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Erosion Characteristics of Tungsten Electrodes in TIG Arc Welding

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In order to develop a tungsten electrode having superior erosion characteristics in TIG welding under the pressurized helium atmosphere, the effect of addition of rare-earth element oxides to tungsten on the erosion of the electrode was experimentally investigated. As the cathodes, tungsten electrodes included 2%ThO_2-W, 2%Y_2O_3-W or 2%La_2O_3-W respectively were used. The diameters of electrodes were 2.4, 3.2, 4.0, 4.8 and 6.4 mm.

Main results obtained are summarized as follows;

(1) The erosion of electrode increases with increasing ambient pressure and arc current, and decreases with increasing electrode diameter.

(2) The critical arc current, Ic, at which the erosion of electrode becomes 5mg was defined and was measured for several pressures and electrodes diameters. The value of Ic has tendency to decrease with increasing pressure and decreasing electrode diameter.

(3) The erosion of La_2O_3-W electrode is much less than that of ThO_2-W electrode. The erosion of Y_2O_3-W electrode is between those of two types of electrodes.

(4) The rare-earth element distribution in electrode tip after erosion test is different among electrodes. The thoriumoxide has tendency to be lost more easily than the other elements. On the other hand, at the tip of La_2O_3-W electrode during welding, La_2O_3 exists at the tip area for longer time and it makes the work function decrease and prevents superheat of the electrode tip. As the result, erosion of the electrode may become smaller than those of other electrodes.

1. Introduction

TIG welding, a non-erosive welding method is widely employed in the welding of various metarials ranging from steel to non ferrous metals. Due to excellent arc stability TIG welding is widely employed, especially in extreme conditions involving high pressure such as maintenance work of oceanographic structures and someparts of nuclear reactors[1)-4)] .

Tungsten rod are usually employed as electrodes in TIG welding. However, about 2% thorium oxide is included in tungsten to improve the discharge of electrons as well as stabilize the arc and slow down erosion of the electrode. It has however been pointed out previously that in extremely high pressure welding situ-

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ations the arc shrinks resulting in an increase in current density, speeding up erosion of the electrode thereby inhibiting the welding process[3)-7)]. Thus, the development of an electrode having excellent erosion resisting properties to replace the existing thoriated tungsten electrode is earnestly being called for. Hence, instead of thorium oxide 2,3 rare-earth oxide elements were added to tungsten on an experimental basis with the main objective of developing a new tungsten electrode. The erosion characteristics of this new electrode was investigated, besides, the effect of arc condition as well as oxide element inclusions on erosion characteristics of the new electrode is clarified in this study.

Results of numerical analysis of temperature distribution at the electrode tip which is thought to directly affect the erosion of an electrode as well as the relationship between temperature distribution and erosion characteristics of this new electrode will be discussed in a second report.

2. Experimental method and electrodes

2.1 Experimental method

As it is shown in Fig. 1, a pressure apparatus which can be pressurized up to 5.1 MPa with a water-cooled TIG welding torch installed in it was employed in this study. The tungsten electrode is soldered on to the electrode holder and then attached to the water-cooled torch with a screw. A DC power source was used, the electrode was negative (DCEN) and a copper block of dimension 60 × 80 mm was employed as the anode. In order to prevent super heating the arc occurrence time was limited within 1-2 min.

First of all, the pressure was depressurized to 133 Pa(1 torr) with the aid of vacuum pump and a high frequency electric discharge was employed in creating the arc after pressurizing it to a fixed pressure with pure herium gas. The initial

