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EXPERIMENTAL STUDY OF EROSION OF HAFNIUM ELECTRODES FOR OXYGEN PLASMA ARC CUTTING

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ABSTRACT

Experimental study has been conducted on an erosion of an hafnium electrodes for oxygen plasma arc cutting. Hafnium (Hf) is used as a refractory cathode material for thermo-electron-emission at high temperature region.

The erosion of an Hf electrode was investigated by measuring the concavity depth on Hf electrodes after operations. The measurements were done on several operating conditions. The erosion properties have been found to be separated to two portions. One of the Hf erosion happens in transient period including start-up and shut-off phases of a plasma arc when arc current is increasing or decreasing. The other erosion happens in the stable arc phase when arc current is kept at operating current.

Spectroscopic measurements of the arc plasma jet coming out from a nozzle have been conducted in order to study the behavior of erosion of Hf electrodes. An atom line of Hf at λ =340nm was observed by a monochromator. Characteristic intermittent radiations of Hf in addition to background continuum were observed in transient period when the arc current or gas pressure changes. It is considered that the intermittent radiation comes from droplets of Hf ejected from a surface on molten electrode. And the ejection is considered to be induced by a break of a balance of fluid dynamic on the melted electrode.

1. INTRODUCTION

Oxygen plasma cutting is known as a high performance cutting method for mild steel from 6mm to 32mm thickness. It is wildly used for cutting process on various manufacturing fields like as construction, shipbuilding, bridge and other welding structure [1]. Increasing electrical current on plasma cutting gives us improving performance of cutting. But, on the other hand, it spoils life of consumables which are an electrode and a nozzle for plasma cutting. The life of a consumable means available time or number of cutting with one consumable. Fig.1 shows relationship between electrical current and maximum cutting thickness, and also, the current and consumable life. The maximum cutting thickness means performance of plasma cutting. Increasing electrical current contributes cutting of thicker material. However, it reduces the life of consumables severely. According to Fig.1, if we use 400 amps cutting condition, we can cut plate of 40mm thickness. However, the cutting condition does not give us enough consumable life. Therefore, 300 amps is practical maximum current.

Long life of a consumable has been the most important subject on plasma cutting. The long life is a requirement for increasing of electrical current of plasma cutting. And also, it can make reduction of running cost that is mostly consumable cost. Therefore, many studies for that have been conducted for dozens of years [2]-[6].

In this experimental study, we investigate erosions of hafnium (Hf) electrodes which are used for oxygen plasma arc cutting. The purpose of the study is to get knowledge of behaviors of an erosion of an hafnium electrode. We altered current or arc-on-time, and measured the erosion of the Hf in order to find out relationship between erosion rate and electrical current, or arc-on-time. And also, we used spectroscopic measurement and high speed video camera to find out when the Hf erosion happens.

2. EXPERIMENTAL SETUP

2.1. Oxygen plasma cutting system

We used TFPL60-300A, plasma torch system made by Komatsu Industries Corp. which rated operating current is 300 amps. The torch system has been modified to be able to supply 525 amps as output current. Fig.2 shows experimental setup that we used in our study. The plasma torch system is consist of a plasma torch, a power supply feeding electric power to the torch, a cooling unit cooling the torch, a gas unit supplying gases to the torch and a high frequency box to ignite a spark between an electrode and a nozzle in the torch. In plasma cutting, an electrode located in a torch is a cathode, and a plate to be cut is an anode. An arc discharge is generated between an electrode and a plate. The arc discharge is constricted by a nozzle that surrounds an electrode. The nozzle makes the arc discharge to be a plasma jet with high temperature and high velocity. The plasma jet liquefies a plate and blows off the molten plate. And it makes a kerf. Both of an electrode and a nozzle are heated by plasma arc. They are cooled by water to get a good life of them. Hf is used as an electrode to emit thermo electrons. The Hf is inserted a copper holder. The copper holder is cooled by water. The shape of the Hf is cylindrical. We used two types of Hf. One is 1.6mm diameter for 135 amps and the other is

2.0mm diameter for higher current more than 135 amps. Instead of a work plate to be cut, a copper target being cooled by water is used.

Fig.3 indicates a sequence of a start of a plasma arc. At first, a plasma power supply receives a start-signal from a CNC of a cutting machine. (1) Pre-flow starts to feed gas to a torch. (2) H.F box is activated to generate high frequency and high voltage between an electrode and a nozzle. And it makes break down there. (3) The break down makes an electrical pass between an electrode and a nozzle, and a pilot arc is established by DC current from the power supply. (4) The pilot arc reaches a work plate (copper target in this study). An anode line is altered from a nozzle to a work plate. A pilot arc is transferred to a main arc. At the transfer period, electrical current increases from low current (10 amps – 30 amps for a pilot arc) to high current (135 amps – 525 amps for a main arc). At the same time, gas pressure increases from low (0.2 MPa) to High (0.8 MPa). (5) Cutting is conducted by a main arc. (6) At an end of cutting, a stop signal inputs to a power supply form a CNC, an electrical current is shut off slowly. And a plasma arc disappears.

2.2. Measurement of an erosion of Hf electrode

We measured an erosion of Hf electrodes in several conditions of varies electrical currents and arc on-time. The concavities of erosions are measured by a microscopy. Operating conditions in our study are shown in Table1. We used electrodes and nozzles which are used for actual production. Fig.2 shows electrical current forms at arc-start and shut-off phase for our study. The current forms are also same as actual production. The start-current level and the shut-off-current level are constant even if operating current is changed.

