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Observation of Anode Boundary Layer of Plasma Torch

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In order to make clear the physical grounds for anode fall in atmospheric free-burning argon arc, the results of the experimental measurements of anode fall with Langmuir-probe method for various arc currents and gas flow rates are presented. In the case of low arc current, the anode fall is positive. The electron temperature and space potential rise on approaching the anode surface within 0.1mm from the anode for low gas flow rate. In the case of high arc current, the anode fall is negative. Furthermore, the electron temperature and the space potential hardly depend on the distance from the anode and are not influenced by gas flow rate.

Key words: Observation, Anode boundary layer, Plasma torch

1. INTRODUCTION

Electrical arcs have been applied to many kinds of industrial material processing, including welding, cutting, heating and plasma spray treatments. On the other hand, many researchers have devoted experimental and theoretical efforts for understanding the physical characteristics of the arcs. These efforts helped to attain the practical understanding of them in the arc column and several books regarding the arc physics have been published [1-3]. However, in the electrode region, which is the narrow boundary layer between the arc column and the metallic electrode, there is even a lack of practical understanding of the physical characteristics. Therefore, even the sign and magnitude of the anode fall in electrical arcs have not yet been explained completely. The electrode region gives rise to steep gradients of the plasma properties due to the boundary layer being affected by the electrode, which exhibits a much colder temperature than that of the arc column and makes experiments difficult due to the steep gradients.

This paper is concerned with the anode fall of atmospheric free-burning argon arcs. Conventionally, the positive anode fall has been accepted and also described in publications such as the above-mentioned books [1-3]. In [1], it was explicated that the role of the anode fall was to ensure conservation of charge carriers, namely, ion production in the boundary layer and that the ion production might occur by two basically different ionization mechanism, namely, field ionization and thermal ionization. Further details were explicated as follows; the field ionization seemed to play an important role in low-current arcs, whereas the thermal ionization dominated in high-current arcs, for which anode falls might be substantially lower (in principle they might even be negative). In [1], the positive anode fall was accepted, even though the negative anode fall was predicted suggestively. However, the physical grounds for the anode fall were not made clear by experimental evidence. Therefore, there is still lack room for discussion of the positive anode fall.

Calculations for the anode region of the arcs were carried out in [4-8]. The authors of [4] classified the anode region into two sub-regions; a sheath and a narrow space-charge sheath (the Langmuir sheath), and applied a two-temperature numerical magneto-hydro dynamics (MHD) model to the former region and the Langmuir-prove theory to the latter region. The numerical results always showed that the positive anode fall occurs independently of the arc current density. In [4] the positive anode fall was assumed in the choice of the boundary condition for solving the Langmuir prove theory. This must be responsible for the resulting positive anode falls. On the other hand, Dinulescu and Pfender [5] performed a one-dimensional analysis of the anode region of argon arcs and predicted the negative anode fall analytically. The negative anode fall is a new hypothesis, in contrast to the positive anode fall. Morrow and Lowke [6] also calculated the anode fall by using a one-dimensional numerical model and predicted both types of anode fall, namely, negative and positive. However, their prediction concerned with the positive anode fall was only a description without numbers. Furthermore, their model had a significant problem because one equilibrium temperature, namely, local thermodynamic equilibrium (LTE) was assumed in spite of the anode boundary layer. Zhu et al [7] and Lowke et al [8] also had a similar problem to that of Morrow and Lowke [6].

Sanders and Pfender [9] make the Langmuir-probe measurements close to the anode surface in argon arcs for the parameter range 100-250A. They showed that the negative anode fall ranged from approximately –2.1 to –1.4 V, which range was similar to the results of Dinulescu and Pfender [5] and they also confirmed the findings of Dinulescu and Pfender [5] experimentally. They employed newly devised measurements which were made by inserting the probe into the arc plasma through a small hole in the center of the anode. However, they also did not make the physical grounds of the negative anode fall clear.

The purpose of this paper is to make clear the physical grounds for anode fall in atmospheric free-burning argon arc. We present results of the experimental measurements of anode fall with Langmuir-probe method for various arc currents and gas flow rates and also present an assumption regarding the physical state of the anode fall in the free-burning arcs.

2. EXPERIMENTAL METHOD

Figure 1 shows schematic diagram of experimental apparatus consisting of power supplying system, arc chamber, gas supplying system, exhaust system and probe system. The arc plasma is produced between a tungsten cathode adding 2%La_2O_3 and water-cooled copper anode in the arc camber. The diameter and the conical angle of the cathode are 3.2mm and 60 deg., respectively. The electrode gap is 5mm. The arc current is set to be 50A or 150A. Argon gas is introduced at flow rate of 15L/min. or 40L/min.