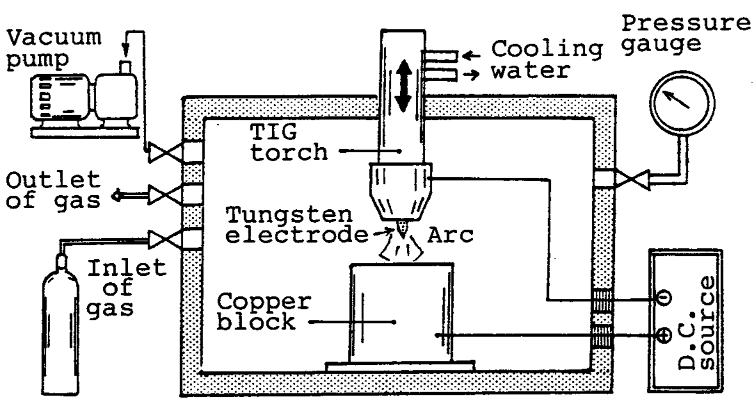

Fig. 1 Arrangement of equipment

current during the pressurizing process was roughly 50 A. The quantity of erosion with a curret of this value is extremely small and can be neglected. The arc length and current were adjusted to a fixed value just immediately after arc occurrence. The adjustment time was about 3 sec and the arc length was held constant at 2 mm. After adjustment, the arc was maintained constant at a time, hereafter referred to as "Arc time". As the quantity of eroded electrode E, the weight of tungsten electrodes before and after the tests were thoroughly weighed (sensitivity 0.1 mg) in a balance and the diffence between the two was calculated. The arc time was maintained constant at 60 sec.

2.2 Tungsten electrode

In TIG welding, a high melting point tungsten rod having excellent heat resistivity is generally used as electrode, however thorium oxide, a rare-earth metallic oxide is added to improve the heat discharge of electrons.

The work function of rare-earth metallic oxides required for discharge of electrons is generally low, and is effective in stabilizing the discharge of electrons even when the electrode temperature is lower than normal. The current discharge from the hot cathode is given by the Richardson-Dashman equation as

$$J = A\,T^2 \exp\left(-eQ/kT\right) \quad (1)$$

where J is current density, A is a constant, k is Boltzman constant, e is electron charge, T is temperature and Q is work function. As the equation indicates, the current density is a function of electrode temperature T and function Q, thus, in a situation of similar electrode temperature, electron discharge is more possible with the lower work function Q of the electrode. In other words, the same current density is obtainable with an electrode with a lower work function at a much lower temperature. The melting point, boiling point, constant A and work function of pure tungsten and tungsten with inclusions of the three rare-earth elements thorium, yttrium and lanthanum as well as values for the individual elements are displayed in Table 1. It can be seen in the table that the work function of the rare-earth metallic oxides are lower than that of pure tungsten. On the other hand, considerable erosion of electrode is encountered in TIG

Table. 1 Characteristics of electrode materials

	Melting point (K)	Boiling point (K)	Work function Q (eV)	A Value kA/m^2K^2
W	3653	5800	4.54	600
WO	1745	2123	9.22	–
Th	2008	5757	3.3	–
W-Th*	–	–	2.63	30
ThO_2	3327	4673	2.6	50
Y	1783	3610	3.3	–
W-Y*	–	–	2.7	70
Y_2O_3	2683	4573	2.4	10
La	1193	3727	3.3	-
W-La*	–	–	2.7 1	80
La_2O_3	2573	4473	2.5	9

*Thermoionic properties of rare-earth metals with adsorbed electroposive layers welding under high ambient pressure conditions.

It is revealed in Table 1 that, whereas the work function of the elements are almost similar, the value of the constant A of La-W and Y-W are higher than that of Th-W, thus, through inclusion of these rare-earth metallic oxides, it is possible to obtain an electrode having similar or higher erosion characteristics than an electrode with thorium inclusion. In this light, three types of tungsten electrodes with inclusions of 2% thoria, 2% yttria and 2% lanthana were produced, and the erosion characteristics of these electrodes was studied. For the former type, four rods of diameter 2.4, 3.2, 4.0 and 6.4 mm were used while four rods of diameter 2.4, 3.2, 4.0 and 6.4 mm were employed for the latter two types. The tip angle of all electrodes used in this study was 30°.