2.3. Spectroscopic measurements and observation by high speed video camera

Spectroscopic measurement was conducted to observe the erosion of Hf and of a copper (Cu) holder of an electrode, on real time. Fig.2 show optical set up for radiation of Hf and Cu. The radiation from a plasma jet is divided to two lights to observe spectrums of both Hf and Cu. The lights are led through optical fiber to a monochromator HR320 made by Horiba which resolution is 0.2nm. We used database of NIST（National Institute of Standards and Technology） in order to decide the spectrums to be observed for Hf and Cu. The criteria to decide the spectrums are as follows. (a) The spectrums have enough intensity to be observed. (b) The spectrums of Hf and Cu are far from each other to be identified. (c) The spectrums of Hf and Cu are far from the spectrum of oxygen as background. And then, the spectrums to be observed were decided λ=340nm for Hf and λ=515nm for Cu. And observation by high speed video camera was done to find out when the Hf erosion happens. The video camera VM-6000 is made by Keyence. Its frame rate is 2000 frames/sec.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Observation of consumption of Hf

In order to find out behaviors of consumption of the Hf, measurements of concavity of Hf electrode has been conducted every after 100 arc-starts with 135 amps and 20 seconds arc-on-time. Fig.6 indicates depth and diameter of the concavity of an Hf electrode. The solid line shows a depth, and the dashed line shows a diameter.

An Hf erosion goes in the shape of crater at first. Both of a diameter and a depth of the concavity increase at the same time until the diameter reaches 1.6mm as same as the diameter of an Hf electrode. After the diameter of concavity reaches 1.6mm on 100 starts, the expanding of the diameter stops and only the depth gets deeper. The depth gets at 1.5mm on 900 starts, and then the diameter grows again beyond the boundary between an Hf electrode and a Cu holder. After the erosion of a Cu holder begins, the depth of the concavity gets deeper more rapidly. The depth reaches 2.0mm on 1100 starts. And then the speed of getting deeper is accelerated. When the depth gets at 2.5mm on 1500 starts, crucial erosion happens and the electrode gets to be unable to generate a normal arc. We have done several experiments with the measurements of electrodes in various conditions with several electrical current. The behavior of erosions takes same progresses as 135 amp condition. We found that the consuming of an Hf electrode takes 4 phases from new to old. The 4 phases are Start-phase when an electrode starts to be used, Stable-phase, Expand-phase and Last-phase when an electrode gets unavailable.

Ⅰ : Start phase : erosion shape is crater when an electrode is new, the diameter of concavity is less than the diameter of an Hf electrode.

Ⅱ : Stable phase : erosion shape is cylindrical, the speed of getting deeper is comparatively slow.

Ⅲ : Expand phase : erosion of both of an Hf electrode and a Cu holder occurs, the speed of getting deeper is comparatively fast.

Ⅳ : Last phase : crucial erosion happens, an electrode gets unavailable.

3.2. Influence of on-off cycle of plasma arc to consumption of Hf

We investigated influence of arc-on-time on Hf consumption. We measured the depth of concavity in conditions with 3 second, 20 seconds and 60 seconds as arc-on-time. The currents were 135 amps for each condition.

Fig.7 (a) shows progresses of consumptions plotted by total arc-on-time. When the depth reaches 2.0mm in each progress, erosion is in Ⅳ-Last-phase. The total arc-on-time as an electrode life increases by prolongation of arc-on-time. When arc-on-time is 60 seconds, the electrode can be used for 14 hours as electrode life. However, electrode life is shortening to only 1 hour with 3 seconds as arc-on-time. 20 seconds as arc-on-time gives 6 hours as electrode life, that is middle of 14 hours and 1 hour.

Fig.7 (b) shows progresses of consumptions plotted by total number of arc starts. Its data are same as Fig.7 (a). The difference between the progresses on Fig.7 (b) is relatively small compared with one on Fig.7 (a) plotted by total arc-on-time. It means that the progress of consumption more strongly depends on number of arc starts than arc-on-time.

We suppose that criterion of electrode life is 2.0mm depth of concavity. On Fig.8, a dot indicates an electrode life for 135 amps with several arc-on-times. The dots are located on a line plotted by total arc-on-time and total number of arc-starts on Fig.8. It means that consumption on of Hf consist of 2 type of consumption. The one depends on arc-on-time. The other depends on number of arc-starts. We consider Hf erosion is divided to steady consumption and transient consumption. The steady consumption occurs during steady arc when the current is constant. And the transient consumption occurs during an arc starts or shuts down.

3.3. Acceleration of consumption of Hf by current-increase

We have investigated the influence on consumption of Hf by electrical current. Operating conditions indicate on Table1 and Fig.4 for our investigation. The results are shown by Fig.9 (a) and Fig.9 (b). Fig.9 (a) shows the results of 20 seconds arc-on-time. Fig.9 (b) shows the results of 3 seconds arc-on-time. On both conditions, bigger electrical current makes consumption of Hf enhanced. According comparison with Fig.9 (a) and Fig.9 (b), bigger current have more influence of enhancing of consuming on 20 seconds than 3seconds as arc-on-time.

We have estimated a transient consumption and a steady consumption during once of arc-start. The results estimated are shown on Table2. The estimations were done by following procedure. At first, we estimated consumptions during once of arc-start both for 20 seconds and 3 seconds. The difference between consumptions of 20 seconds and 3 seconds were supposed to a steady consumption of 17 seconds. Therefore, we could estimate steady consumption that unit is μg/sec. And then, we estimated the transient consumption that unit is μg/cycle estimated.

