On the Estimation of Temperature Distribution and Erosion of Electrode in Hyperbaric TIG Arc Welding

Bulletin of University of Osaka Prefecture
Vol. 42, No. 1, 1993, pp.99–107.

On the Estimation of Temperature Distribution and Erosion of Electrode in Hyperbaric TIG Arc Welding

Koichi OGAWA* and Yasuo SUGA**

(Received Jun 15, 1993)

The applicability of the finite element method (FEM) to the analysis of temperature distribution of tungsten electrode in TIG arc welding was discussed. Moreover, effects of welding factors on the temperature distributions of electrodes and relation between the temperature at the electrode tip and the erosion of the electrode in TIG arc welding under the pressurized helium atmosphere were investigated.

Main results obtained are summarized as follows:

1) When proper boundary conditions and physical properties are used, relatively precise temperature distribution of electrode can be calculated by FEM.
2) As the ambient pressure increases, the cathode spot area tends to decrease and concentrate at the electrode tip. Accordingly the temperature at the electrode tip increases remarkably with pressure.
3) Electrode temperature increases with an increasing arc current and with a decreasing electrode diameter.
4) The erosion of electrode begins to increase over a critical condition, at which the maximum temperature of electrode tip T_{max} calculated by FEM reaches melting point T_m.
5) The erosion of electrode can be estimated quantitatively by calculating the temperature of electrode tip.

1. Introduction

The TIG arc welding method is used for welding of various materials, especially it is applied to welding under high pressure atmosphere due to the arc stability[1)-4)]. Generally, in TIG arc welding a tungsten rod contained 2% thorium-oxide, which makes the discharge of electron easy, is used as an electrode. However, the erosion of electrode increases with an increasing pressure, and accordingly the stable arc welding tends to become difficult under high pressure atmosphere[3)-5)]. Therefore, effect of some factors on the erosion of electrode has been studied experimentally, and moreover applicability of some new electrodes to high pressure welding was tried[6)7)]. However, the basic relationship between temperature distribution in electrodes and their erosion has not been investigated, because the measurement of temperature distribution in arc welding especially under high pressure atomosphere is difficult. Accordingly,

* Course of Instrument Science, College of Integrated Arts and Sciences.
** Faculty of Science and Technology, Keio University.

the application of the finite element method (FEM) to the estimation of temperature distribution and the erosion of electrode was tried in this study.

2. Estimation of Temperature Distribution of Electrode

2. 1 Modeling of electrode and boundary condition

The erosion of electrode seems to depend on the temperature distribution at an electrode tip. Therefore the temperature distribution was calculated by FEM. Figure 1 shows an example of finite element division of the electrode which has a vertex angle of 45°, diameter of 3.2mm and length of 20mm. The shape of the finite element is triangle, element number 250 and node number 156.

Figure 2 shows a schematic illustration of electrode model in which some boundary conditions of heat flow are shown.