3. Experimental results and discussion

3.1. Effect of oxide inclusion on rate of erosion

3.1.1 Effect of arc time

In general, the erosion of an electrode increases with time after occurrence of a welding arc. Thus, to fully evaluate the erosion characteristics of an electrode it is more practical to maintain the arc time deemed most appropriate constant before evaluating the erosion quantity at the fixed arc time. In this study, since a relatively large copper block was used as the anode, maintaining the arc for a long duration in a large current would result in overheating of the copper block resulting in the melting and evaporation of the surface. Thus, the relationship between arc time and erosion rate of electrodes was first of all derived. An example of the relationship between arc time and erosion quantity of the electrodes E at ambient pressure P of 3.1 MPa and arc current I of 100 A is displayed in the semilogarithmic curve in Fig.2.

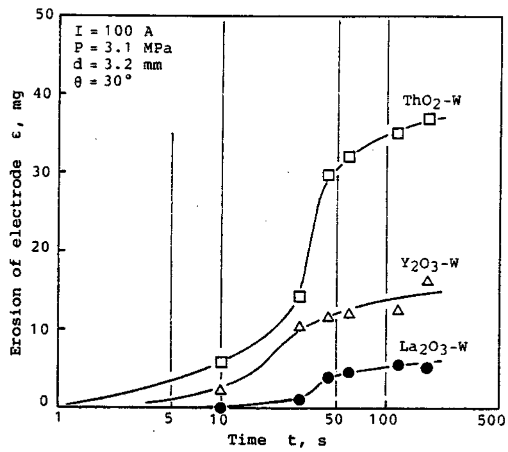

Fig. 2 Relation between arc time and erosion of electrode

As the figure reveals, the rate of erosion of all the electrodes increases markedly after occurrence of a welding arc and after a while the pace drops, a look at the curves after 45 sec reveals a drop in the pace at which the electrodes erode. Taking the above facts into consideration, evaluation of electrodes erosion was carreid out by utilizing the erosion quantity E at arc time of 60 sec. It was discovered that the erosion quantity of tungsten electrodes with rare-earth metallic oxide inclusions decreased in the order thoria, yttria and lanthana.

3.1.2 Effect of ambient pressure and arc current

The appearance of the tip of tungsten electrodes after the tests are shown in Fig.3. Photographs labeled (A) depict tests performed at atomospheric pressure and current of 150A, for (B) the pressure was raised to 3.1 MPa and current was 150 A while (C) depicts test results at pressure of 3.1 MPa and current of 200 A. As it can be observed in the photographs, under atomospheric pressure, traces of electrode erosion is almost non existent on any of the electrodes, however, it can be observed that erosion of electrodes incease as the pressure increses. This observed trend was most pronounced in tungsten electrodes with thoria inclusion and vice versa in tungsten electrodes with lanthana inclusion. It can be inferred from the above results that the erosion characteristics of the tungsten electrodes differed considerably. Thus, the effect of ambient pressure and arc current on the erosion of each type of electrode was next investigated in detail.

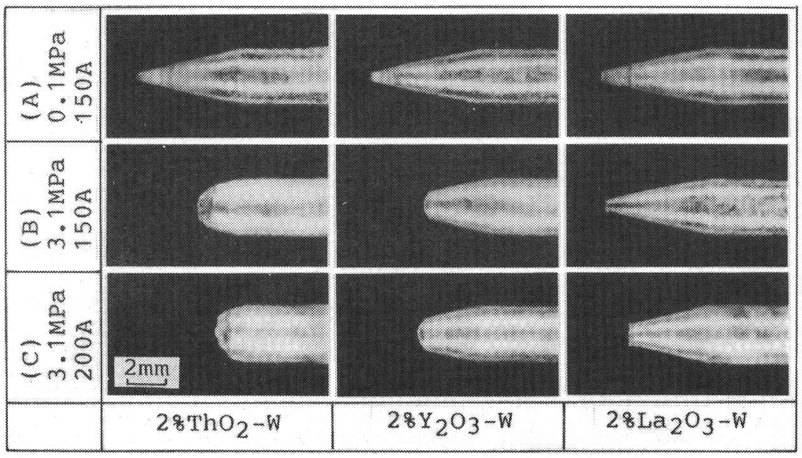

Fig. 3 Effect of electrode materials on erosion of electrodes

The compiled results of the effect of ambient pressure and arc current on erosion rate ε of tungsten electrodes with inclusions of 2% thoria, yttria and lanthana in the erosion tests are shown in Fig.4—6. The arc length and arc time in the erosion test were respectively 2 mm and 60 sec. It is shown in the Fig. 4 that the erosion rate ε increases as the ambient pressure P and arc current I increase.

