Effects of Metal Vapor on Thermodynamic State in Helium GTA †

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Abstract

In order to investigate effects of metal vapor on the thermodynamic state of arc plasma in the welding process, electron temperatures in the pure helium plasma and helium plasma during welding in Gas Tungsten Arcs (GTA) were measured by using the laser scattering method. The experimental results showed that metal vapor led to a significant decrease in the electron temperature compared with that of pure helium GTA plasma.

KEY WORDS: (Helium) (Electron temperature) (GTA) (Welding) (Arc) (Metal vapor) (Thomson scattering)

1. Introduction

The arc plasma during welding includes the metal vapor from the molten pool. Thus, it can be expected that the arc plasma during welding will have a different thermodynamic state compared with pure arc plasma.

Many researchers have tried a variety of investigations on metal contaminated arc plasma. Glickstein[1] presented the results of spectroscopic measurements on a 100 A, 2mm arc length, argon arc with evaporation from heated alloy 600 plate. He showed that the arc temperature results determined with a stationary molten anode are similar to the results with a cooled anode. He measured the arc temperature only using the Boltzmann plot method. If there is a slight change of slope which is derived from relation between the line intensity and the excitation energy, the results were drastically changed in this method[2]. Etemadi and Pfender[3] presented the results of spectroscopic measurements on a 150 A, 10 mm arc length, 800 Torr argon arc with evaporation from the molten copper. They found that the order of temperature decrease was 1000 K at 1 mm above the anode compared to pure argon arc with a water-cooled copper anode. Razafinimanana et al[4] showed a result of spectroscopic measurements on a 90 A, 18 mm arc length, atmospheric argon arc with evaporation from the copper anode. They also found that the order of temperature decrease was 2000 K near the anode. Furthermore, they recorded the density of neutral copper atoms derived from the measurement of line spectrum intensity. However, the experiments mentioned above have been carried out based on the assumption of Local Thermodynamic Equilibrium (LTE) for the arc. Recently, some non-LTE states in GTA plasma were shown for the case of pure argon. Snyder et al directly measured temperatures of electron and heavy particles in a DC plasma jet[5] and free-burning arc[6] at atmospheric pressure by the method of laser scattering measurement which needs no assumption of LTE. They showed that the electron temperature was different from the heavy particle temperature. Bentley[7], Murphy[8] and Tanaka[9] also showed deviation from LTE in GTA plasma. These experiments with Thomson scattering were for pure GTA plasma. In the case of a metal contaminated arc, a non-LTE result is also expected. Thus, the diagnosis without LTE assumption should be very important for analyzing the metal contaminated arc plasma.

In the present paper, electron temperature measurement of the arc during welding was conducted using the Thomson scattering method which needs no LTE assumption.

These results show that the metal vapor leads to significant decrease in the electron temperature compared with a pure arc plasma.

2. Experimental set up

The theory of Thomson scattering was explained in

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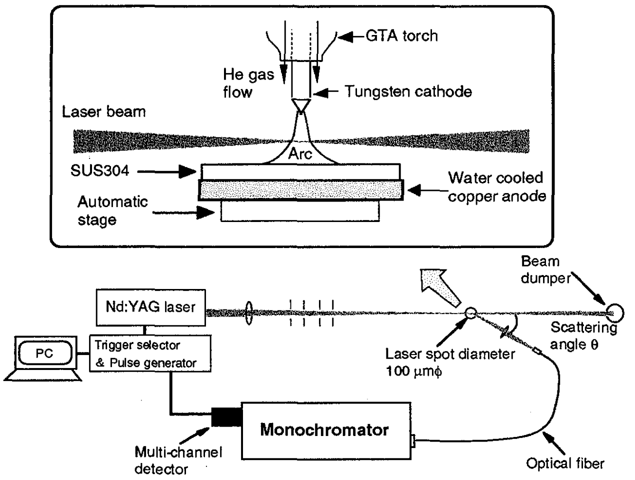

Fig. 1 Schematic illustration of the apparatus for laser scattering measurements.