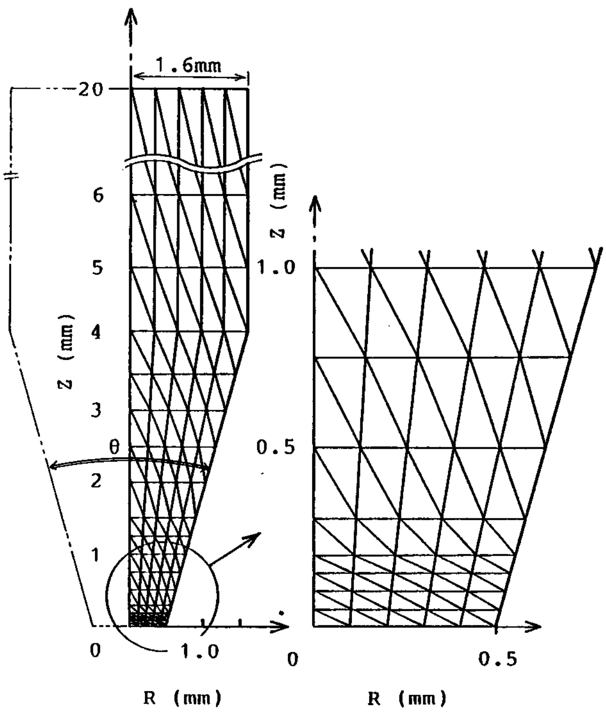

Fig. 1 An example of finite element division for electrode

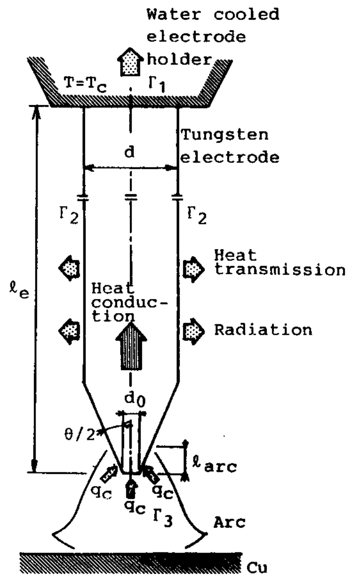

Fig. 2 A heat transfer model of electrode for calculation

As the boundary condition at the electrode holder (boundary Γ_1), constant temperature condition was used because the holder was cooled by water. That is,

$$T=T_c \quad \text{at } \Gamma_1 \tag{1}$$

The electrode is cooled by heat transfer and heat transmission from the side wall (boundary Γ_2). The heat flux q was shown as follows.

$$q=\alpha(T-T_s)$$
$$q=\varepsilon\sigma F(T^4-T_r^4) \text{ at } \Gamma_2 \tag{2}$$

where, α: coefficient of heat transmission, T_s: temperature of shielding gas, ε: emissivity, σ: Stefan-Boltsmann constant, F: shape factor, T_r: temperature of atmosphere.

Physical properties used in the calculation are shown in Table 1[8)9)]. As the factors

Table 1 Physical properties used in the calculation

Melting point, T_m	3653K
Boiling point, T_b	5800K
Specific heat, C	151J/kgK
Thermal conductivity, λ	100W/mK
Coefficient of heat transmission, α	0.418−4.18J/m²sK
Emissivity, ε	0.39−0.45
Shape factor, F	1.0

of heat input into the electrode, there are heat generation at the electrode tip, heat transmission from the arc, radiation from the arc and Joule heat generated by welding current. However, since the Joule heat was negligible small in the welding current up to 150A, it was not taken into consideration in the calculation. On the other hand, J. F. Lancaster[10)] studied experimentally on the total of heat input into electrode tip, Q_c, in TIG arc welding. The heat flux q was obtained by Q_c and electrode tip area S which was measured and estimated by direct observation of arc. That is to say, $q_c=Q_c/s$.

Figures 3 and 4 show the relationships between arc length and heat input into electrode tip Q_c and between arc current I and heat input Q_c. From the figure, it is seen that the value of $k(=Q_c/I)$ changes from 0.7 to 1.1 with variation of arc length from 0 to 2 mm. Therefore, the relation between arc current and heat input into electrode can be shown as follows:

$$Q_c=kI \quad (k=0.7-1.1) \tag{3}$$

2. 2 Comparison between calculation and experimental results

In order to confirm the validity of the calculation, the calculation was compared to experimental results studied by Matsuda et al[11)]. They have measured the temperature of electrode tip area in welding by two-color pyrometer. Figure 5 shows the calculation and experimental result of electrode temperature. The arc current was 200A and 2% thorium-oxide tungsten rod of 3.2mm in diameter was used as electrode. In the figure, calculation is shown by solid line and measurement by plots. In calculation,