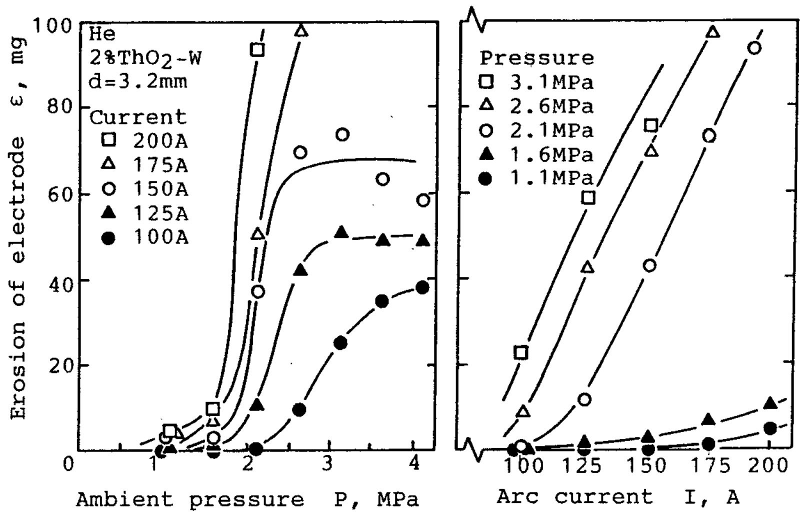

Fig. 4 Effect of ambient pressure and arc current on erosion of electrode

In general, the arc column shrinks with increasing pressure and the electrode tip overheats easily due to concentration of the cathode spot at the electrode tip [6] and thus increasing the erosion rate. The erosion rate of electrodes increase with increasing arc current, this increase is thought to be due to the increase in the heating effect which is proportional to the current. Except in cases of comparatively low pressure and current, it was observed that incrasing the pressure and current gradually above a critical value resulted in rapid increase in erosion rate, this trend was observed in each type of electrode.

A comparison of erosion characteristics of tungsten electrodes with inclusions of thoria, yttria and lanthana as shown in Fig. 4 – 6 reveals considerable defferences in erosion rate. In the case of thoriated tungsten electrodes, the erosion quantity starts to increase rapidly when the pressure is above 2.1 MPa and at a pressure of 3.1 MPa the rate of increase of the erosion rate is saturated and remains stable even at pressures above 3.1 MPa. Besides, it was observed that the erosion rate of thoriated tungsten electrodes was considerably large compared to the other two types of tungsten electrode. Tungsten electrodes containing lanthana exhibited a gradual increase in erosion rate with increasing pressure and compared to thoriated tungsten electrode the quantity of eroded material was considerably small, while tungsten electrodes with yttria inclusion exhibited an intermediate trend between the two.

3.1.3 Effect of electrode diameter

Figure 7 in the same manner shows the effect of various electrode diameter on erosion rate of the three types of electrodes with inclusions of rare-earth elements, tests were performed at ambient pressure of 2.1 MPa and at five different arc current values ranging from 100A to 200A. As it can be seen in the figure, the erosion rate reduces with increasing electrode diameter. It was ob-