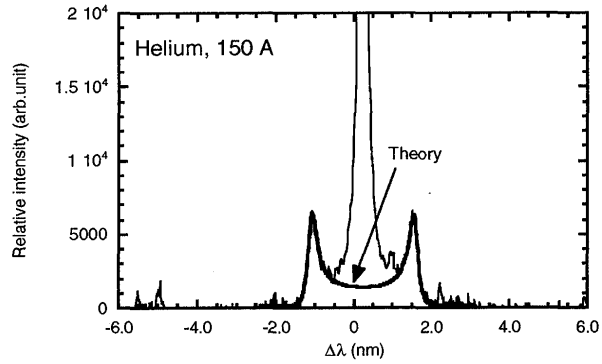

Fig. 2 Typical line profile of an electron feature. Measurement is carried out at 3.5 mm from cathode tip and 2 mm from arc axis in helium GTA plasma during welding under the condition of 150 A arc current.

our previous paper[9].

In the present work, helium gas was used as a shielding gas. This exploited three characteristics of helium gas. One is low arc pressure[10]. This characteristic makes it possible for more metal vapor to arise. Thus, it is possible to investigate the effect of metal vapor on the arc plasma. The next is the optically thin characteristic of helium. This characteristic prevents line spectrum absorption in the plasma. Thus, this is applicable to observation of the metal line spectrum. The third is the characteristic of high ionization potential. If the ionization potential of the arc shielding gas is higher than that of the metal elements, larger effect of metal contamination on the electric properties of the arc can be expected[11, 12].

Fig. 1 shows a schematic illustration of the apparatus for the Thomson scattering measurements. As laser light, a pulsed Nd:YAG laser with second harmonic generation was used. The laser beam was focused on the arc plasma. The beam waist at the focal point was approximately 100 μm and the laser power was 0.7 W (The pulse rate was 10 Hz). The sampled volume is geometrically dependent on the diameter of the incident laser beam and the focal distance of the lens. This means that measured temperature is the mean value in this area. The scattered light was detected at the scattering angle of 30 deg. and introduced to the Intensified Charge Coupled Device (ICCD) detector through the optical fiber (200 μm in diameter) and the monochromator. Scattering angle is discussed in the next section. The slit width of the monochromator-entrance was 300 μm and the height was 20 mm. At first, helium GTA plasma was established between a tungsten cathode with 2% La_2O_3 (cathode diameter is 3.2 mm with tip angle) and SUS304 (8Ni-18Cr-austenitic stainless steel). The arc gap was fixed at 5 mm, and the helium gas flow rate was 40 l/min. Automotive bead-on-plate welding with a moving SUS304 anode on a water-cooled copper support stage was conducted. Welding travel speed was 0.5 mm/s. This speed is very slow compared with that in usual applications, but this slow speed enabled the arc to be more stable. After the arc plasma became stable, background measurements were conducted. After that, the scattering signal was acquired. **Fig. 2** shows a typical example of Thomson scattering profile. After fitting a theory profile, a scattering parameter and Doppler shift width of electron profile peak were acquired. From these data, electron temperature and electron density were derived.

3. Results and Discussion

3.1 Electron temperature dependence on scattering angle

In this section, we focus on discussions about electron temperature dependence of the scattering angle in Thomson scattering measurements. Gregori et al[13] showed dependence of electron temperature on scattering angle in an argon DC plasma jet. They concluded that the density gradient in the scattering volume caused a significant increase in the electron temperature measured by Thomson scattering because the theory assumed uniform density. The spectral profile of Thomson scattering depends on the scattering parameter which consists of scattering angle and Debye length in the case of constant wavelength of the laser beam. The Debye length also consists of the electron

