Some Properties of Magnetically Controlled Plasma Arc†

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Abstract

By virtue of magnetic constriction in cusp magnetic field, a plasma arc column changes its cross section into an oval shape. In this report, some experimental results are described on fundamental properties of magnetically controlled plasma arc, such as the deformation of arc column, potential gradient, current distribution and the dynamic pressure distribution.

1. Introduction

In gas tungsten arc welding or plasma arc welding, the heat flux distribution on the work piece is influenced by the shape of arc plasma column. It is well known in gas tungsten arc welding that the arc is highly constricted at the cathode when a sharply pointed tip was used. A deep, narrow weld bead is, in this case, formed as the result of increases in heat flux density and plasma stream velocity.

These phenomena suggest that the shape of the weld bead will be strongly influenced by the cross-sectional shape of plasma arc column through which arc discharge is ustained.

The authors have reported previously on the effects of cusp magnetic field upon the gas tungsten arc and plasma arc welding.[1] It was found that the gas tungsten arc column was changed into a high energetic elliptical column by the magnetic constriction with a cusp field, so weld bead width has been reduced and penetration increased in practical welding.

Similar effects were also observed in the case of plasma arc welding of stainless steel plate:[2] the width of welds made by plasma arc under the influence of cusp magnetic field was fairly narrow compared with those in ordinary plasma welding procedure, and also welding range to give a satisfactory under-cut free weld could be expanded markedly wider.

The purpose of present investigation was to make clear the change of fundamantal properties of plasma arc in the cusp magnetic field, which was considered to be closely related with the above distinctive performances.

2. Experimental Equipment

Experimental equipment consists of plasma torch, electromagnets to produce a cusp field and water cooled copper anode. The plasma. torch and electromagnet used in this series of experiments were the same as described in previous reports.[2] The torch was installed in the cylindrical magnet holder insulated from each other, and multi-gapped pole pieces were installed to give a strong magnetic constriction against the plasma arc column over a wide area. The diameter of the orifice of the torch was 3 mm.

Power supply used was a conventional DC arc welder having a constant current characteristics. Arc current was changed over a range from 50 A to 200 A. Flow rate of plasma working gas, argon, was in a range from 2 *l/min* to 7 *l/min.*

For the measurement of stagnation pressure of plasma flame on the anode surface, a copper anode with a hole (0.5 mm in diameter) drilled in the center of the face was installed in place of the regular anode. One leg of the U-tube manometer was connected to the pressure tap in the anode, and the other was exposed to the open atmosphere.

The determination of actual current flowing area into the anode surface was carried out by drilling a hole (1 mm in diameter) in the copper anode through which small wire, 0.5 mmϕ, is exposed at the anode surface.

Currents flowing into the wire and surrounding copper anode were recorded respectively with the traverse of plasma torch and magnet assembly.

3. Experimental Results and Discussion

3.1 Deformation of plasma arc in the cusp magnetic field

An ordinary plasma arc column shows a symmetric pattern with respect to the axis of the arc. When the cusp magnetic field was imposed, arc

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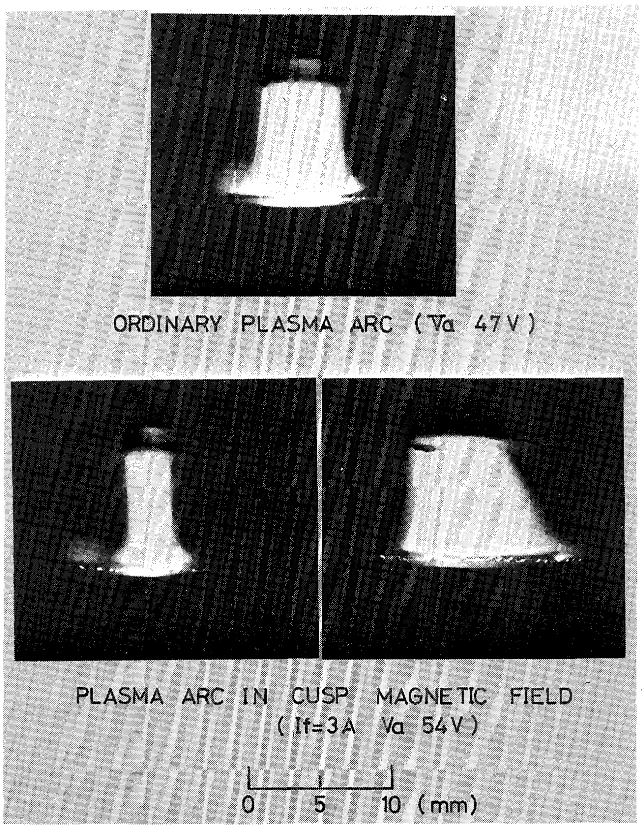

