In an automatic welding system using a visual sensor, it is necessary to clearly observe the weld pool to control the welding phenomenon with a visual sensor. However, since the arc light is too strong, it is difficult to take clear weld pool images. It is important to reduce the influence of the arc light. Therefore, the spectral distribution of the weld pool and arc light in plasma arc welding and pulse MAG welding was measured changing the current. Based on the measurement results, the characteristics of the spectral distribution in each welding method were found. Using the results, a filter suitable for the weld pool observation was selected.

Key Words: Weld Pool, Arc Light, Plasma Arc Welding, Pulse MAG welding, Planck’s Law, Interference Filter

2. Experimental procedure

2.1 System Configuration

In this paper, a welding robot, a robot controller, a robot motion control personal computer, a plasma arc welding power supply, Ar gas, a CCD camera for observing a weld portion, a camera control personal computer, a spectrometer control personal computer, and a current-voltage measurement NR 600 are used. A mild steel plate was used as a base material. Fig. 1 shows a system configuration in which these devices are combined.

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2.2 Welding Conditions for Measurement and Spectroscope Installation Method

Plasma arc welding was conducted using 4 current values: 30 A, 100 A, 150 A, and 200 A. In order to ensure reproducibility, the measurement conditions from the arc to the spectrometer should be the same. Therefore, four types of currents were used in the same experiment. The current was changed in synchronization with the measurement by the spectrometer. In consideration of the measurement time of the spectrometer, measurements were made at 50 ms intervals as shown in Fig. 2(a). In pulse MAG welding, for 1 pulse 1 droplet, the pulse frequency was 80 Hz, the base current was 100 A, and the peak current was about 400 A. In order to measure the peak current and the base current, the measurement interval was adjusted at a pulse interval slightly longer than the current pulse interval. Since the emission intensity of the arc light was strong, the exposure time of the spectroscope for measurement was 1 ms\(^1\). As shown in Fig. 2(b), the trigger signal and the pulse peak current first coincide with each other. Thereafter, the pulse interval of the current gradually deviated, and the pulse peak was made to coincide again with the trigger signal of six times. A spectrum and an image are acquired at such timing.

In order to examine the spectral intensity of the arc light and the weld pool received by the visual sensor, as shown in Fig. 3, the tip of the optical fiber was set at a distance of 0.15 m from the arc, and absolute irradiances were measured. However, since the emission intensity is strong at a wavelength longer than the visible light, the measurement result is saturated when the current value is large. Therefore, when the current value is 100 A or more, the distance of the spectrometer from the plasma arc was changed to 1.0 m. In order to compare the measurement results at a short distance and a long distance, the solid angle is calculated from the area of the optical fiber and the distance from the light emitting point.

Using the ratio of solid angles, the results measured at 1.0 m were compared with those at 0.15 m. Since the solid angle can be obtained from the light receiving area of the optical fiber with respect to the area of the spherical surface, the solid angle is inversely proportional to the square of the distance. In pulse MAG welding, a mixed gas of 80% Ar and 20% CO\(_2\) was used as a shielding gas. The weld pool observation was carried out at a distance of 0.15 m directly under the wire. An ND4 filter was placed in front of the optical fiber receiving surface of the spectrometer to prevent saturation of spectral brightness when measuring arc light.

In plasma arc welding and pulse MAG welding, the spectral characteristics of the weld pool were measured at the moment when the welding was completed and the welding current reached zero, which implies immediately after the cooling of the weld pool started and there was no arc light.

3. Measurement results and discussion

3.1 Spectroscopic Characteristics in Plasma Arc Welding

The observed weld pool images and spectral distributions of plasma arc welding with welding currents of 30 A, 100 A, 150 A, and 200 A are shown in Fig. 4 (a), (b), (c) and (d). The spectral irradiance of the arc light increases as the welding current increases. Although the emission line spectrum has been measured, it is necessary to examine whether it is due to the emission intensity of the arc itself or the effect of the emission intensity due to the melting of the base material. In order to clarify this cause, the base metal was changed from mild steel to aluminum plate, and the experiment was carried out without changing other conditions.
Fig. 5 shows the spectral distribution when the base material is aluminum or mild steel. From this figure, emission line spectra are generated in the same wavelength region in mild steel and aluminum. This suggests that those peaks are mainly caused by the emission of Ar used as a shielding gas\(^{14, 15}\). The peak intensity of the spectrum increases at the wavelength in the visible light region, but decreases at the near infrared light region. On the other hand, it became smaller in the ultraviolet region. The spectral characteristics of the weld pool are shown in Fig. 6. The spectral intensity starts to increase from 600 nm. As shown Fig 6, the spectral irradiance of the weld pool becomes larger as the wavelength becomes longer. It is thought that the result follows Planck's law.