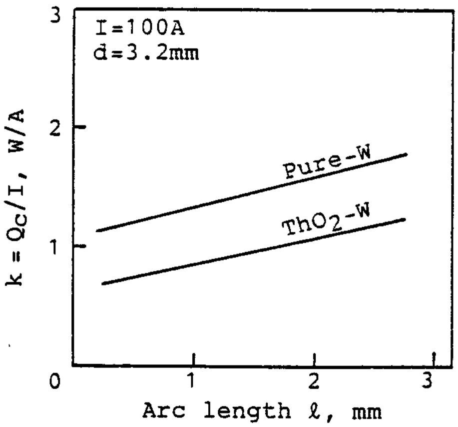

Fig. 3 Effect of arc length on k-value

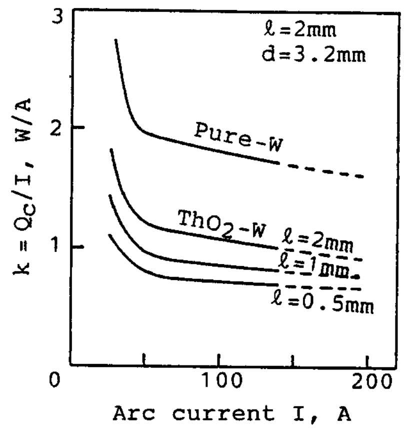

Fig. 4 Effect of arc current on k-value

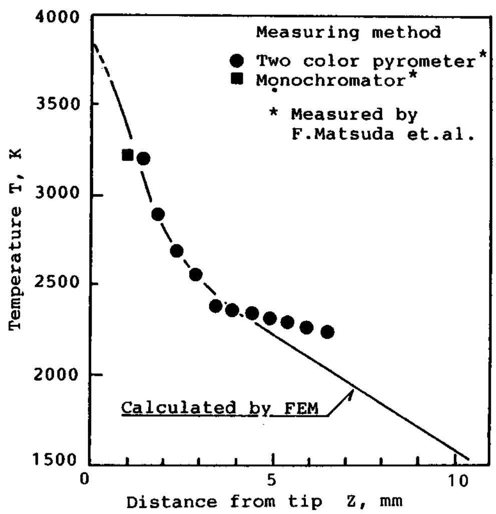

Fig. 5 Comparison between electrode temperatures measured by experimental method and those calculated by FEM

the physical properties shown in Table 1 were used. Since the calculation agrees approximately with experimental value reported by Matsuda et al., accordingly the validity of the calculation can be confirmed.

2. 3 Effect of ambient pressure

Figure 6 shows the effect of ambient pressure on arc appearance in arc current of 100A and arc length of 2 mm. As the electrode, thorium-oxide tungsten of 3.2 mm in diameter and vertex angle of 30° was used. As the ambient pressure increases, the arc column tends to constrict and accordingly the brightness of the arc increases. Moreover, the cathode spot concentrates to the electrode tip. Figure 7 shows the effect of ambient pressure on radius of cathode spot, which was measured from photographs of arc generated under pressure range of 0.1 to 5.1MPa. In the figure, the arc radius is indicated by radius on the flat surface r_{arc}, in case the arc radius is smaller than $r_0(=d_0/2$, see Figure 2), and it is indicated by length ℓ_{arc}, in case the arc radius is larger than r_0. From the figure, the cathode spot area has tendency to decrease with an increasing pressure. For example r_{arc} becomes about 0.5 mm at 2.1MPa and about 0.25 mm at 5.1MPa.

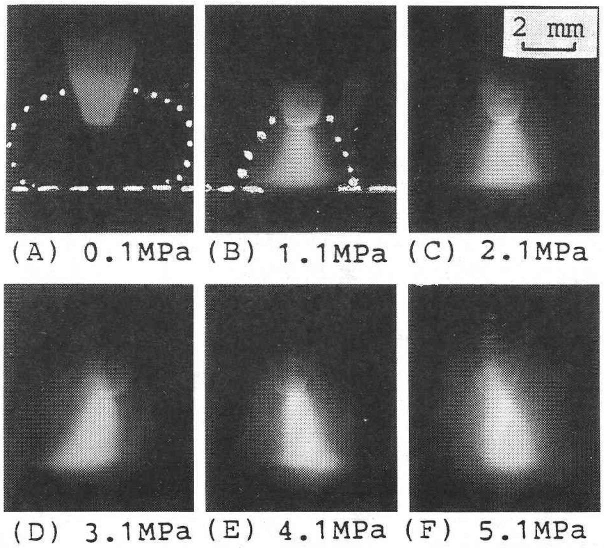

Fig. 6 Effect of ambient pressure on arc shape (ℓ=2mm, I=100A)