Photo 1. Magnetic deformation of plasma arc column in the cusp magnetic field. I_a=120 A

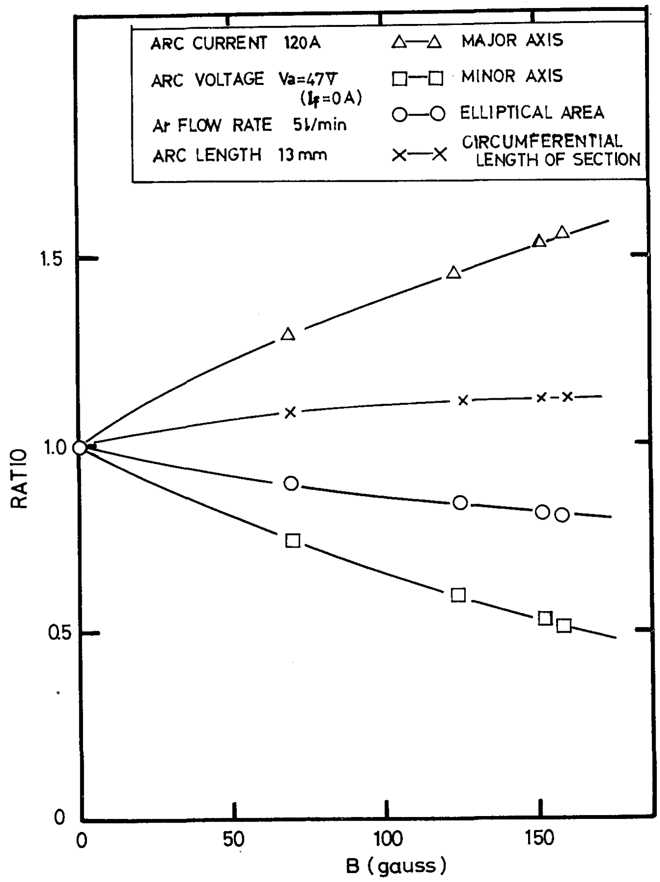

Fig. 1. Effect of cusp magnetic field on the deformation of plasma arc column. Strength of magnetic field is measured at the location 4 mm apart from the center of torch.

plasma could not take a symmetric configuration. An example of appearance of plasma arc column at a site between the two pole pieces of magnet is shown in **Photo. 1.** It was observed that the plasma arc column was constricted from both sides and expanded somewhat along the perpendicular direction. Deformation of plasma column became extensive in accordance with the field strength applied, and cross section of plasma column appeared to be changed from circular into an elliptical shape.

Figure 1 shows the variation of plasma arc column determined by taking the photographs from two directions. So far as observed visually, its cross sectional area had a tendency to decrease slightly as the magnetic field became stronger, but its peripheral area appeared to increase through which electric energy input was dissipated toward the surrounding atmosphere.

3.2 Arc voltage and potential gradient in plasma arc column

It was observed that the arc voltage was increased as the strength of cusp magnetic field became stronger. Contrary to the case of transverse deflection of arc column by uni-directional magnetic field, the change of arc length is not considered so great as to sufficiently explain the arc voltage rise. It may also be important to know the actual change of potential gradient in plasma arc column under the magnetic constriction of cusp field.

