Imaging Spectroscopy for Transient Transport of Chromium Vapor During Helium TIG Welding*

by TANAKA Keigo**, SHIGETA Masaya***, TANAKA Manabu*** and MURPHY Anthony B.****

The transient transport process of the chromium vapor during Tungsten Inert Gas (TIG) welding was revealed by imaging spectroscopic analysis. During TIG welding, the metal vapor generated from the weld pool surface is transported to the arc plasma. The metal vapor affects the plasma properties such as electrical conductivity and radiation coefficient. However, the transient transport process of the metal vapors including ions inside TIG arc plasma has not been clarified. In this paper, the experiments were performed under the special conditions such as helium TIG welding on pure chromium. After the arc ignition, the chromium vapors were generated from a pure chromium base metal and transported through the inside of the arc plasma to the tungsten cathode. As time passed, the He I spectral intensity gradually decreased. In contrast, the Cr I and Cr II spectral intensities gradually increased near the weld pool, near the electrode and the intermediate region. At a certain time, the chromium vapor reached the center of the arc plasma when using an electrode with a flat tip. The metal vapor distribution inside the arc plasma transiently changed when the plasma flow slowed down due to the electrode deformation during TIG welding.

Key Words: TIG welding, Metal vapor, Chromium, Imaging spectroscopy, Transient transport, Plasma flow

1. Introduction

During TIG welding, metal vapors are generated from a weld pool surface. Metal vapors are ionized in TIG arc plasma and these are transported through the arc plasma to a tungsten electrode by cataphoresis1-2). Then, metal vapor affects the physical properties of the arc plasma, such as electrical conductivity and a net emission coefficient3). In addition, the amount of electrode consumption increases because of metal vapor4). When the metal ions were transported to the tungsten electrode, the electrode was deformed by the deposition of metal ions and the melting of tungsten5). Therefore, the transient transport mechanism of metal vapor in arc plasma should be understood in order to suppress temporal changes in the welding heat source and the electrode consumption. Tanaka and Tsujimura6) observed the He I, the Cr I, the Fe I and the Mn I spectral images in TIG arc plasma by imaging spectroscopy. However, the transient behavior of metal vapor in TIG arc plasma has not been clarified in detail because the images were not spectral images but directly-observed images as observed. The metal ion spectral images have not been revealed, either.

In this paper, the transient transport processes of metal vapors including ions in a helium TIG arc plasma on pure chromium after ignition were revealed by imaging spectroscopy.

2. Experimental procedure

2.1 Experimental conditions

Table 1 shows the experimental conditions. In order to easily observe the metal vapor inside the arc plasma, the experiments were performed under the special conditions such as helium TIG welding on pure chromium. This is because helium TIG arc plasma has a lower continuous spectrum intensity than argon TIG arc plasma. In addition, pure chromium was used as a base metal because chromium has a lower boiling temperature than that of iron, generates numerous vapor. Two types of tip-shaped electrodes were used. When the electrode tip was chamfered, the arc pressure significantly dropped7,8). The arc pressure suggests the speed of the plasma flow9). In addition, it is possible to suppress the transport of metal vapor to the electrode by speeding up the plasma flow10). That is, the transport amount and the transport process of metal vapor to the electrode might be different because the plasma flow induced by the electrode shape is different when the electrode is deformed during welding. In this paper, the electrode with the grounded tip was defined as type 1, and the electrode with a 1 mm diameter chamfered tip was defined as type 2. A spot TIG welding was performed on pure chromium.

2.2 Experimental set up for spectroscopic measurement

Table 2 shows the measurement species and their line spectral wavelengths and the selected continuous spectrum wavelengths11). The continuous spectral intensity was simultaneously measured at a wavelength close to the line spectral wavelength because the line spectral intensity includes the continuous spectral intensity.

Received: 2019.11.21, Presented at Visual-JW or WSE 2019
** Student Member, Joining and Welding Research Institute, Osaka University
*** Member, Joining and Welding Research Institute, Osaka University
**** CSIRO Manufacturing
Figure 1 shows a schematic illustration of the imaging spectroscopy system. The radiation from the arc was split into two light paths by a right-angle prism mirror. The split images were divided into the line spectral wavelength and the continuous spectral wavelength inside the monochromators, respectively. The wavelength resolution of the monochromators was set at 1.0 nm. The spectral images were simultaneously recorded by a computer through the high-speed cameras. The high-speed camera had a 12-bit gray scale and the shooting speed was set as 100 fps. TIG arc plasma has better reproducibility than gas metal arc plasma. Therefore, the spectral images of He I, Cr I and Cr II were measured three times under the same welding conditions. However, the exposure time of the high-speed camera was adjusted for the measurement species. The aspect ratio of the recorded images was corrected because the recorded image was vertically long in the imaging spectroscopy system. The wavelength sensitivity of the image element of the high speed cameras was corrected for each measurement wavelength. The spectral images in the central cross-section were obtained by Abel inversion processing because the recorded images were line-integrated images. Only the line spectral intensity image was extracted by subtracting the continuous spectral image from the line spectral image including the continuous spectral intensity.