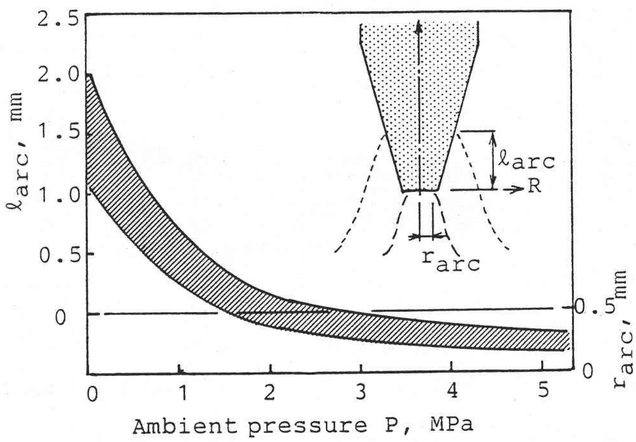

Fig. 7 Effect of ambient pressure on cathode spot area of arc

Figure 8 shows the temperature distributions on the surfaces of electrodes calculated by FEM. The calculation was executed under the assumption that the heat flux $q_c(=Q_c/S)$ distributes uniformly in the cathode spot area. In the calculation, the physical properties shown in Table 1 were used and as the k-value 1.0 was adopted. From the figure, it is seen that the temperature at electrode tip is lower than 3000K under the condition of relatively low pressure and large arc radius. However, as the arc radius decreases with an increasing pressure, the temperature increases. When the pressure reaches 2.1MPa, the cathode spot concentrates at a flat surface of electrode tip and the temperature rises approximately to 3250K. Under the pressure over 3.1MPa, the temperature at the electrode tip indicates over 3653K which is the melting point of tungsten. Therefore, the erosion of electrode tip should increase under the pressure more than 3.1MPa. Figure 9 shows the effect of pressure on the temperature of electrode tip and the erosion. From the figure, the erosion begins to increase drastically at a condition under which the temperature of electrode tip reaches melting point of tungsten electrode.

Figure 10 shows the temperature distributions in the longitudinal sections of electrodes. From the figure, it is confirmed that the temperature of electrode tip increases considerably with an increasing pressure.

2. 4 Effect of arc current and electrode diameter

Figure 11 shows relationship between arc current I and maximum temperature at electrode tip T_{max}, in the case of electrode diameters are 2.4, 3.2, 4.8, and 6.4 mm. In every electrode diameter, T_{max} increases in proportion to the arc current I and it

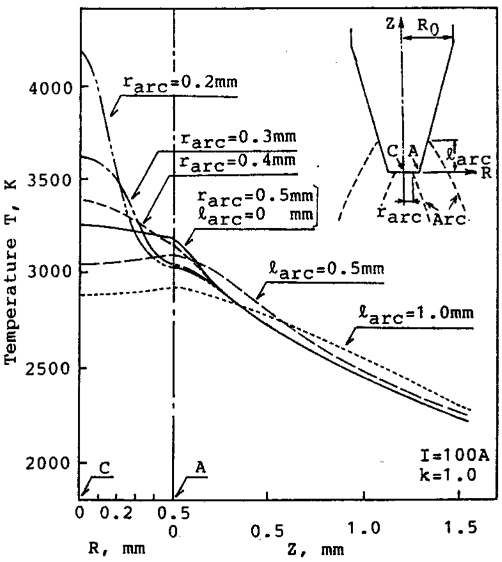

Fig. 8 Effect of cathode spot size on temperature distributions of electrode

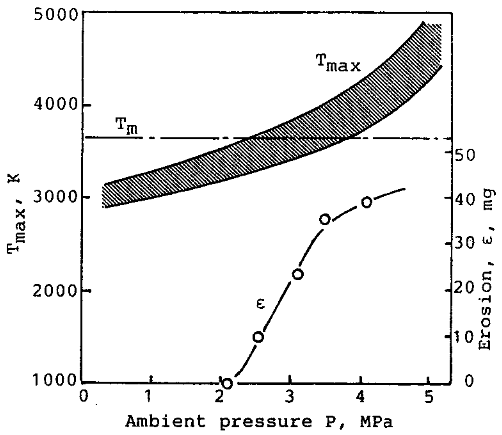

Fig. 9 Effect of ambient pressure on maximum temperature, and erosion of electrode