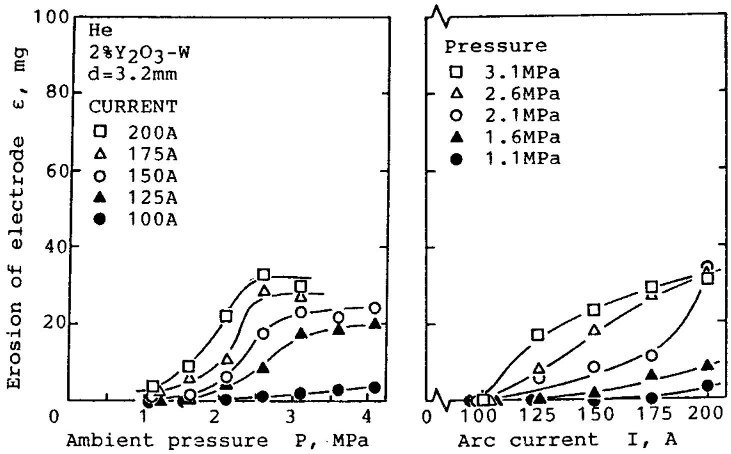

Fig. 5 Effect of ambient pressure and arc current on erosion of electrode

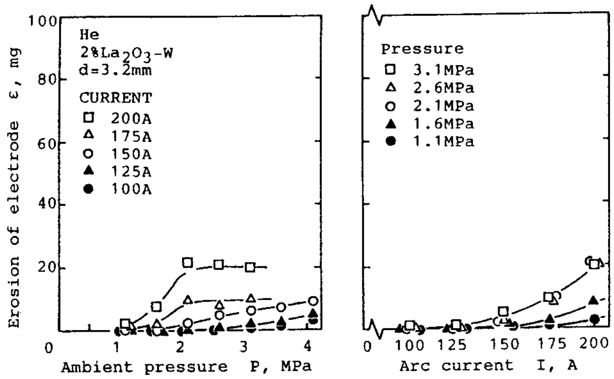

Fig. 6 Effect of ambient pressure and arc current on erosion of electrode

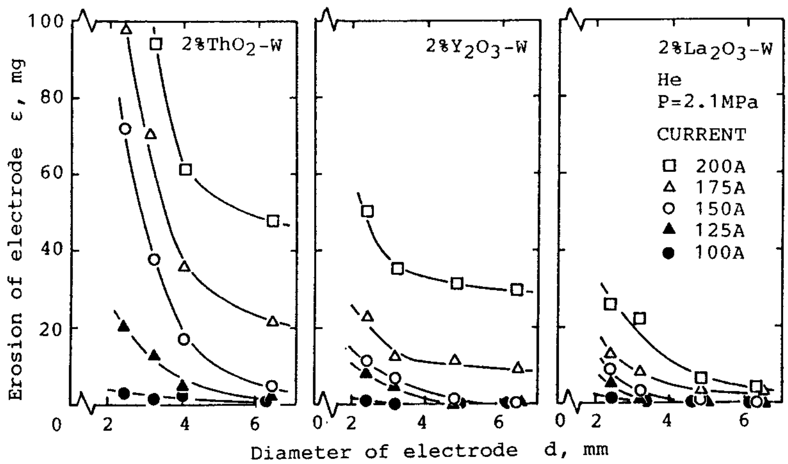

Fig. 7 Effect of electrode diameter on erosion of electrode

served within the range of test conditions employed in this test that the erosion rate was suppressed significantly especially with electrodes of diameter over 4 mm. An interesting observation made was that under a high crrrent exceeding 175 A, the erosion rate of electrodes containing thoria and yttria is not curbed when the size of electrode is increased to 6.4 mm. Whereas, the erosion rate of electrodes containing lanthana is greatly curbed by employing electrodes of diameter exceeding 4.8 mm.