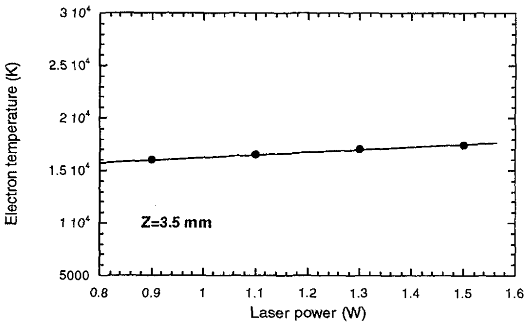

Fig. 3 Experimental values of electron temperature of 150 A helium GTA plasma during welding at 3.5 mm from cathode in the arc axis. It is plotted as a function of laser energy.

density. Gregori et al[13] considered that synthetic spectral profile of Thomson scattering would be practically measured because the density gradient occurred in the scattering volume as a result of the steep density gradient in the arc plasma. They believed that this synthetic spectral profile should lead to the significant increase in the electron temperature because its profile was fitted to the theoretical profile based on the assumption of uniform density. They explained that this increase in the electron temperature was dependent on the scattering angle because the scattering volume is a function of scattering angle. They supposed that the result of the Thomson scattering method was dependent on the scattering angle. However, they selected the 2 mm diameter in beam waist of the incident laser for measurements.

On the other hand, Snyder et al[14] insisted that electron temperature dependence on scattering angle was determined by the relation between Landau damping rate and the collision frequency rate. They suggested that the condition of Landau damping rate lagrer than collision frequency rate was the most important for consistency of Thomson scattering theory which assumes non-collision. They insisted that the density gradient in the scattering volume had no significant effect on the electron temperature measurements and demonstrated it by changing the wavelength of the incident laser. The beam waist was same as that of Gregori et al[13]. The electron temperature dependence on the scattering angle was confirmed at scattering angles shallower than and an incident laser wavelength of 532 nm. On the other hand, no dependence on the scattering angle was found at an incident laser wavelength of 355 nm. In their explanation, Landau damping rate was larger than the electron-ion collision frequency rate at 355 nm wavelength and 532 nm in the scattering angles wider than because Landau damping rate is dependent on the incident laser wavelength and the scattering angle. They concluded that the Thomson scattering method was a reasonable measurement technique under the above conditions. The findings of Snyder et al[14] suggest that accuracy of the Thomson scattering method also depends on plasma conditions, because the electron-ion collision frequency rate is dependent on the plasma conditions. Thus, electron temperature measurement in some scattering angles was carried out as part of the present research. In our experiments, wavelength and beam waist of the incident laser at focal point were fixed 532 nm and 100 μm respectively. This beam waist is much smaller than that of Gregori et al[13] and then the density gradient in the scattering volume would be negligible. But, the narrow beam waist causes heating of the electrons by inverse bremsstrahlung[6]. Therefore, it is necessary to extrapolate to the unperturbed electron temperature at 0 mJ pulse-1 laser energy[6,9,15,16]. **Fig. 3** shows measured electron temperature as a function of laser energy. This

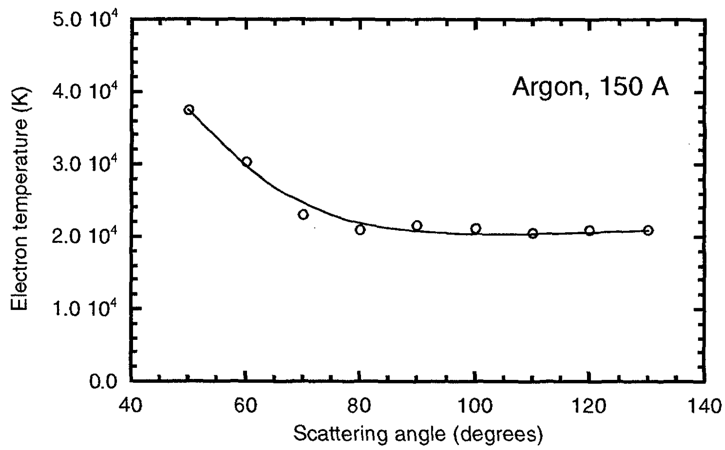

Fig. 4 Electron temperature dependence on scattering angle in Thomson scattering measurements for an atmospheric pressure, 150 A, argon arc. It is measured at 2 mm from the cathode in the arc axis.