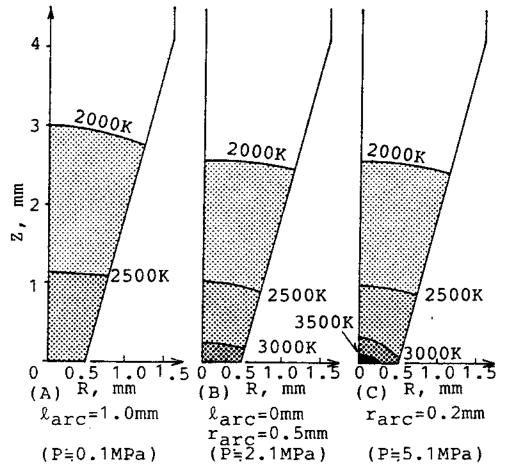

Fig. 10 Effect of cathode spot size on distributions of temperature in electrodes

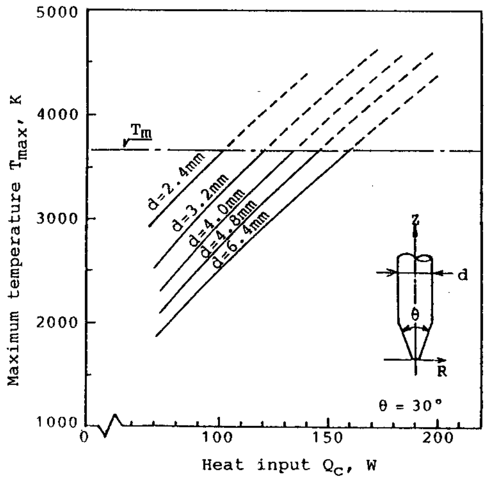

Fig. 11 Effect of heat input into cathode tip on maximum temperature

reaches finally the melting point of tungsten T_m at an arc current. Besides, the temperature tends to decrease with an increasing electrode diameter. Accordingly, in the case of thick electrode the temperature of electrode tip does not reach the melting point in relatively high current. These knowledge obtained by the calculation agrees with experimental results reported[4]. That is to say, it has been already known that the erosion of electrode has a tendency to increase gradually with an increasing current and it increases drastically over a critical current. Besides, the erosion decreases with an increasing electrode diameter. These experimental facts agree with the results obtained by the calculation.

3. Estimation of Erosion of Electrode by FEM

Figure 12 shows the effect of radius of the flat surface at the electrode tip R_t on the maximum temperature of electrode T_{max}. In the case of R_t is 0.25 mm, the maximum temperature T_{max} increases drastically with an increasing heat input and it reaches the melting point at a heat input of 70W. However, T_{max} decrease with an increasing R_t, and for example, in the case of R_t is 1 mm, it reaches the melting point at a heat input of 165W. In other words, if the heat input at the electrode is 165W, the tungsten electrode tip ground will melt and the erosion increases with time. However, when the radius of flat surface of electrode tip R_t becomes 1 mm approximately, the maximum temperature T_{max} will decrease to melting point or just below it. Therefore the erosion of electrode may stop at R_t of 1 mm.

Figure 13 shows the relation between heat input and R_t in the case of T_{max} reaches the melting point T_m. That is to say, the critical curve shown in the figure indicates the erosion limit (R_t) of electrode in a heat input Q_c. For example, in the case of 165W, the electrode tip melts and erodes away until the R_t becomes 1 mm.

Figure 14 shows the relationship between erosion ε and R_t. The erosion of electrode increases in proportion to R_t^3 approximately. Using the rerlations shown in the Figures 13 and 14, the erosion can be calculated when heat input data are given.

Figure 15 shows the relationship between arc current and erosion of electrode. In the figure, the solid line shows calculatin and plots experimental results. As shown in the figure, the calculation agrees to experiments approximately. Therefore, it is confirmed that the erosion of electrode can be estimated by considering the temperature of electrode tip which can be calculated by FEM.