Fig.10 (a) illustrates Table2. Transient consumptions are equal to steady consumption for dozens of seconds. For example, the transient consumption for 135 amps is equal to a steady consumption for 40 seconds. The transient consumption for each current does not have significant difference. There is still slight difference between them. We consider difference is caused by difference of a diameter of an Hf electrode. We used 1.6mm-diameter for 135 amps. For more than 220 amps, 2.0mm-diameter is used. We consider transient consumptions are almost constant for different operating current if the start-current, the shut-off-current and the diameter of Hf are same.

The steady consumptions rapidly increase according to increasing of operating current. We also estimated steady consumptions per electrical current on Table2 as μg/(sec・amp). They are also increasing according to current. That is reason of rapid increasing of steady consumptions by current.

Fig.10 (b) shows consumptions of once of arc-start for 20 seconds. The transient consumption takes major portion of total consumption for relatively small current. On the other hand, steady consumption gets major for bigger current.

3.4. Spectroscopic analysis of erosion of Hf

We have conducted spectroscopic analysis of plasma jet coming out from a nozzle, in order to recognize when an Hf erosion happens. The radiations of Hf, λ=340nm usually indicate a same form as an electrical-current-form. However, we sometimes observed intermittent radiation of Hf added on background continuum as same as the current-form. When the spikes of radiations of 340nm are observed, we did not observe such kind of spikes near by 340nm. Therefore, we considered the spike is a sign of Hf-droplet that gets into plasma arc from an Hf molten electrode. The spikes are observed at particular timing during arc-start and arc-shut-off. That suggests the transient consumption consist of Hf droplets spattering from an Hf molten electrode.

During steady period when current is kept constant, no spike of Hf-radiation is usually observed. The steady consumption is supposed to be consisted of static vaporization of Hf. And the vapor of Hf is supposed to be too small to identify from background radiation.

Fig.11 – Fig.14 show spikes of Hf radiation. The data are observed with 135 amps. And also, with other current condition, similar spikes are observed. Fig.11 shows spikes during arc-start. The spikes of Hf-radiation are observed following period during arc-start. On Fig.11, the spike of (a) is observed in 10 msec just after arc start from break down by HF. The spike of (b) is observed from 100 msec to 200 msec during current increasing. The spike of (c) is observed when gas pressure changes from low to high.

The spikes are not observed on every time. They do not appear occasionally. The reason is supposed as follows. Our observation can catch radiations only from Hf-spatters from a molten electrode that go through a nozzle orifice. If spatters stick on the wall of a nozzle-inside, we can not see its radiation.

The frequency that we can observe spikes depends on electrode life phase. The spikes during arc-start are often observed during Ⅰ-start-phase, and are hardly observed during Ⅱ--stable-phase. No spike is observed when current is stable during Ⅰ and Ⅱ, however, spikes of Hf and spikes of Cu also are observed during Ⅲ-expand-phase as showing Fig.12. During Ⅲ-expand-phase, the Cu holder starts to be eroded, and it is supposed that Cu erosion enhances Hf erosion. It is reason why Hf consumption rate is fast during Ⅲ-expand-phase than Ⅱ-stable-phase.

Fig.13 shows spikes also during arc-shut-off. The spikes are observed when current is decreasing from 135 amps as operation current to 30 amps as shut off current. We changed the current as step form between 100 amps and 30 amps as shown in Fig. 14, in order to investigate phenomena of Hf erosion during arc-shut-off. Spikes are observed after the current decreases to 30 amps. The observation suggested us that Hf spattering could happen after a arc disappears.

3.5. Observation of Hf droplets during arc shut-off by high speed camera

We tried to observe Hf spattering after an arc disappears by a high speed camera. We could take a photograph of Hf spattering with 526 amps and 3.2mm nozzle orifice. The photograph is shown in Fig.15 with 2000 fps. The spattering takes place in 1.5 msec after the arc disappears. The droplets spout in the shape of cone from a nozzle. It suggests us that Hf droplets are induced by swirling gas flow.

3.6. Fluid dynamics of melted Hf electrode

Hf electrode is known to be in liquid phase when it is emitting electrons. Heberlein et al of University of Minnesota suggest that there is certain pressure balance on melted Hf electrode [8]. Shown in Fig.16 (a), the pressure balance consists of surface tension, plasma pressure and shear force of gas flow. We consider that Hf droplets are induced by a break of the balance of fluid dynamic on the molten electrode. When current is increasing during arc start, the plasma pressure is supposed to get too big to keep the balance. And the plasma pressure pushes out molten Hf as shown in Fig.16 (b). During arc shut off, gas flow increases rapidly. It is supposed to induce shear force to scatter molten Hf as shown in Fig.16(c).

We are convinced that the investigation of the fluid balance on Hf electrode is necessary to improve an electrode life for plasma cutting.

4. CONCLUSIONS

In this study, we experimentally investigated consumption of an Hf electrode which is used for oxygen plasma cutting. The results obtained are as follows.

(1) The consuming of Hf electrode takes 4 phases from new to old. The 4 phases are Start phase when an electrode starts to be used, Stable phase, Expand phase and Last phase when an electrode gets unavailable.

(2) The consumption of Hf consists of a transient consumption and a steady consumption. The transient consumption is depended on the number of arc-start. The steady consumption is depended on total arc-on-time.

(3) In the transient phase for short time period, much amount of loss of Hf equal to loss for dozens of seconds as the steady phase takes place. The higher level of consumption rate in the transient phase is found that it is caused by loss of droplets of Hf ejected from the melted electrode surface.

(4) In the steady phase, ejection of Hf droplets does not occur except Ⅲ-expand-phase and Ⅳ-last-phase. The consumption is considered to be occurred by static vaporization of Hf. And the steady consumption significantly increases according to electrical current increasing.