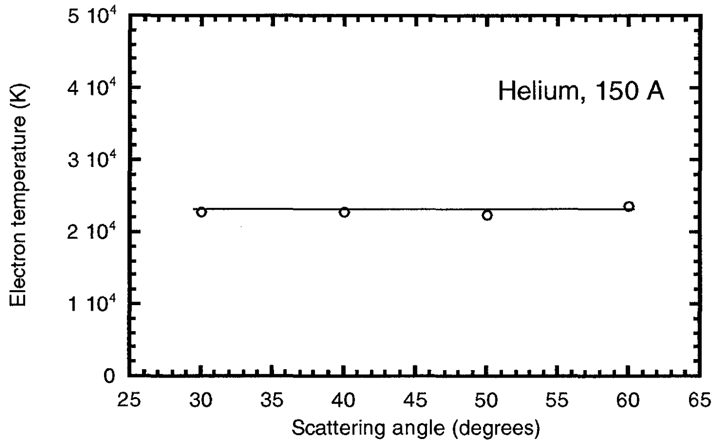

Fig. 5 Electron temperature dependence on scattering angle in Thomson scattering measurements for an atmospheric pressure, 150 A, helium arc. It is measured at 2 mm from the cathode in the arc axis.

results shows that temperature increase is 250 K per 0.1 W laser power. The uncertainties of the electron temperature are approximately 5% in the present work. The uncertainties correspond to those reported by Snyder et al[5]. **Fig. 4** shows dependence of electron temperature on scattering angle in argon GTA plasma with water cooled copper anode in the present experimental conditions. The electron temperature increases sharply at shallow angles, while the dependence on scattering angle disappears at wider angles than . This result is consistent with both the results of Snyder et al[14] and Gregori et al[13]. In order to confirm the findings of Snyder et al[14], the plasma condition, namely, electron density was changed by using helium shielding gas and the electron temperature was measured in some scattering angles. The electron-ion collision frequency rate in helium GTA plasma would be smaller than that in argon GTA plasma due to the lower electron density of helium plasma. The result is shown in **Fig. 5**. It is clear that electron temperature is independent on the scattering angle in helium GTA plasma.

From the above, the findings of Snyder et al[14] on this question were supported. The usual theory of Thomson scattering was used and the scattering angle was set to in helium GTA plasma measurements.

3.2 Measured Electron temperature of pure helium arc and arc during welding using Thomson scattering method.

Measured electron temperature distributions of pure helium arc plasma on water-cooled copper anode are shown in **Fig. 6**. The arc current is 150 A and arc length is 5 mm. The isotherm was estimated using measured electron temperature. The maximum electron temperature reached 23000 K in the arc axis. It decreased to 17000 K at 4 mm from the cathode tip in the arc axis and 13000 K in the arc fringe. Measured electron temperature distributions of helium arc plasma during welding on SUS304 anode are shown in **Fig. 7**. The arc current and the arc length are same as that of the pure one. The maximum electron temperature reached 23000 K in the arc axis. It decreased to 13000 K at the 4 mm from cathode tip in the arc axis and 7000 K in the arc fringe. The difference of electron temperature between pure arc plasma and arc plasma during welding became 6000 K in the arc fringe.

A decrease of electron temperature can arise through two mechanisms when metal vapor contaminates arc plasma[4]. The first is an increase of electrical conductivity in the low temperature range. Abdelhakim et al[17] showed, by calculating the collision cross section, that contamination of copper vapor in the arc led to a large increase in the electrical conductivity between 5000 K and 7000 Ks. Glickstein[11]Jayaram[18] and Ogawa[19] also showed the same result. This means that Joule heat arising in arc plasma decrease and electron temperature decrease. The arc voltage of arc during welding and pure arc using water-cooled copper anode were measured in the present experimental conditions. In the case of welding arc, the measured arc voltage was 18.2 V. In the case of a pure arc, it was 22.2 V. The voltage of the arc during welding is 4.0 V smaller than that of a pure arc in the present experimental conditions. This

