel, respectively. The velocity of each cathode spot is calculated by the changing distance between two consecutive frames. With the frame rate of 500000 fps and calibration scales in x-direction (0.049 mm/pixel), y-direction (0.082 mm/pixel), the maximum calculation error of velocity is \( \frac{\sqrt{0.049^2 + 0.082^2}}{2,10^{-5}} \times 0.001 = 47.7 \text{ m/s} \). The velocity of CS is averaged from three videos in each times (A), (B) and (C). The position of weld pool center is calculated from the positions of three points on the edge of the weld pool. The weld pool center \((x_c, y_c)\) and the radial distance between the cathode spot and the center are used for calculating the radial position \(R\) of the cathode spot as in Fig. 2.

3. Experimental results

The influence of aluminum alloy composition is studied by comparing the results in the case of A5052 with those in the case of A1050 already shown in reference \(^\text{(5)}\). Fig. 3 shows the appearances of weld pool and arc during EP polarity and the base metal surface after the arc stopped. The smooth area appearing in the center of the right image corresponds to the region where the weld pool existed. Because the observation was taken at 3 s after arc started, the weld pool radius was stable at 5.5 mm during one EP polarity. The radius of weld pool after the arc stopped was approximately 5.5 mm. The weld pool was seen to be surrounded by a white zone. The average width of this white zone was approximately 0.8 mm. A large amount of weld smut was formed as the black area outside the white zone. The smut is suggested to be made of the metal vapor \(^\text{(16)}\). In Fig. 3(a), the center of the arc was clearly brighter than the surrounding area. Moreover, cathode spots are found to exist as small and bright area in both of the weld pool and the white zone. Inside the weld pool, the cathode spot size was observed to be slightly smaller than that in the case of A1050 in Fig. 6 of reference \(^\text{(15)}\). The dark area around each cathode spot was not noticeable than that in the case of A1050.

Fig. 4 shows the comparison of voltage waveforms during EP polarity in the cases of A1050 and A5052. The temporal variation of voltage in two cases shows a similar tendency. However, there were two differences between both cases. Firstly, in the case of A5052, the peak voltage at the beginning of EP polarity was approximately 35 V, which was lower than 65 V in the case of A1050.
A1050. Secondly, the voltage in the case of A5052 was averagely 2 V higher than that in case of A1050 except for the peak value at the beginning of EP polarity.

Fig. 5 shows the average number of cathode spots on A5052 according to their radial position to the center of the weld pool at times A, B and C as in Fig. 1(b). The data was processed with the same procedure as that in the case of A1050. It could be seen that the total number of cathode spots in times A, B and C was 28 ± 1, 28 ± 3, 31 ± 3, respectively. The error of total CS number shows the standard deviation which was calculated from 15 frames of 3 videos per each observation time. The average value of current per spot was 7.1 A, 7.1 A and 6.5 A in times A, B and C. The ratio of the number of cathode spots located in the weld pool to the total number of cathode spots in times A, B and C was 49.2%, 30.3% and 34.9%, respectively. The central area, where cathode spot did not exist, has the radius more than 2 mm and slightly increased over time. This area was also larger than that in case of A1050. The peaks of the average number of cathode spots inside and outside the weld pool were located at the radial position of 4.5 mm and 7 mm respectively. Around the radial position of 4.5 mm, the peak of the average number was the highest at time A. This peak number inside the weld pool decreased and deflected slightly away from the center with the increase of EP time. Whereas, the average number of cathode spot outside the weld pool increased. The absence outside the position of 8 mm means that the spots were hard to reach the oxide zone at the observation moment.

Fig. 6(a) shows an example of traces of the cathode spot movement in the case of A5052 taken from the observation at time A presented in Fig. 1(b). The division of cathode spot was frequently seen to form two or more new cathode spot from one old cathode spot. It occurred continuously inside the weld pool especially around the radial position of 4.5 mm. The cathode spot tends to circulate locally in a narrow range rather than move linearly as observed in the case of A1050.

From the tracing process of cathode spot location, the velocities were also calculated as in Fig. 6(b). The figure shows the correlation between the average velocity and position of the cathode spot relative to the center of the weld pool at times A, B and C as in Fig. 1(b). The average velocity of cathode spots inside and outside the weld pool was 110 ± 37 m/s and 33 ± 23 m/s, which was lower than that on A1050. The average velocity tended to decrease as the radial position increased also in the weld pool. The difference in average velocities was around 100 m/s between in the weld pool and the oxide zone. Moreover, the average velocity on the weld pool slightly increased over time.