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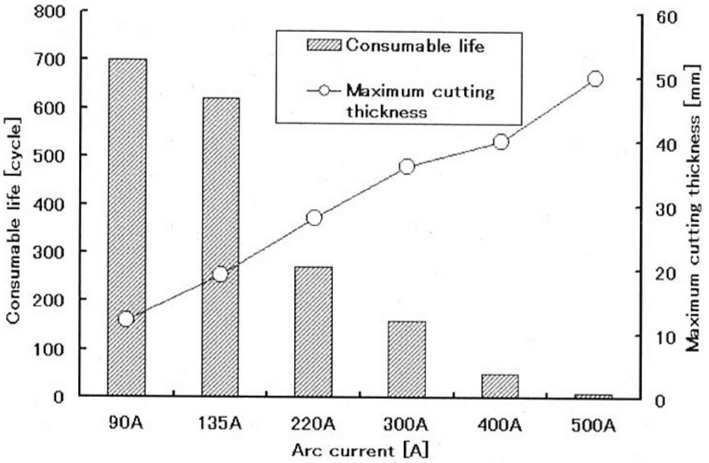

Fig.1 Relation between arc current and consumable life and maximum cutting thickness

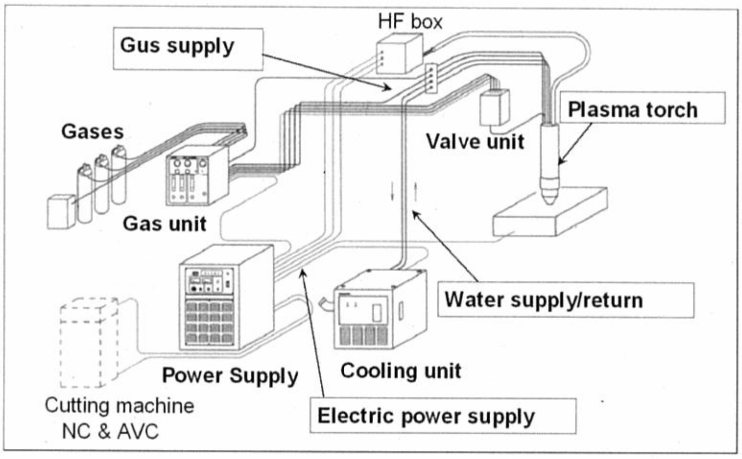

Fig.2 Plasma torch system

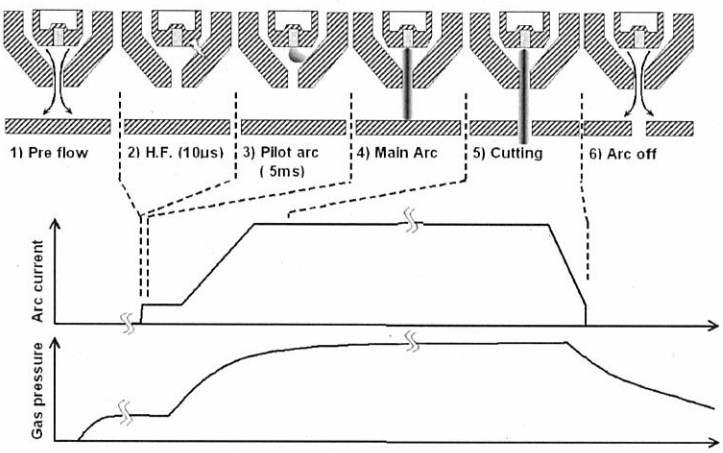

Fig.3 Start sequence of plasma torch

Table1 Operating condition

arc current	nozzle diameter	Hf electrod	start gas: gas	start gas: pressure	main gas: gas	main gas: pressure	arc on-time
135A	φ1.3mm	φ1.6mm	N_2	0.20MPa	O_2	0.85MPa	3sec
220A	φ1.7mm	φ2mm				0.65MPa	20sec
300A	φ2.2mm					0.55MPa	60sec
525A	φ3.2mm					0.65MPa	