The electron temperature and space potential in front of the anode are measured by using a Langmuir probe. The measurements were made by inserting the probe into the arc plasma through a small hole (diameter 0.7mm) in the center of the anode. A micrometer was automatically controlled with an up-down motor and used for determining the position of the probe relative to the anode surface. The micrometer could control the motion of the probe within a high accuracy of 0.25μm and had a high speed of 500μm/s maximum. Details of the anode arrangement for Langmuir-probe measurements are shown in Figure 2. Very useful information about this Langmuir-probe assembly was offered in [9]. The probe consisting of a tungsten wire (diameter 0.25mm) was coated with alumina as shown in Figure 3. The probe tip was hand lapped to a flat metallic finish. Namely, only the end face of the probe was electrically active. In order to measure the axial distributions of the electron temperature and space potential, we inserted the probe into the arc plasma so that the end face of the probe corresponded to the plane perpendicular to the axis. Therefore, the influence of the probe diameter on the measurements should be neglected because the radial variations were much smaller than the axial variations due to the thickness of the anode boundary layer being small.

The position accuracy of the probe measurements was maintained by the following experimental procedure. A position of the probe tip was set at zero distance from the anode surface before arcing. The probe tip under the anode surface was moved up gradually until it touched a copper plate placed on the anode surface, which was confirmed by a tester as shown in Figure 4. The position just touching the copper plate was treated as zero distance from the anode surface. Since the surface both of the anode and of the copper plate had been hand lapped to a flat metallic finish, each roughness of the surface measured by a surface-roughness recorder was about 0.2μm. Therefore, it should be considered that the positional error of Langmuir-probe measurements was no more than 1μm in an unfavourable estimation.

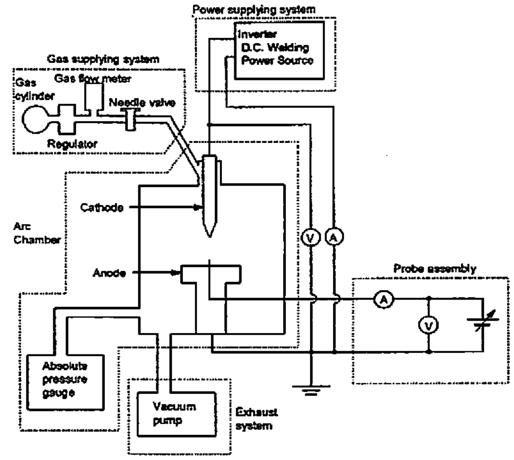

Fig. 1. Schematic diagram of experimental apparatus.

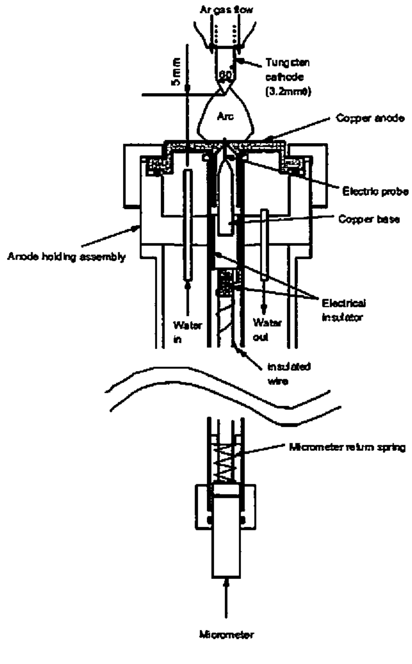

Fig. 2. Details of the anode arrangement for Langmuir-probe measurement.

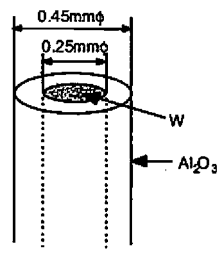

Fig. 3. A Schematic drawing of the probe used in this study.

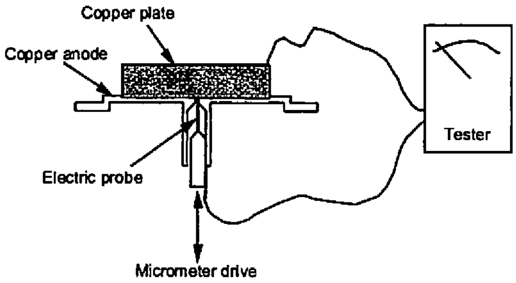

Fig. 4. A Schematic illustration of the procedure for ensuring the positional accuracy of the probe tip.

3. RESULTS AND DISCCUSION

Figure 5 shows electron temperature distribution in front of the anode for 50A current. It is seen that the electron temperature rises on approaching the anode for both gas flow rates and, especially, rises steeply within 0.1mm from the anode for 15L/min. In addition, an average electron temperature rises with gas flow rate. Figure 6 shows space potential distribution in front of the anode under the same conditions as those in Figure 5. It was found that the anode fall is positive because of increase in space potential on approaching the anode. The anode fall and its thickness decreases with increase in gas flow rate. Figure 7 shows electron temperature distribution in front of the anode for 150A current. Figure 8 shows space potential distribution in front of the anode under the same conditions as those in Figure 7. The anode fall is negative because the space potential is higher than that of the anode (0V). Furthermore, the electron temperature and the space potential hardly depend on the distance from the anode and are not influenced by gas flow rate.