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**Figure 4** Comparison of EP polarity voltages between A1050 and A5052.

**Figure 5** Average number of cathode spots on A5052.
4. Discussion

As presented in Fig. 3(b), the weld smut could be produced of oxidized metal vapor\textsuperscript{16}. The boiling temperatures of aluminum and magnesium are 2793 K and 1363 K, respectively. In the same welding parameter setup on A1050\textsuperscript{17}, the surface temperature of weld pool can exceed the magnesium boiling point. Therefore, the evaporation of magnesium is predicted to occur strongly in the center of weld pool with the calculation on reference\textsuperscript{18}. Ushio et al.\textsuperscript{8} also showed the existence of magnesium vapor in arc on aluminum alloy by spectroscopic method. The metal vapor is considered to make the arc voltage slightly increased as in Fig. 4 through the radiation energy loss\textsuperscript{19}. The evaporation is related to the relatively brighter arc around the center as in Fig. 3(a).

The high density of magnesium vapor in background arc led to the smaller dark area around the cathode spot. The high pressure of the background arc suppressed the flux from the old cathode spot. Consequently, it determined the formation of new cathode spot. The moving range of each cathode spot on A5052 was seen to be limited locally in a smaller dark area when the vapor density increased. It showed the reason of the difference in cathode spot movement traces as in Fig. 6(a). The average velocities of cathode spot inside the weld pool were 110 m/s (Fig. 6(b)), far lower than that in case of pure aluminum cathode, probably because of the decrease in the current per spot.

From the experiment of A5052, it can be seen that magnesium affects some characteristics of the cathode spot such as distributions of the velocity and number of cathode spot. The number of cathode spot in case of A5052 was higher than that in case of A1050. Accordingly, an average current per spot on A5052 was only around 6.9 A.

As discussed in the previous study\textsuperscript{14}, the number of cathode spot was increased by two kinds of phenomena: spontaneous formation (sudden appearance) of a new cathode spot and formation of several new cathode spots by the division of the one old cathode spot.

The former was seen mainly on the oxide surface outside of the weld pool only immediately after polarity switching to EP. This phenomenon is considered to be related to the lower work function of magnesium oxide. The lower work function enables to enhance
the electron emission from the surface. From this, the cathode spot was formed easily on the oxide. It is one of the reasons to increase the number of cathode spot\(^1\).

On the other hand, the latter was seen to occurs inside the weld pool (Fig. 6(a)) where oxide layer was almost cleaned. The cathode spot outside the weld pool did not spontaneously appear except for the beginning of EP polarity; most of the cathode spots on the oxide were provided by outward movement from the inside of the weld pool\(^1\). The peak of average number of cathode spot around the radial position of 4.5 mm at time (A) in Fig. 5 is a result of the intensive division of cathode spot at that position. Thus, the division was found to preferentially occur on the weld pool despite the work function is higher than that on the oxide.

It means that the work function is not the unique factor to cause the change in cathode spot behaviors. The evaporation could cause the change of the plasma properties over the weld pool, thus affecting the behaviors of cathode spot. When metal vapor concentration is high, collisions between atoms and multiply charged ions occurred significantly as the following. As a result, the charge exchange happens to reduce the charge amount of multiply charged ion in the flow from the old cathode spot\(^6\) as:

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\text{Al}^3 + \text{Mg} \rightarrow \text{Al}^{+1} + \text{Mg}^+ \]

The electrically neutral particles such as metastable A* and atom of metal vapor cannot emit a new electron from the cathode through the collision. On the opposite way, when the concentration of metal vapor atom increases, the volatility of the cathode sheath was reduced by the above charge exchange. Therefore, the electron emission of new cathode spot is considered to be restricted, leading to the division of cathode spot The current per cathode spots hence decreases. It can explain the increase in the number in case of A5052.

5. Conclusion

In this study, the cathode spot behavior in AC TIG welding of aluminum was investigated by using the HSVC which has the maximum frame rate of 500,000 fps. The influence of the base metal composition was mainly discussed by using the base metal of aluminum alloy A5052. The following conclusions can be drawn from the results.