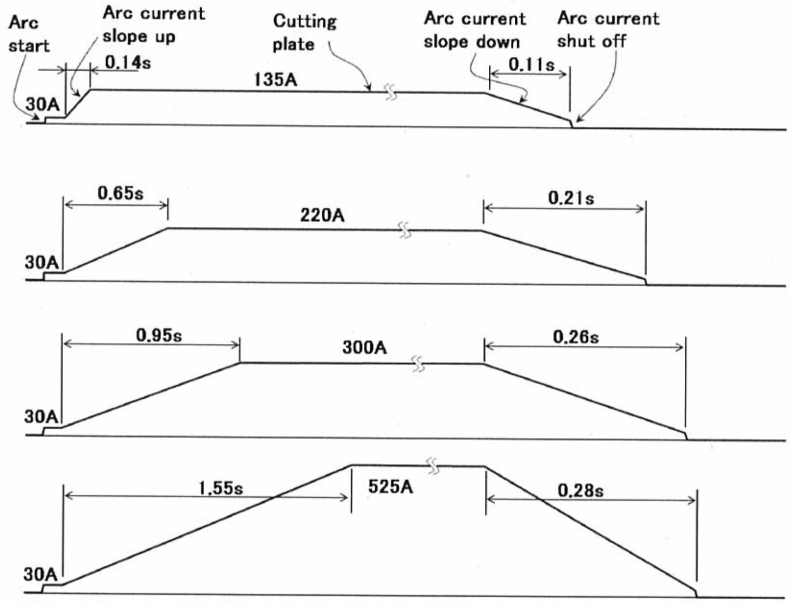

Fig.4 Operating condition of Current start and shut off

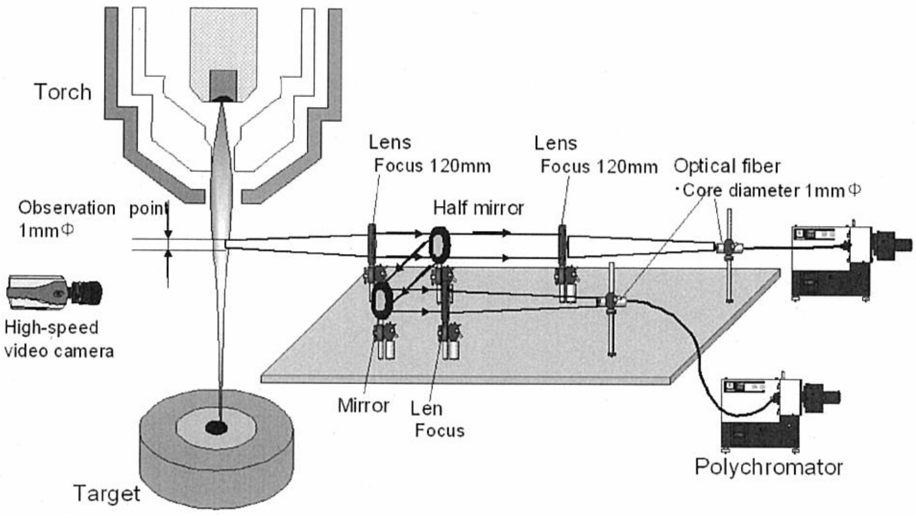

Fig.5 Optical set up for radiation of Hf and Cu spectrum

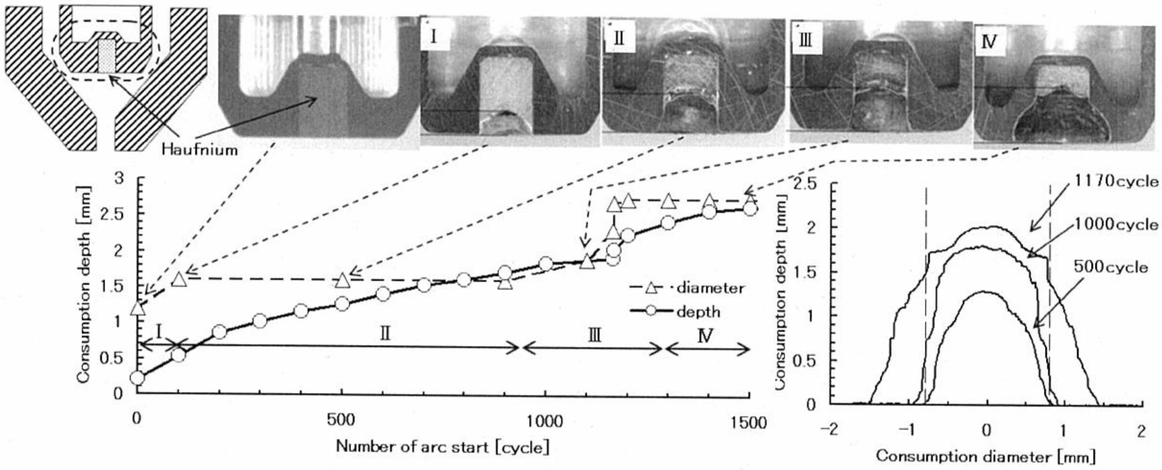

Fig.6 Hf electrode consuming for 135A on 20sec cycle

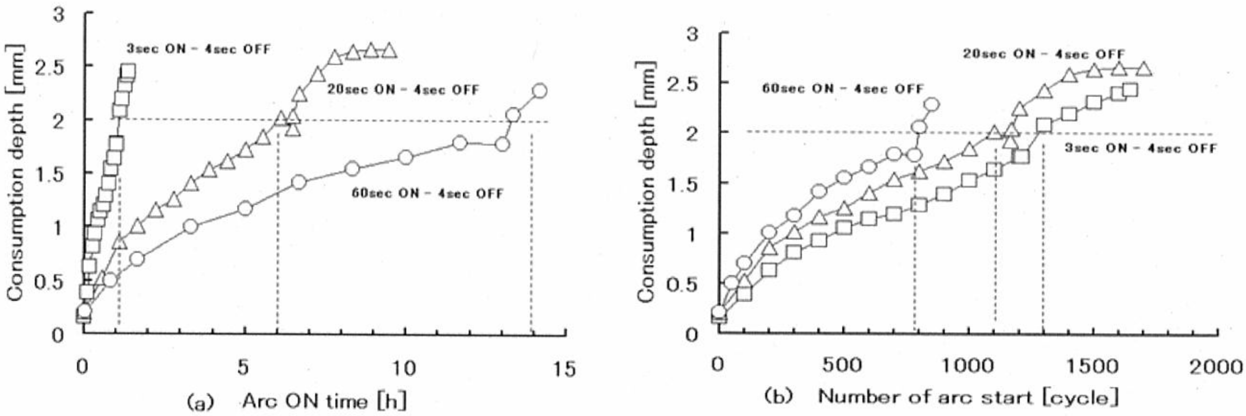

Fig.7 Hf electrode consuming for 135A on 3sec and 20sec, 60sec cycle

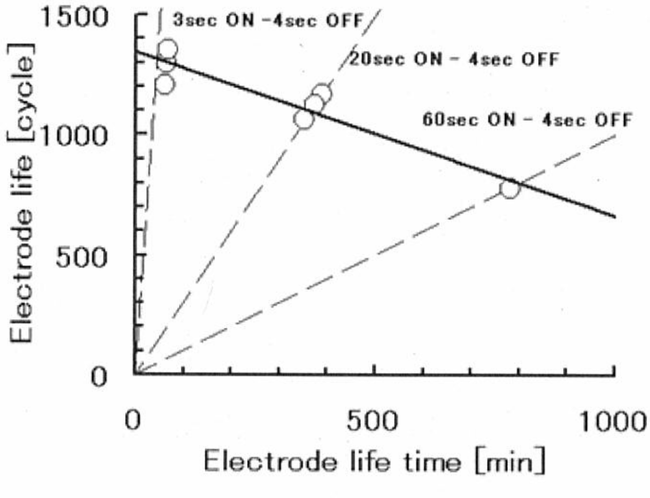