3.1.4 Correlation between electrode erosion and critical conditon

As mentioned above, the erosion characteristic of an electrode is exquisitely influenced by factors such as the type of material inclusion, ambient pressure P, arc current I and electrode size. Whereas as shown in Fig.4-6 where the electrode diameter is constant, there exist a current value or critical current where a gradual increase of the ambient pressure and arc current result in a sudden rise of the erosion rate. Thus, the pressure and current at which the quantity of eroded electrode exceeded 5 mg were respectively defined as the critical pressure Pc and critical current Ic. An example of the relationship between ambient pressure P, electrode diameter d and critical current Ic is shown by the solid line in the plot in Fig.8, where d is 3.2 mm and θ is 30°. In the lower left region of the solid line, the quantity of eroded electrode is small and no problem is encoutered, whereas erosion in the upper-right region of the solid line is remarkable, making this region impractical. The figure also shows that in all the electrodes critical current increases with increasing electrode diameter and reduces with increasing pressure. The critical current can also be seen to increase in the order thoria, yttria and lanthana. The above results indicate that tungsten electrode with lanthana inclusion exhibit the best erosion characteristics.

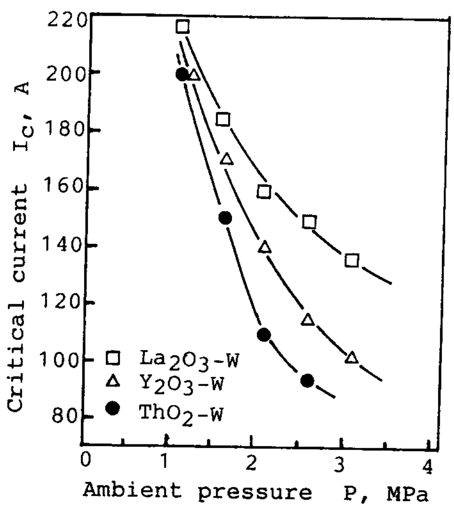

Fig. 8 Relation between ambient pressure and critical current for erosion of electrode

3.2 SEM observation of electrode tip

Electrode tip of thoria, yttria and lantana employed in the erosion test under the condition of ambient pressure 2.1 MPa, arc current 100 A and arc time of 60 sec are shown in the SEM micrographs in Fig.9. The sections labeled (A) de-