The potential gradient of arc plasma column outside the torch was determined as the increment in arc voltage per unit length between the torch and anode. Through the whole experiment relative position of the torch and electromagnet was kept constant.

Experimental results are given in **Fig. 2,** which shows clearly that the potential gradient of plasma column increases considerably if cusp magnetic field was applied. Although potential gradient has a tendency to increase with the arc current in this experiment, the increase by the application of cusp field was quite distinctive.

3.3 Current distribution at the anode

It is necessary to seek the effective cross sectional area through which arc discharge current flows into the anode, in order to evaluate the heat flux at the surface of the work piece. In the present study, current flowing region was determind by detecting the current in a small area which is insulated by ceramic

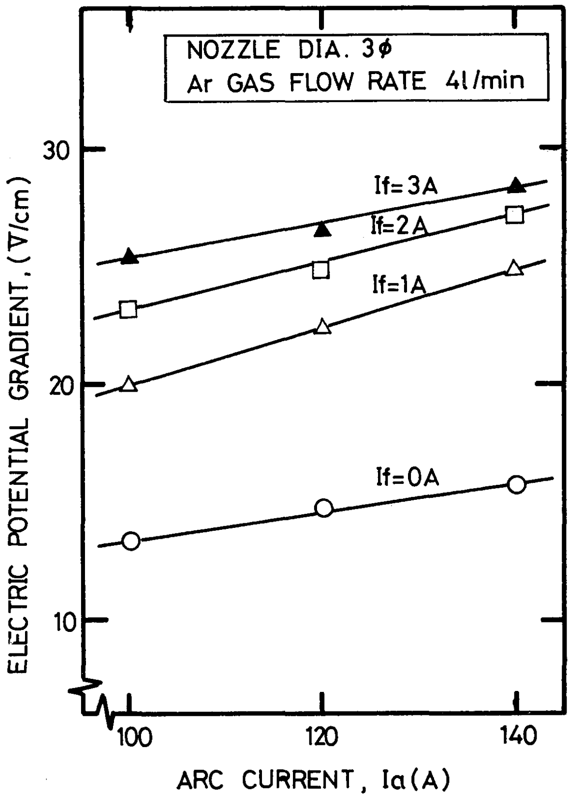

Fig. 2. Relation between arc current and electric potential gradient under various strength of magnetic field.

tube from surrounding copper anode, as illustrated in **Fig. 3** schematically. To protect the wire material from melting, refractory tungsten wire was installed. No melting of wire was observed throughout the experiments.

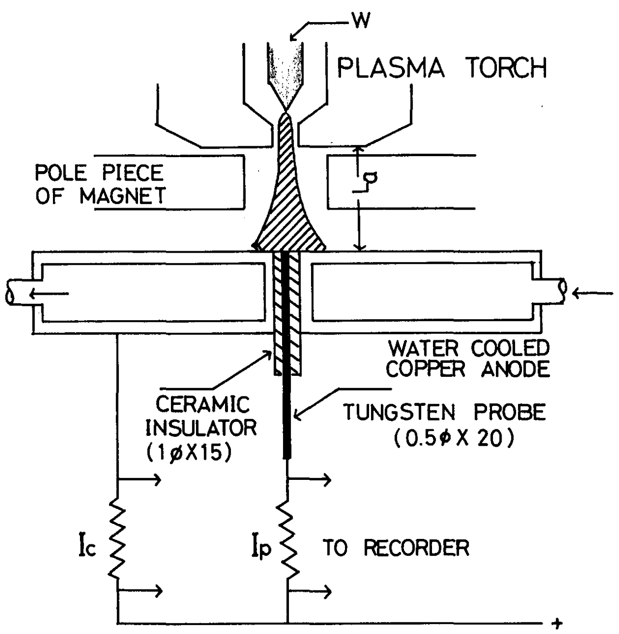

Fig. 3. Schematic illustration of equipment for the measurement of current distribution.