Fig.8 Cart of Electrode life for 135A

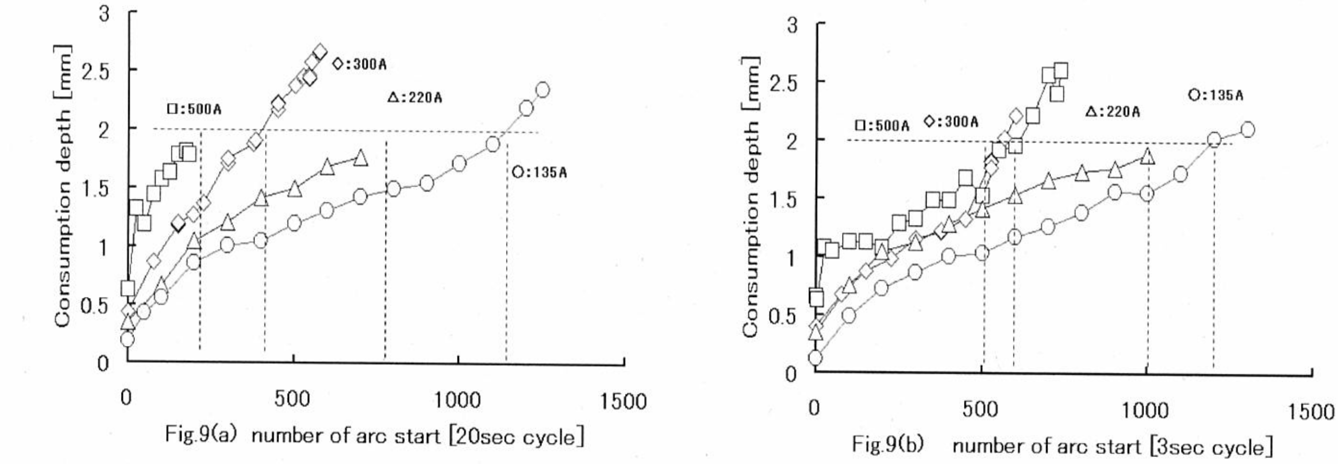

Fig.9 Hf electrode consuming for 135A and 220A, 300A, 500A plotted by number of arc starts

Table 2 Consumption rate of Hf electrode

arc current	Consumption rate		
	Transient arc [μg/cycle]	Steady arc [μg/s]	Steady arc [μg/(s·A)]
135A	1.9×10^{1}	4.6×10^{-1}	3.4×10^{-3}
220A	4.1×10^{1}	1.0	4.5×10^{-3}
300A	5.8×10^{1}	2.4	8.0×10^{-3}
525A	4.5×10^{1}	7.0	1.3×10^{-2}