Taking the bright line spectrum positions in Fig. 4 into consideration, the weld pools were observed using 4 kinds of interference filters (600 nm, 700 nm, 760 nm, 950 nm) by lowering the welding current to 30 A at the trigger signal shown in Fig. 2 (a) in accordance with the case where there is no bright line spectrum position or where there is bright line spectrum position. A typical weld pool image is shown in Fig. 7, and the spectral characteristics of each filter used in the experiment for incandescent bulbs are shown in Fig. 8. Fig. 7(a) shows an image of a weld pool when an interference filter of 600 nm is used. At 600 nm, the arc light is not extremely bright because there is no emission line spectrum of Ar. However, the brightness of the weld pool is low. As shown in the weld pool image, the contrast between the base material and the weld pool becomes weak. Therefore, it is difficult to detect the boundary between the weld pool and the solid portion by image processing. Fig. 7(b) and 7(c) show weld pool images taken using interference filters of 700 nm and 760 nm, respectively. Since the wavelength of the interference filter transmits the emission line spectrum of Ar, the intensity of the plasma arc light is increased. In
the weld pool images, the vicinity of the keyhole is bright and the luminance is saturated. In order to observe the weld pool, it is necessary to reduce the light by the ND filter. When dimming is performed, the brightness of the weld pool part and the solid part is lowered. Therefore, the contrast ratio of the solid portion to the weld pool portion is lowered, and observation of the weld pool boundary becomes difficult. Fig. 7(d) shows a weld pool image when a 950 nm interference filter is used. The longer the wavelength, the higher the brightness of the weld pool, and since there is no emission line spectra at this wavelength, the influence of the arc light is suppressed and the weld pool can be clearly observed.

### 3.2 Spectroscopic Characteristics in Pulse MAG Welding

Fig. 9 shows the spectral characteristics of the observed weld pool images and arc light at the peak current and base current of pulse MAG welding. Unlike plasma arc welding, the emission spectra of MAG welding become significant in the ultraviolet region where the wavelength is short. This may be due to the emission of metal vapor in the arc. On the other hand, the emission spectra in the visible light region agreed with that in the plasma arc welding, but the emission spectrum of O₂ existed. This is thought to be caused by the decomposition of CO₂ in the shielding gas at high temperature.

In MAG welding, the weld pools were photographed using 4 types of interference filters (600 nm, 700 nm, 760 nm, 950 nm). These images are shown in Fig. 10. The spectral characteristic of the weld pool during pulse MAG welding are shown in Fig. 11. Fig. 10(a) shows a weld pool image observed using an interference filter of 600 nm. At this wavelength, due to the existence of the emission line spectra of O₂, the arc light became very strong and it was difficult to observe the weld pool. The weld pool images observed with the interference filters of 700 nm, 760 nm and 950 nm are shown in Fig. 10(b), 10(c) and 10(d), respectively. No dominant emission line spectra exist near these wavelengths. However, as shown in Fig.11, the spectral intensity of the weld pool increases as the wavelength increases. Therefore, among the wavelengths of 700 nm, 760 nm and 950 nm, the one using the interference filter having the longest wavelength can be observed relatively clearly as shown in Fig. 10(d). When the spectral distribution of Fig. 9 was examined in detail, no emission line spectra could be confirmed at 920 nm or more and 1000 nm or less. Also, considering the spectral characteristics of the near-infrared visual sensor, the use of a long-pass filter is more likely to receive light from the weld pool than the use of an interference filter. Therefore, a long pass filter that transmits light having a wavelength of 925 nm or more was used in consideration of a range in which no emission line spectra exists. An example of a weld pool image using this is shown in Fig. 12. As shown in Fig. 12(a), the weld pool brightness was too bright only with the long pass filter. Therefore, an ND4 filter was used in combination with a
long-pass filter to achieve 1/4 luminance. The weld pool image is shown in Fig. 12(b). As shown in the Fig. 12(b), the boundary between the base material and the weld pool became clear, and an image of the weld pool could be obtained while suppressing the influence of arc light.

4. Conclusions

Spectral distributions of arc light and weld pool were measured at various values of 30 A, 100 A, 150 A and 200 A in plasma arc welding. Thereafter, the spectral distribution of arc light and weld pool at a peak current of 400 A and a base current of 100 A was also measured in pulse MAG welding. The emission spectrum of the arc light becomes larger as the current is larger. In the case of plasma arc welding, it was present not only in the visible light region but also in the near infrared region. On the other hand, in the case of pulse MAG welding, the emission spectrum existed in the ultraviolet and visible light regions, and the emission spectrum in the near infrared region was small. From these results, the emission spectra could not be confirmed above 920 nm when the welding current was small. Therefore, in order to observe the weld pool, it was confirmed that it was useful to select a long pass filter of about 920 nm or more by lowering the welding current.

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