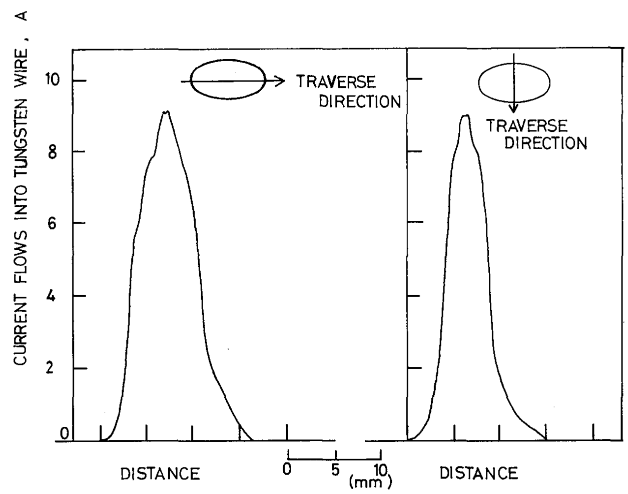

Fig. 4. An example of current distribution within the plasma arc in the cusp magnetic field. I_a: 100 A, I_f=3 A

When the cups magnetic field was applied current flowing area is generally deformed as shown in **Fig. 4** These deformations in current flowing area correspond closely to the deformation of arc column determined by taking photographs.

As for the peak value of current flowing into the tungsten wire, it was found to remain almost unchanged in spite of application of cusp magnetic field. Approximate current density calculated from the area of tungsten wire and current in it was around 45 A/mm^2 for the plasma arc of 100 A, and 50 A/mm^2 for 140 A. True current density must be determined carefully considering the errors arising from the thermionic emission of electrons at the surface of tungsten and also potential difference between the tungsten wire and surrounding copper anode.

Current flows into tungsten wire will, however, be considered to be unchanged for the different arc plasma if their true current density are the same value. And also total arc current must be regarded as the definite integral of current density over the whole cross-sectional area. Integration of above observed current density was carried out for both plasma with and without cusp field. It was found the integrals agreed with the arc currents within a error of 10 % of arc current. The observed current density seemed to be a fairly good approximation.

3.4 Energy density of plasma arc

As pointed out in previous sections, arc voltage and potential gradient in plasma column increased markedly by the application of cusp magnetic field. Potential gradient was indeed·evaluated as twice as much, or more those with no magnetic field applied. Average current density has a tendency to increase slightly as a result of decrease in cross-sectional area of arc column.

Consequently electric energy input per unit volume $W = j \cdot E$ when j is current density and E is potential gradient was considered to increase almost proportionally to the potential gradient. Although a large increase of energy density occurred in plasma column, an increase in current density was not observed. Although the increase in energy density is difficult to explain, it can be seen from **Fig. 5** that the potential gradient has a close relation to the peripheral area of arc plasma column in the region of cusp magnetic field. Assuming that the energy balance might be established at the increasing peripheral area of arc plasma, the increase of potential gradient and also energy density are considered to be relative to the situation.

3.5 Pressure distribution at the anode surface

In practical welding, dynamic pressure distribution at the work piece has a close relation to the formation of weld crater. In welding with magnetically controlled plasma arc, it was proved that the narrow key hole is formed at the front crater and followed with somewhat longer tailed molten pool.

Figure 6 shows the comparison of pressure distribution when cusp field was applied and when it was not applied.

It should be noted that the maximum dynamic pressure was reduced by the application of cusp magnetic field. Also, pressure distribution has a similar elliptical distribution as that observed in measurement of shape of plasma and current distribution. Maximum pressure has increased, as a matter of course, with increasing gas flow rate, as shown in **Fig. 7**. But at any gas flow rate of plasma working gas,