Table 1 Experimental conditions.

| Condition               | Value            |
|-------------------------|------------------|
| Welding current         | 150 A            |
| Shielding gas           | Pure helium      |
| Gas flow rate           | 25 L/min         |
| Nozzle inner diameter   | 12.7 mm          |
| Electrode               | W - 2 wt.% La2O3|
| Electrode diameter      | 3.2 mm           |
| Tip angle               | 60 deg           |
| Electrode extension     | 3.0 mm           |
| Arc length              | 3.0 mm           |
| Base metal              | Pure chromium    |
| Base metal dimension    | (50 mm×50 mm×9 mmt) |
| Welding time            | 40 s             |
| Polarity                | Direct Current   |
|                         | Electrode Negative |

Table 2 Measurement species, their line spectrum wavelengths and selected continuous spectrum wavelengths.

| Species                  | Spectrum wavelength (nm) | Line | Continuous |
|--------------------------|--------------------------|------|------------|
| Helium atom (He I)       | 587.6                    | 586.0|
| Chromium atom (Cr I)     | 520.8                    | 510.0|
| Chromium ion (Cr II)     | 455.9                    | 450.0|

3. Results and discussion

Figure 2 shows the He I, Cr I and Cr II spectral intensity distributions on pure chromium at 0.80 s, 8.00 s, 18.00 s, 28.00 s and 38.00 s after arc ignition when type 1 electrode was used. The exposure time of the high-speed cameras was set at 300 μs for He I, 1000 μs for Cr I and Cr II. The colors indicate the spectral intensity values. The left end is the central axis of the arc plasma. The time from the arc ignition. At $t = 0.80$ s, the maximum value of He I spectral intensity exceeded 500 and He I was distributed in the maximum radius of about 5.0 mm. The Cr I spectral intensity exceeded 500 near the weld pool. The Cr II spectral intensity could hardly be measured. At $t = 8.00$ s, the maximum value of He I spectral intensity decreased to about 200 and the distribution width shrunk to the maximum radius of about 4.0 mm. The Cr I spectral intensity exceeded 500 not only near the weld pool but also near the electrode. The Cr II spectral intensity was measured near the weld pool and near the electrode, it showed the same tendency as the Cr I spectral intensity distribution. After that, as time passed ($t = 18.00$ s, 28.00 s, 38.00 s), the He I spectral intensity gradually decreased. In contrast, the Cr I and Cr II spectral intensities gradually increased near the weld pool, near the electrode and the intermediate region. Cr I distributed in the outer layer of the arc plasma, and Cr II distributed in the inner layer of the arc plasma. This is because Cr I emits strong light at 7000 K, whereas Cr II emits strong light at 15000 K.

Figure 3 shows the He I, Cr I and Cr II spectral intensity distributions on pure chromium at 0.80 s, 8.00 s, 18.00 s, 28.00 s and 38.00 s after arc ignition when type 2 electrode was used. At $t = 0.80$ s, the maximum value of He I spectral intensity exceeded 250 and He I was distributed in the maximum radius of about 4.0 mm. The Cr I and Cr II spectral intensity exceeded 500 near the weld pool. At $t = 8.00$ s, the maximum value of He I spectral intensity decreased to about 50 and the distribution width shrunk to the maximum radius of about 3.0 mm. The Cr I and Cr II spectral intensity exceeded 500 not only near the weld pool but also near
Fig. 2 He I, Cr I and Cr II spectral intensity distributions on pure chromium at 0.80 s, 8.00 s, 18.00 s, 28.00 s and 38.00 s after arc ignition when type 1 electrode was used.