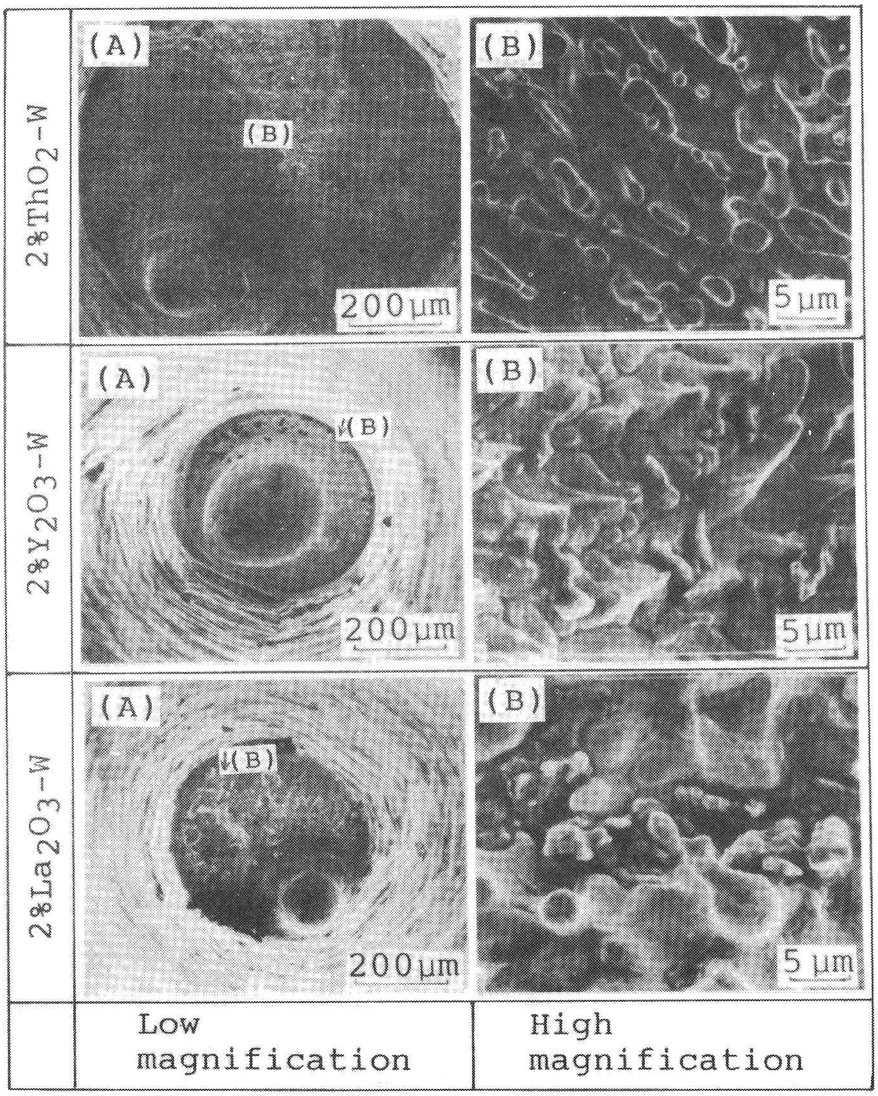

Fig. 9 SEM images of electrode tips

note observation of the electrode tip at a comparatively low magnification while (B) denotes a higher magnification of section (A) . The protrusion at the lower left part of photograph (A) in thoriated tungsten electrodes is believed due to arc occurring just immediately before extinction of the arc. Numerous circular traces roughly 300 microns in diameter can also be observed in the plane around the periphery of the electrode tip. It is assumed from this marks that the arc was probably rotating in a counterclockwise direction around the plane of the electrode tip. In the center of the electrode tip (part B), traces of partially melted tungsten particles undergoing cooling and solidfication can be observed. It can be inferred from the above observations that the tip of thoriated tungsten electrodes attain high tempertature and while melting and evaporation is taking place the arc cathode spot rotates around the electrode tip. The erosion rate of tungsten electrodes with yttria inclusion is smaller than that of thoriated tungsten electrodes apart from that the electrode tip is comparatively small diameter, on the other hand, the diameter of the protruded portion thought to indicate where the arc was occurring just before it's extinction is comparatively large exceeding 200 microns. In the enlarged photograph (B), tungsten particles in a semimolten state overlapping each other can be seen and almost revealing a solidified shape. This has the effect of lowering the electron-discharge work function by yttrium in electrodes with yttria inclusion thus, lowering the electrode temperature and as a result the erosion quantity is believed substantially reduced as compared to thoriated tungsten electrodes. It was however observed that near the cathode spot the temperature is sufficiently close to the melting point of tungsten, while the center of the tungsten elctrode tip is in a molten state. In the case of tungsten electrodes with lanthana inclusion, the diameter of the surface of the electrode tip is 500 micron, and alike electrodes containing yttria, the erosion quantity is small. In addition, vestiges of the arc occurrence point are fewer as compared to electrodes containing yttria. This indicates that the electrode tip was not necessarily in a fully molten state. The existence of unmolten tungsten particles near the center (B) of the electrode tip, in addition, particles resembling lanthana were observed exposed in the spaces between the tungsten particles. Lanthana helps to lower the electron-discharge work function in electrodes containing lanthana and as a results the temperature of the electrode tip remains low.

3.3 Observation of electrode surface

The electrode surface was polished and etched after the tests and then observations of the surface were performed under an optical microscope. The observed results are shown in Fig.10. In each type of electrode, white-striped structures can be obsereved spanning the longitudinal section of the electrode, and the white-striped structures in an elongated state along the logitudinal section of the electrode tip are the rare-earth metallic oxide inclusions elongated during extrusion of electrodes.