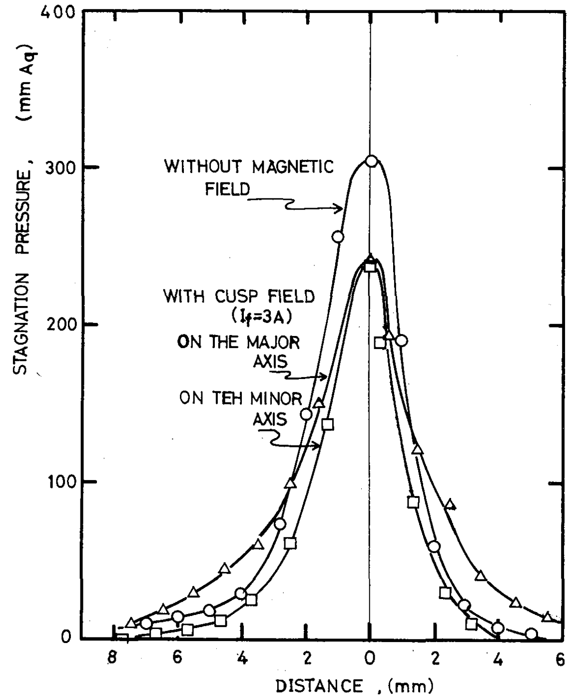

Fig. 6. Dynamic pressure distributions at the anode. I_a: 140 A

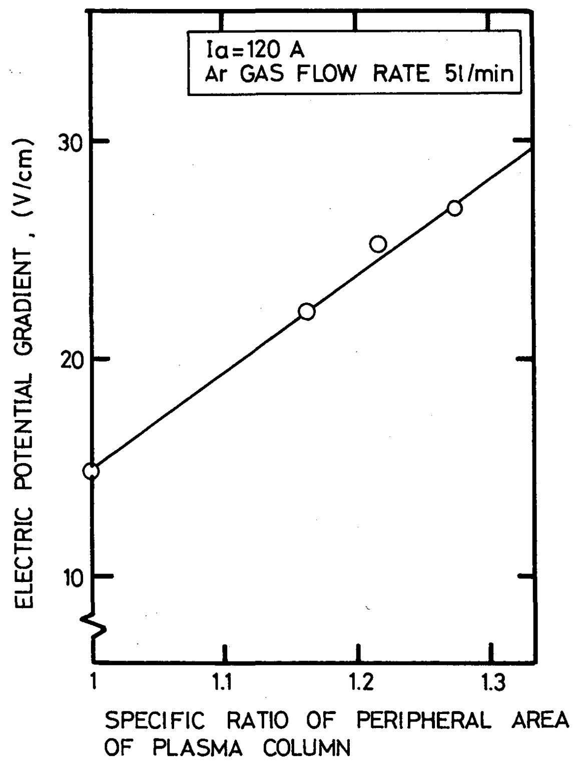

Fig. 5. Relation between specific ratio of peripheral area and electric potential gradient.

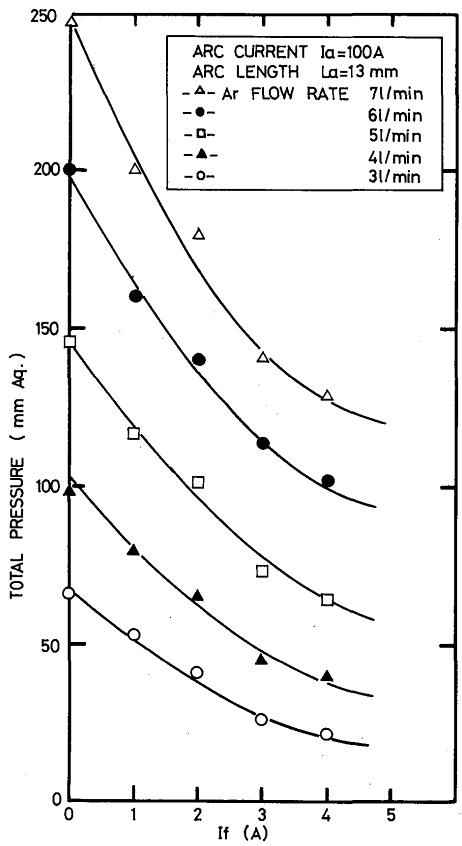

Fig. 7. Effect of cusp magnetic field on the peak dynamic pressre at various argon flow rate.