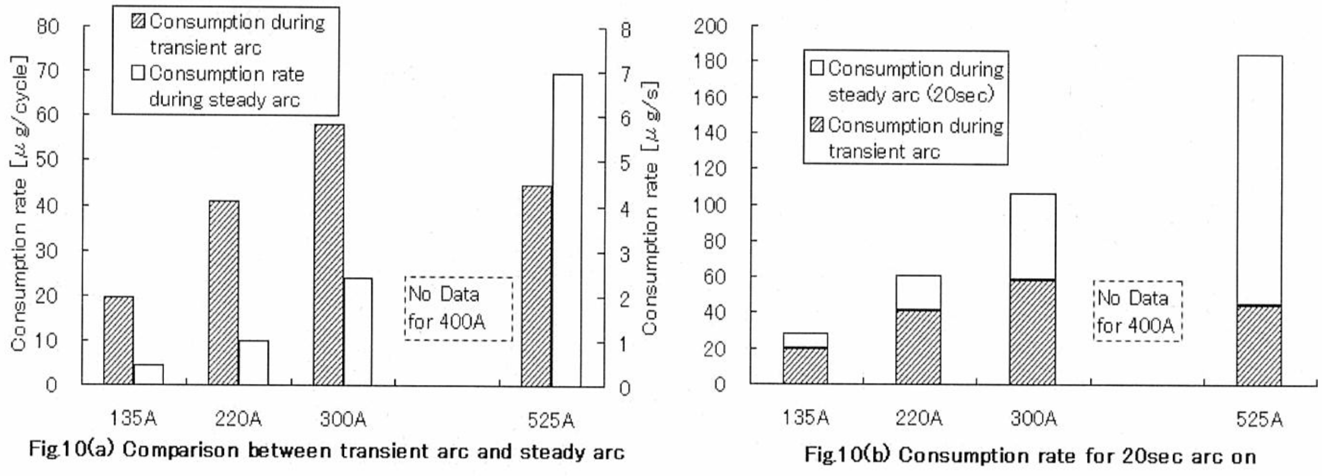

Fig.10 Comparison between consumption rate of transient arc and steady arc

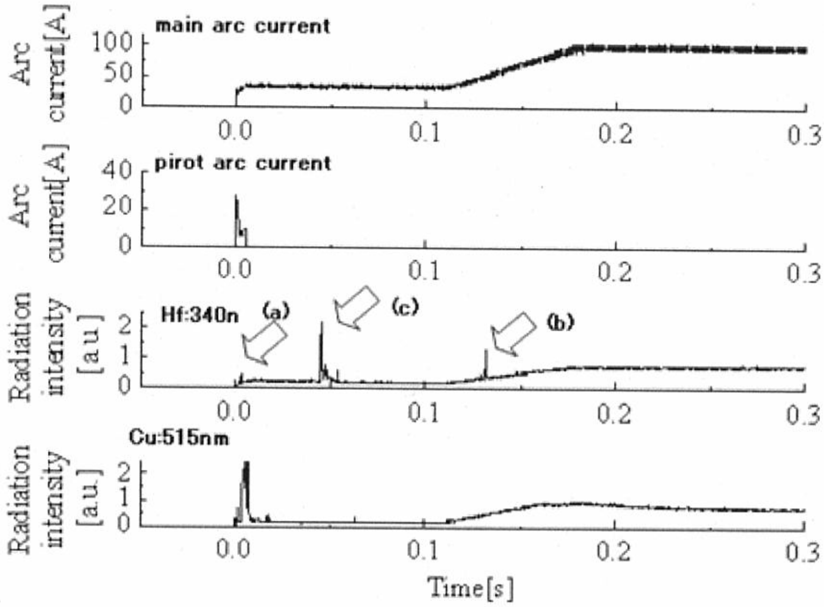

Fig.11 Radiation of Hf during arc start

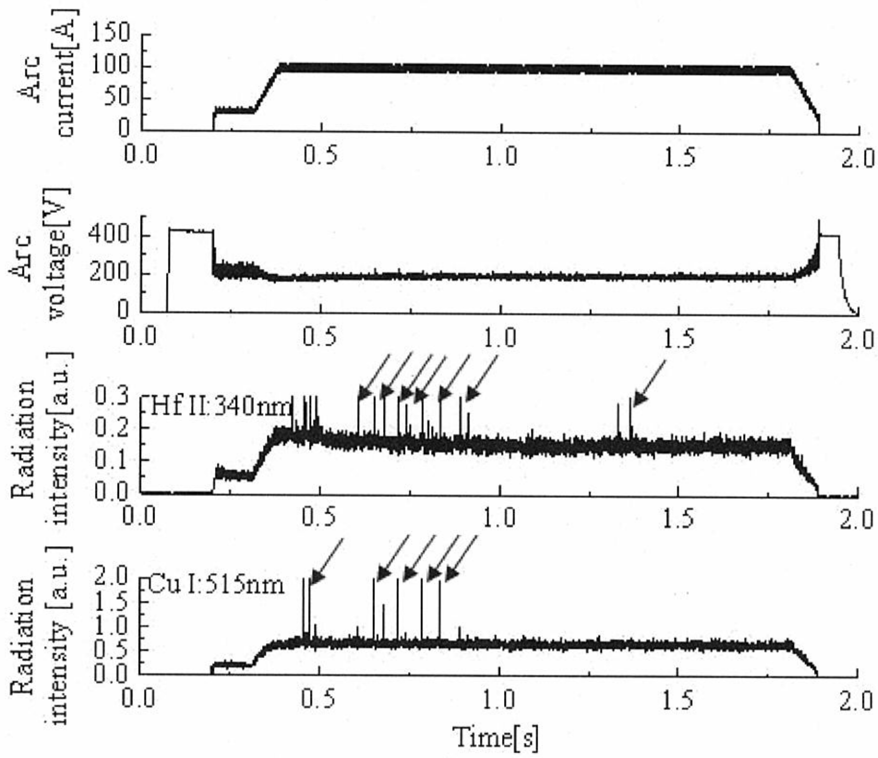

Fig.12 Radiation of Hf and Cu during consumption expanding stage