Here, each space potential for zero distance from the anode surface differs from zero. This is considered to be the reason why the slight derivation from the absolute measurement position at zero distance should occur since the plasma slightly soaks into the small hole in the center hole of the anode. Therefore, the influence of the soaking of the plasma on the measurement position becomes larger in the case of a smaller thickness of the anode boundary layer. In the case of 150A, there is larger difference in the space potential, namely, about 2V at zero distance.

From these results, we should be permitted to hypothesize about the physical state of the anode boundary layer in the arc plasma, as follows. It is expected that motion of ions tend to be affected by convective force of gas flow or cathode jet because ion velocity is much lower that of electron due to its heavier particle weight. Therefore, it is considered that ions approach to the anode and thickness of the anode fall is reduced due to the convective force. In fact, in the case of low arc current such as 50A, the characteristics of the anode fall strongly depend on gas flow rate. On the other hand, In the case of high arc current such as 150A, since stronger cathode jet caused by electromagnetic pinch force promotes to transport ions from the arc column toward the anode instead of gas flow, the anode fall decreases without depending on gas flow rate.

In the case of low arc current, for high gas flow rate, the arc plasma near the anode can be maintained by thermal ionization and positive anode fall decreases, since larger amount of high temperature plasma is transported toward the anode. In contrast, because the transport of the high plasma temperature tends to decrease near the anode for low gas flow rate, field ionization due to electron collision caused by acceleration in positive anode fall is required to maintain the arc plasma and it leads to larger anode fall. The increase in the electron temperature near the anode occurs because of this acceleration. In the case of high arc current, it is supposed that the negative anode fall should be necessary in order to reduce the electron flux to the anode because of the excessive arc current due to the large number density of electrons near the anode.

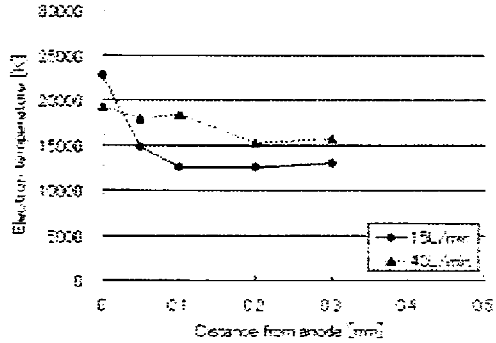

Fig. 5. Electron temperature distribution in front of the anode for I=50A.

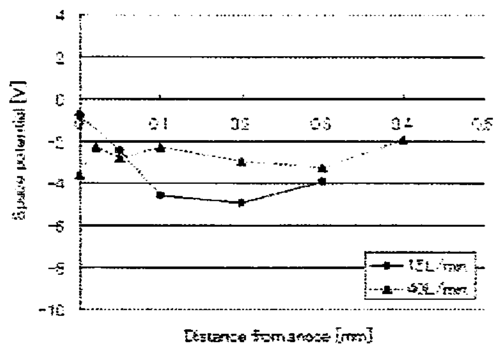

Fig. 6. Space potential distribution in front of the anode for I=50A.

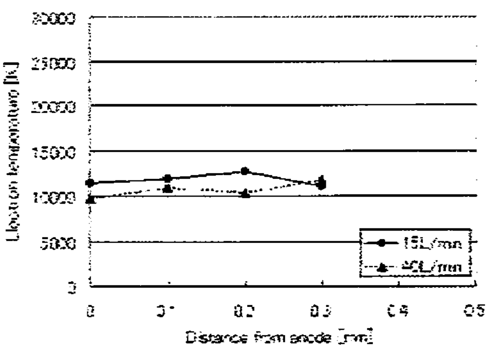

Fig. 7. Electron temperature distribution in front of the anode for I=150A.

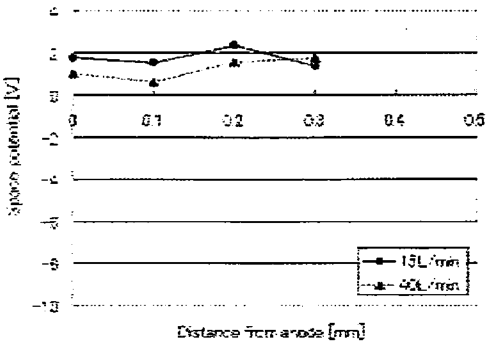

Fig. 8. Space potential distribution in front of the anode for I=150A.

4. CONCLUSIONS

The results of the experimental measurements of anode fall with Langmuir-probe method for various arc currents and gas flow rates and an assumption regarding the physical state of the anode fall in the free-burning arcs are presented. The conclusions are summarized as follows.

1) In the case of low arc current, the anode fall is positive. The electron temperature and space potential rise on approaching the anode surface, especially, rises steeply within 0.1mm from the anode for low gas flow rate.
2) In the case of high arc current, the anode fall is negative. Furthermore, the electron temperature and the space potential hardly depend on the distance from the anode and are not influenced by gas flow rate.
3) It is expected that motion of ions tend to be affected by convective force of gas flow or cathode jet. Therefore, it is considered that ions approach to the anode and, consequently, anode fall and its thickness are reduced due to the convective force.

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