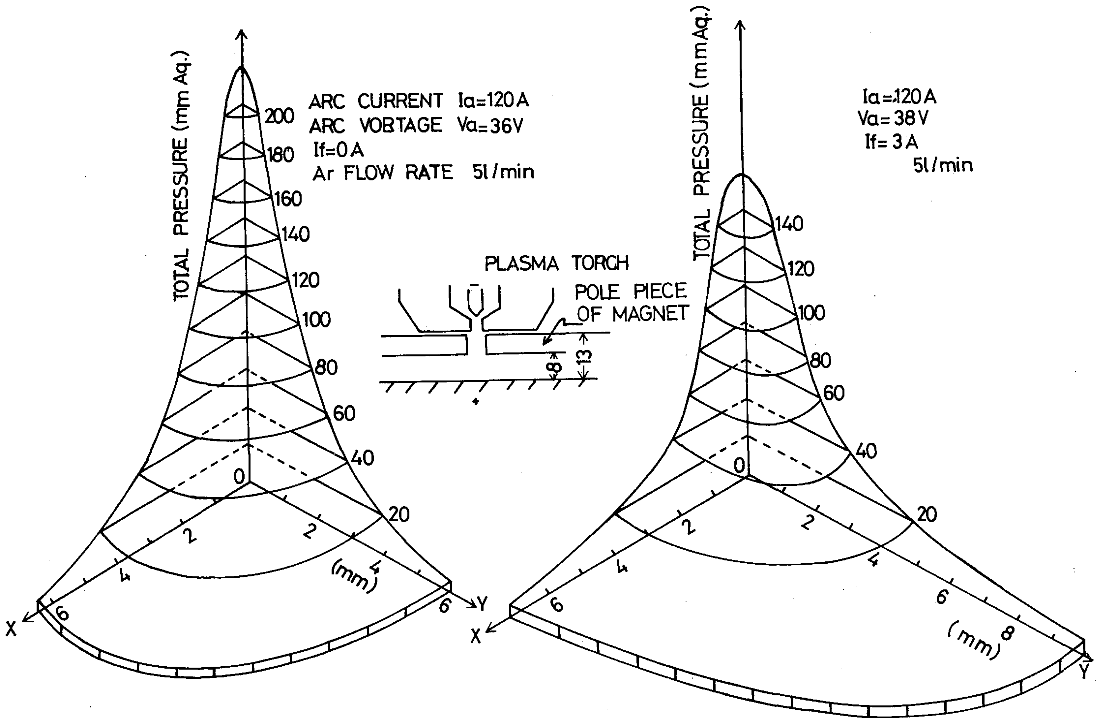

Fig. 8. Stereographic illustration of pressure distributions at the anode surface.

peak value at the center of arc column decreased with the strength of cusp field applied.

Figure 8 is a stereographic illustration of dynamic pressure for both cases $I_f=0$ and $I_f=3A$. Formation of long and narrow weld crater, as reported previously, will be explained by these experimental results.

4. Summary

Experimental results obtained in this experiment are summarized as follows:

(1) Plasma arc column changes its cross section by the application of cusp magnetic field from circular to elliptical.
(2) Potential gradient in arc column in the cusp magnetic field was much higher than that without the magnetic field.
(3) Current flowing into the anode distributes elliptically. Approximate current density at the center of plasma arc was evaluated around 45 A/mm^2.
(4) Energy balance within a plasma arc column was explained well considering the increase in peripheral area of arc in magnetic field.
(5) Dynamic pressure at the anode shows the similar elliptical distribution as observed in current distribution.

References

1) Y. Arata and H. Maruo: "Magnetic Control of Arc Plasma and Its Application for Welding", Welding in the World, Vol. 10, No. 7/8 (1972) IIS/IIW-497-72.
2) Y. Arata and H. Maruo: "Magnetic Control of Plasma Arc Welding", Transactions of JWRI Vol. 1, No. 1 (1972).