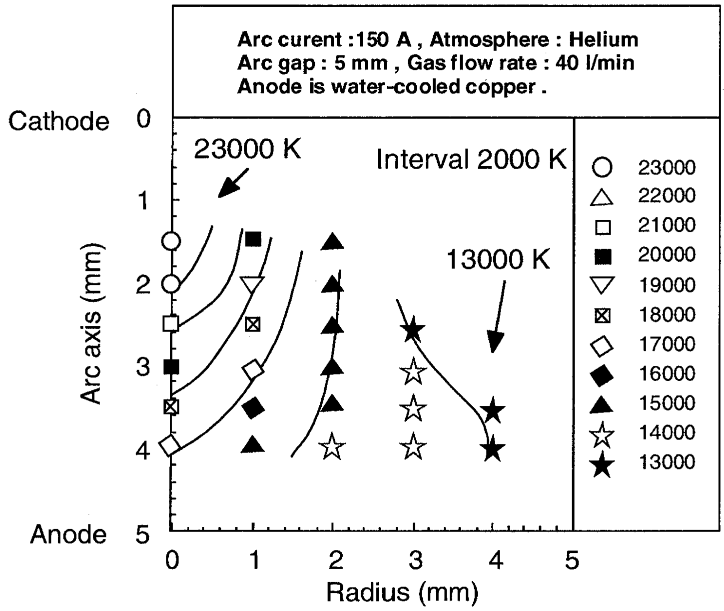

Fig. 6 Electron temperature of pure arc plasmas using a water-cooled copper anode under the condition of 150 A in the arc current.

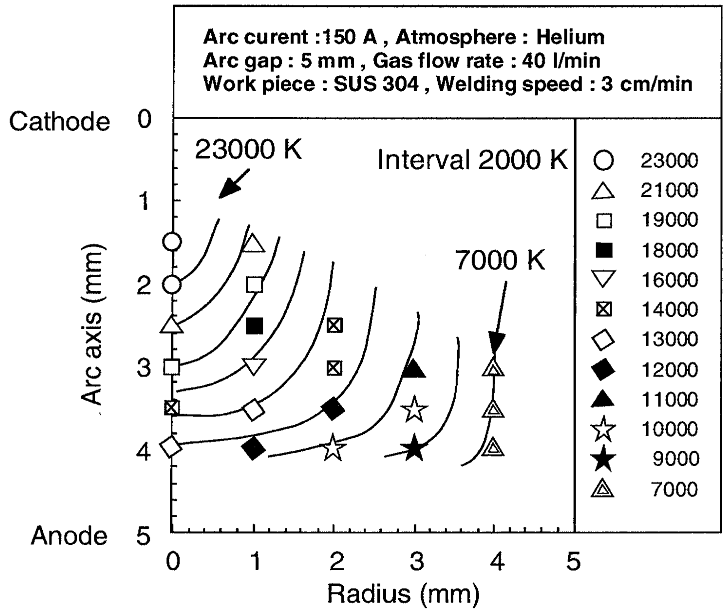

Fig. 7 Electron temperature of arc plasmas in GTA welding under the condition of 150 A in the arc current.

result is consistent with the first mechanism mentioned above. The second mechanism is an increase in the radiation emitted by the arc[4]. It causes energy loss of the arc. Gleizes et al[20] showed that metal vapor contamination of the arc led to increase in the energy loss by the radiation, especially at lower temperatures. The maximum difference of electron temperature between pure helium arc and arc plasma during welding appeared in the low temperature region as shown in fig. 6-7. This result would be consistent with the second mechanism. From the above, it can be concluded that the multiplication effect of these two mechanisms causes electron temperatures to decrease.

4. Conclusions

Electron temperatures in pure helium GTA plasma and helium GTA plasma during welding were measured by the Thomson scattering method without the LTE assumption. The results showed that electron temperature decreased sharply compared with that of a pure helium plasma in the blue luminous region of arc plasma. The maximum difference of electron temperature reached 6000 K. This value is much larger than the results which were derived with LTE assumption.

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