Fig. 3 He I, Cr I and Cr II spectral intensity distributions on pure chromium at 0.80 s, 8.00 s, 18.00 s, 28.00 s and 38.00 s after arc ignition when type 2 electrode was used.
the electrode. After that, as time passed ($t = 18.00 \text{s}, 28.00 \text{s}$), the He I spectral intensity decreased to less than 25. In contrast, the Cr I and Cr II spectral intensities gradually increased near the weld pool, near the electrode and the intermediate region. At $t = 38.00 \text{s}$, the He I spectral intensity could hardly be measured. The He I spectral intensity decreases with decreasing the plasma temperature\(^1\). The temporal change in the He I spectral intensity suggest that the helium arc plasma was cooled by strong radiation of chromium vapor when chromium vapor was transported through the arc plasma to near the electrode. Moreover, the rate of decrease and the degree of decrease in the He I spectral intensity differed depending on the electrode tip shape. This depends on the amount of chromium vapor transported. The line spectral intensity depends not only on the temperature but also on the particle number density. When type 2 electrode was used, the strong spectral intensity of Cr II was measured not only near the electrode but also to the center of the arc plasma. This indicated that more chromium ions were transported when the type 2 electrode used than when type 1 electrode was used. This is because when type 2 electrode was used, a slower plasma flow is induced than that when type 1 electrode was used\(^3\). When the electrode tip deforms into the flat tip, the electrode might be further deformed by more metal vapor transport, as reported in previous study\(^5\).

4. Conclusions

The transient transport of metal vapors including ions in a transient helium TIG arc plasma on pure chromium were revealed by imaging spectroscopy. Conclusions of this study are summarized as follows:

1) As time passed, the Cr I and Cr II spectral intensities were high not only near the weld pool surface but also near the electrode. In contrast, the He I spectral intensity was weak and the He I distribution shrunk toward the center of the arc. This is because the helium arc plasma was cooled by the strong radiation of chromium vapor.

2) After that, Cr II reached to the center of the arc when using the electrode with the chamfered tip. This is because of the slower plasma flow than that using the electrode with the grounded tip.

References

1) K. Tanaka, M. Shigeta, M. Tanaka and A. B. Murphy: Investigation of the bilayer region of metal vapor in a helium tungsten inert gas arc plasma on stainless steel by imaging spectroscopy, J. Phys. D: Appl. Phys., 52 (2019), 354003.
2) H. Park, M. Trautmman, K. Tanaka, M. Tanaka and A. B. Murphy: A computational model of gas tungsten arc welding of stainless steel: the importance of considering the different metal vapours simultaneously, J. Phys. D: Appl. Phys., 51 (2018), 395202.
3) A. B. Murphy: The effects of metal vapour in arc welding, J. Phys. D: Appl. Phys., 43 (2010), 434001.
4) A. Uchida: The Properties of Tungsten Electrode in TIG Arc Welding -Current Capacity and Consumption-, Quart. J. Japan Weld. Soc., 32 (1963), 1006-1007 (in Japanese).
5) K. Tanaka, M. Shigeta and M. Tanaka: Effect of Metal Vapor Transport on Tungsten Electrode Consumption During TIG Welding, 72nd IIW Annual Assembly and International Conference, (2019), Doc. 212-1624-19.
6) M. Tanaka and Y. Tsujimura: Visualization of metal vapor behavior in TIG welding - Visualization of phenomena of welding arc by imaging spectroscopy -, Quart. J. Japan Weld. Soc., 30 (2012), 164-170 (in Japanese).
7) K. Hiraoka, A. Okada and M. Inagaki: Effect of Helium Gas on Arc Characteristic in Gas Tungsten Arc Welding, Quart. J. Japan Weld. Soc., 3 (1985), 241-246 (in Japanese).
8) K. Hiraoka, A. Okada and M. Inagaki: Effect of Electrode Geometry on Maximum Arc Pressure in Gas Tungsten Arc Welding, Quart. J. Japan Weld. Soc., 3 (1985), 246-252 (in Japanese).
9) J. J. Lowke, P. Kovitya and H. P. Schmidt: Theory of free-burning arc columns including the influence of the cathode, J. Phys. D: Appl. Phys., 25 (1992), 1600-1606.
10) K. Konishi, M. Shigeta, M. Tanaka. A. Murata and T. Murata: Influences of welding conditions on the constricted TIG arcs, Quart. J. Japan Weld. Soc., 32 (2014), 207-212 (in Japanese).
11) A. Kramida, Y.Ralchenko, J. Reader and NIST ASD Team 2016 NIST Atomic Spectra Database (Version 5.6) (Gaithersburg, MD: National Institute of Standards and Technology) (Online) Available: https://physics.nist.gov/PhysRefData/ASD/lines_form.html (Accessed: 18 March 2019).