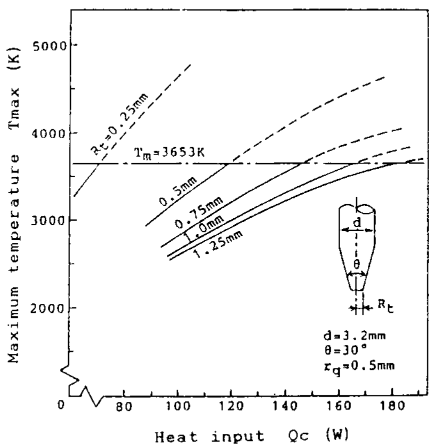

Fig. 12 Effect of diameter of electrode on critical current

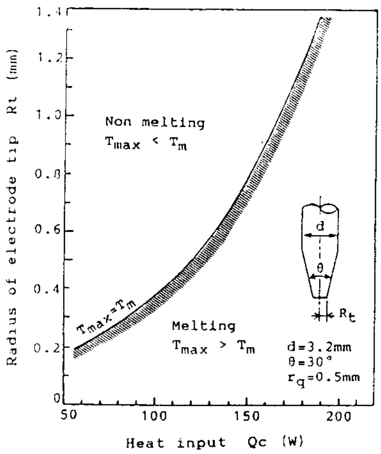

Fig. 13 Critical condition for melting of electrode tip

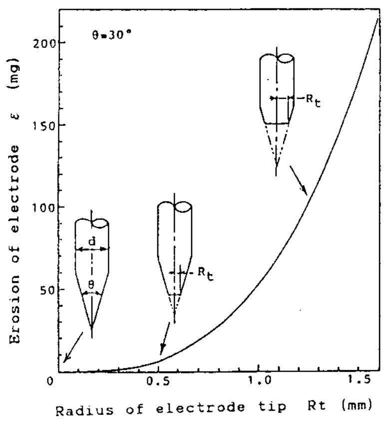

Fig. 14 Relation between R_t and e

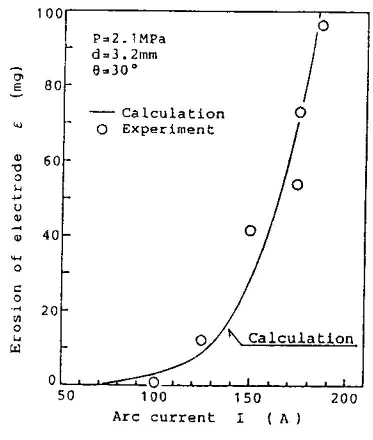

Fig. 15 Comparison between calculation and experimental results in erosion of electrodes

4. Conclusions

Main results obtained are summarized as follows:

1) When proper boundary conditions and physial properties are used, relatively precise temperature distribution of electrode can be calculated by finite element method.

2) As the ambient pressure increases, the cathode spot area tends to decrease and concentrate at the electrode tip. Accordingly the temperature at the electrode tip increases remarkably with pressure.

3) Electrode temperature increases with an increasing arc current and with a decreasing electrode diameter.

4) The erosion of electrode begins to increase over a critical condition, at which the maximum temperature of electrode tip T_{max} calculated by FEM reaches melting point T_m.

5) The erosion of electrode can be estimated quantitatively by calculating the temperature of electrode tip.

References

1) C. J. Allum: TIG's Underwater Role: Present and Future, Weld. Fab., (1982).

2) Y. Suga: Arc Welding under High Pressure Atmosphere, J. High Temp. Soc., 4-4 (1986), (in Japanese).

3) Y. Suga, A. Hasui: On Arc Characteristics in High Pressure Helium Atmosphere, Quat. J. JWS, 6-1 (1988), (in Japanese).

4) Y. Suga: On the Arc Welding under High Pressure Argon and Helium Atmosphere, Proc. Intn. Conf. in Helsinki under auspices of the IIW, (1989).

5) G. Huismann, H. Hoffmeister, H. O. Knagenhjelm: Effect of TIG Electrode on Wear Behavior under Hyperbaric Conditions of 37 to 40 bar, Proc. Intn. Conf. under auspices of IIW, (1989).

6) Y. Suga: On Erosion of Tungsten Electrode in GTA Welding under High Pressure Atmosphere, J. High Temp. Soc., 15-4 (1989), (in Japanese).

7) Y. Suga: On Erosion Characteristics of Tungsten Electrodes in Hyperbaric TIG Arc Welding, Doc. 43rd Int. Inst. Weld. in Montreal, CREau-106-90 (1990).

8) C. J. Smithells et al.: Materials Reference Book (Fifth edition), (1976), Butterworths.

9) Metal data book, (1984), Maruzen, (in Japanese).

10) J. F. Lancaster: Energy Distribution in Argon-Shielded Welding Arcs, Brit. Weld. J., Sept. (1954).

11) F. Matsuda, M. Ushio, H. Fujii: Gas-Tungsten-Arc Electrode, (Report 2), Trans. JWRI, 15-2 (1986).