1. The average value of current per spot was 7.1 A, 7.1 A and 6.5 A in times A, B and C.
2. The ratio of the number of cathode spots located in the weld pool to the total number of cathode spots in times A, B and C was 49.2%, 30.3% and 34.9%, respectively.
3. The central area, where cathode spot did not exist, has the radius more than 2 mm and slightly increased over time. This area was also larger than that in case of A1050.
4. The average velocity of cathode spots inside and outside the weld pool was 110 ± 37 m/s and 33 ± 23 m/s, which were lower than those on A1050. It is considered to be caused by smaller current per spot.

The larger content of magnesium in A5052 led to the increase in the cathode spot number inside the weld pool. The predicted mechanism could be the more easy evaporation of magnesium than that of aluminum.

Reference

1) Jenney, CL and O’Brien, A.: Welding handbook, American Welding Society, 5, (2015).
2) Hertel, M., Rose, S., et al.: “Numerical simulation of arc and droplet transfer in pulsed GMAW of mild steel in argon”, Welding in the World, 60, (2016), 1055–1061.
3) Anders, A.: Cathodic arcs: From Fractal Spots to Energetic Condensation, (Springer, 2008).doi:10.1007/978-0-387-79108-1.
4) Juttner, B.: “Cathode spots of electric arcs”, J. Phys. D. Appl. Phys., 34, (2001), 103–123.
5) Beilis, B.: “State of the theory of vacuum arcs”, IEEE Transactions on Plasma Science, 29, (2001), 657–670.
6) Anders, A. and Juttner, B.: “Influence of Residual Gases on Cathode Spot Behavior”, IEEE Transactions on Plasma Science, 19, (1991), 705–712.
7) Kimblin, C.W.: “Cathode spot erosion and ionization phenomena in the transition from vacuum to atmospheric pressure arcs”, Journal of Applied Physics, 45, (1974), 5235–5244.
8) Ushio, M., Nakata, K., et al.: “Observations of Cathode Spot Welding of Aluminum Alloy”, Transactions of JWRI, 23, (1994), 169–174.
9) Balanovskii, A.E.: “Structure of the Welding Arc Cathode Spot with a Nonconsumable Electrode”, High Temperature, 56, (2018), 1–9.
10) Sarraf, R. and Kovacevic, R.: “Cathodic Cleaning of Oxides from Aluminum Surface by Variable-Polarity Arc”, Welding Journal, 89, (2010), 1–10.
11) Rose, S., Zähringer, J., et al.: “Arc attachments on aluminum during tungsten electrode positive polarity in TIG welding of aluminum”, Welding in the World, 55, (2011), 91–99.
12) Tashiro, S., Sawato, H., et al.: “Experimental Observation of Cleaning Action of Cathode Spots in AC TIG Welding of Aluminum Plates”, Japan Welding Society, 29, (2011), 5–8.
13) Yuji, T., Tashiro, S., et al.: “Observation of the Behavior of Cathode Spots in AC Tungsten Inert Gas Welding on Aluminum Plate”, Quarterly Journal Of The Japan Welding Society, 33, (2015), 135–138.
14) Phan H. Le, Tashiro, S., et al.: “Investigating cathode spot behavior in argon alternating current tungsten inert gas welding of aluminum through experimental observation”, Journal of Physics D: Applied Physics, 52, (2019), 26LT02.
15) Phan H. Le, Tashiro, S., et al.: “Behaviors of Cathode Spot in Alternative Current Helium TIG Welding of Aluminum Behaviors of Cathode Spot in Alternative Current Helium TIG Welding of Aluminum”, Journal of Smart Processing for Materials, Environment & Energy, 7, (2018), 243–250.
16) Tashiro, S., Zeniya, T., et al.: “Numerical analysis of fume formation”, Journal of Physics D: Applied Physics, 43, (2010), 1–12.
17) Trinh, Q.N., Phan H. Le, et al.: “Optical Measurement of Surface Temperature Distribution of Weld Pool in AC Tungsten Inert Gas Welding of Aluminum A1050”, Journal of Smart Processing for Materials, Environment & Energy, 8, (2019), 213–218.
18) Block-Bolten, A and Edgar, TW.: “Metal vaporization from weld pools”, Metallurgical Transactions B, 15, (1984), 461–469.
19) Anthony B Murphy: “The effects of metal vapour in arc welding”, Journal of Physics D: Applied Physics, 43, (2010), 165204.