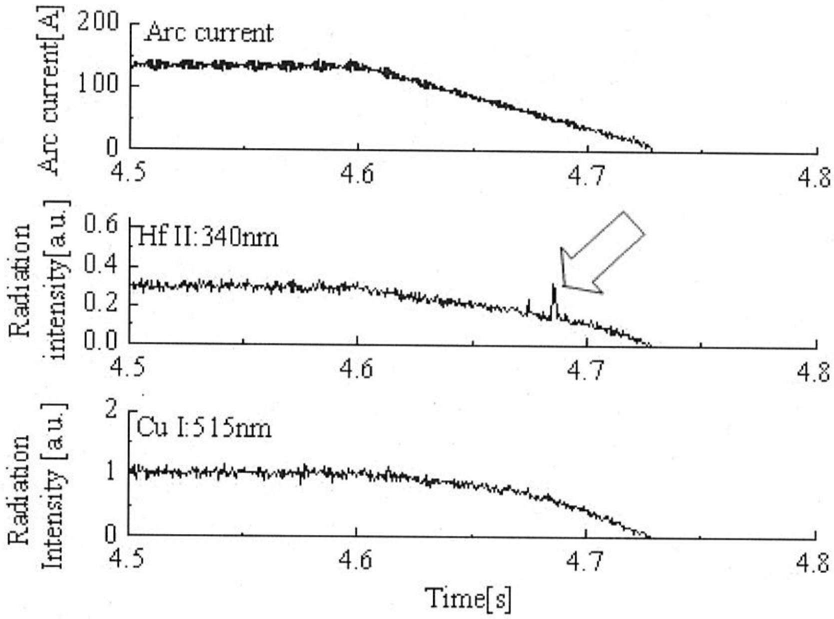

Fig.13 Radiation of Hf during arc shut off

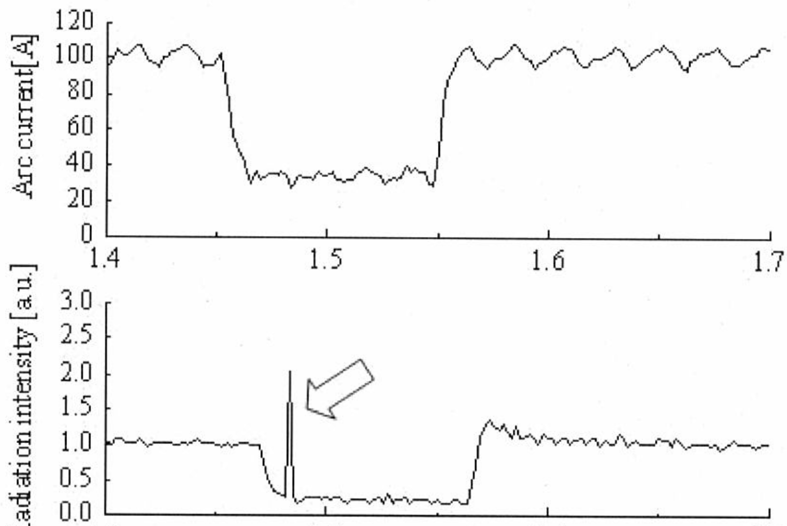

Fig.14 Radiation of Hf during arc current change

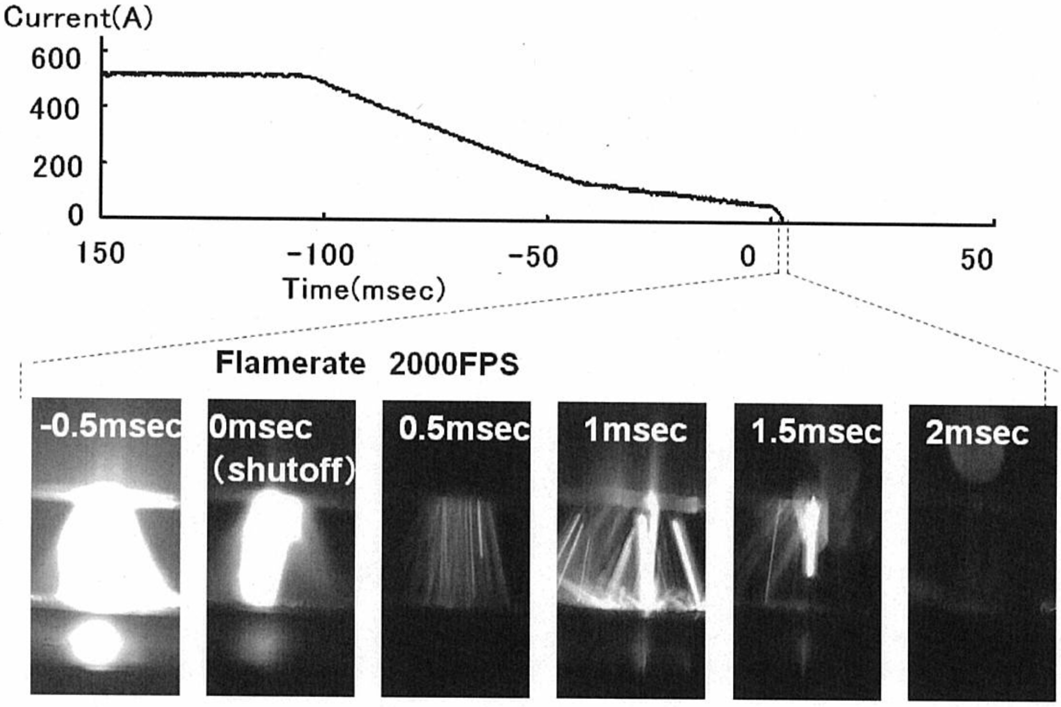

Fig.15 Spattering of Hf on 500A

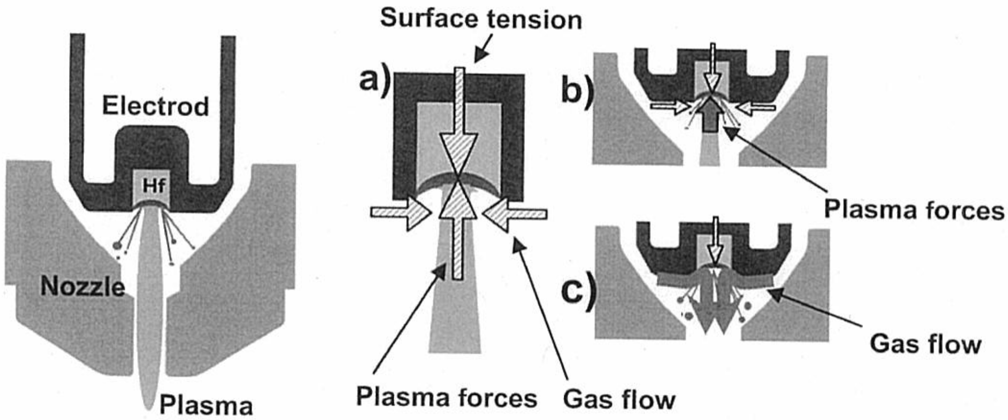

Fig.16 Fluid balance on Hf electrode