The electrode tips after further magnification are displayed in Fig.11. On the

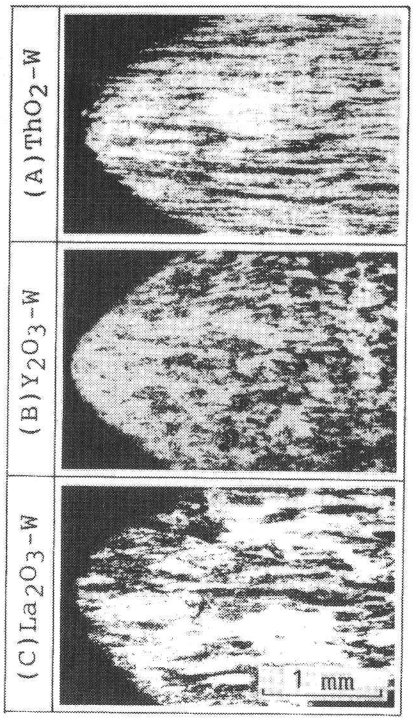

Fig. 10 Micro-structures of hongitudinal-section of electrodes after welding

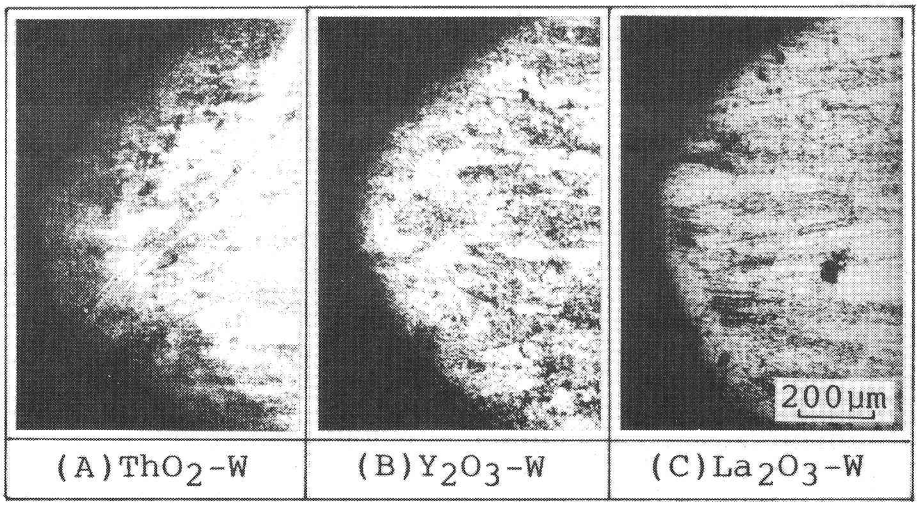

Fig.11 Micro-structures of longitudinal-section of electrode tips after welding

surface of thoriated tungsten electrodes erosion of thoria spanning 100 microns can be observed, whereas the rate of erosion on electrodes containing yttria and lanthana is lesser and sufficient traces of inclusions can be observed even around the electrode surface. This results conform closely with SEM observation results of the electrode tips.

4. Conclusion

The effect of added rare-earth elements on the erosion characteristics of tungsten electrodes in TIG welding under a high ambient pressure was inveatigated. Three types of tungsten electrodes containing 2% thoria, 2% yttria and 2% lanthana of diameter ranging from 2.4 mm to 6.4 mm were employed.

The main results obtained are as follows:

(1) All three types of electrode showed an increase in electrode erosion with increasing ambient pressure and arc current, whereas, erosion decreases with increasing electrode diameter.

(2) The critical current for various ambient pressure and electrode diameter at which the erosion quantity was 5 mg was specified. It was discovered that the critical current Ic decreases with decreasing electrode diameter and increasing pressure.

(3) The rate of erosion of an electrode with lanthana inclusion is much lower than that of a thoriated electrode while the erosion rate of an electrode containing ytttium oxide exhibits an intermediate trend. Thus, of the three types of electrode, an electrode containing lanthana is best suited to TIG welding under high pressure.

(4) The distribution of rare-earth element on the electrode tip after occurrence of an arc varied remarkably among the various types of electrode. Thorium oxide expends the fastest while the contrary can be said of lanthanum oxide. Compared to the other two types of electrode, the longer existence of lanthana on the electrode tip helps to reduce the work function thus, effectively inhibiting overheating and erosion of the electrode tip. Hence, among the three types of rare-earth element lanthana is judged to be best suited to TIG welding under high pressure.

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