HIGH TEMPERATURE PLASMA FURNACE USING GAS TUNNEL TYPE PLASMA JET AND ITSIAPPLICATION TO SURFACE MODIFICATION

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Abstract

The high-energy gas tunnel type plasma jet was used as a heat source of the furnace and a new type of high temperature plasma furnace was developed as a furnace for multi purpose use. The performance of this plasma furnace was investigated by measuring the efficiency of this furnace and temperature inside the furnace.

The efficiency of this furnace was about 80% for Ar plasma, on the other hand, the efficiency for nitrogen plasma was a little higher than the case of argon plasma. The temperature distribution in the furnace was measured and the results showed that radial distribution of argon plasma was broader than the case of nitrogen plasma. For nitrogen plasma the maximum temperature was about 4000 K at the center of furnace tube.

As an application of this nitrogen plasma furnace, the experiment for the surface nitriding of titanium materials was carried out. As the result, TiN film of 10 μm thickness could be formed in a short time within 30 seconds. The Vickers hardness on this surface was more than Hv=1500.

INTRODUCTION

As science and technology progress, demands on materials become more severe. Conventional metals are often not adequate for the performances needed. Functional materials, such as ceramics, have attracted the attention of many researchers. The preparation of such functional materials needs a higher technology than that used until now. Therefore, new type of high performance furnace has been developed.

The plasma jet is a heat source with a high energy, and is easy to operate. Therefore, the adoption of the plasma jet for a plasma furnace will offer big advantages for applications such as, the melting of materials, fabrication, processing, and high temperature chemical reactions. The availability of a high performance plasma furnace will help to expand the application fields.

The gas tunnel type plasma jet developed by the author is a high performance plasma jet, operating at a high voltage and with easy control of power [1,2,3]. The thermal efficiency of the gas tunnel type of plasma jet has been proved higher than of other conventional types of plasma jet [4].

The properties of the gas tunnel type of plasma have been described in previous studies [1,2,3]. In particular, studies have shown that the gas tunnel type plasma jet is very useful in its application to thermal processing of materials. High quality coatings were obtained by a gas tunnel type plasma spraying method [5,6]; for example, on of the alumina coating produced had a high Vickers hardness of Hv=1200-1600 [7]. Therefore, to apply this gas tunnel plasma jet to the furnace will be also offer the possibility of new application fields [8].

The development of a high temperature plasma furnace has therefore been started using the gas tunnel type plasma jet. In this study, performance tests on this new furnace were carried out , and its properties examined. Thermal efficiency was measured, and the energy balance of the plasma furnace discussed.

As one application of this nitrogen plasma furnace, the experiment for the surface nitriding of titanium materials was carried out in order to form a TiN coating. The fundamental characteristic of the TiN coating formed was investigated by measuring the Vickers hardness, and the formation mechanism was discussed.

EXPERIMENTAL

Figure 1 shows a block diagram of the total composition of the high temperature plasma furnace using the gas tunnel type plasma jet. The apparatus consisted of the plasma furnace, (which was formed by a water cooled chamber (300 mm diameter) with a gas tunnel type plasma torch), power supply units, a cooling water unit, a gas supply unit, and a gas exhaust unit.

The mechanism and properties of the gas tunnel type plasma torch used as a heat source have been described in previous papers[1,2,3]. The torch was located at the center of the side wall of the cylindrical chamber. For the furnace tube, alumina or stainless steel pipe of 50 mm in diameter and 300 mm in length was used.

Performance tests of this plasma furnace were carried out various conditions. The experimental conditions for the testing of the furnace are shown in **Table 1**. Experiments were carried out between atmospheric pressure and a low pressure of about 40hPa using argon(Ar) and/or nitrogen(N2) as a working gas. The working gas flow rate, $\boldsymbol{Q}$, was kept at a constant value of 200 l/min. The power input to plasma torch: $\boldsymbol{P}$ was 20-30 kW.

The thermal efficiency of the furnace was determined from the efficiency of the gas tunnel plasma torch. The energy loss of the torch was calculated from the temperature of the cooling water of the torch.

The temperature in the furnace during operation was measured using by thermo-couples, fine rods of high temperature materials such as titanium, molybdenum, and tantalum, alumina small pipe, and a radiation thermometer.

A few detectors such as fine rods of those metals were located at certain positions away from the plasma torch; the distance between the torch and the detector is the distance: $\boldsymbol{l}$. Then plasma jet was operating for a certain time until the pressure distribution was stable. In these experiments, the main distance as a furnace center was set as l =100 mm.

The experiment for nitriding of titanium material was carried out at a low pressure in the nitrogen plasma furnace under the condition as shown in **Table 2**. Ti substrate was the size of 25x25mm and 3mm in thickness. The substrate temperature was measured by the thermo-couple during nitriding.

The Vickers hardness Hv was measured on the surface of the TiN film formed under the various irradiated conditions. The hardness test was also done on the cross section of the TiN film. The conditions for the measurement of the Vickers hardness were: loading weight 5 g, holding time 25 s, number of measuring points more than 10.

Table 1 Experimental conditions

Power input:	P = 20 - 30 kW
Working gas (N2, Ar) flow rate:	Q = 200 l/min
Pressure :	p=39-1000 hPa
Furnace tube Dia.:	D = 50 mm
Gas divertor nozzle dia.:	d = 15 mm

Table 2 Experimental conditions for nitriding

Power input:	P = 18 - 24 kW
Working gas (N2) flow rate:	Q = 180 l/min
Environmental gas(N2) flow rate:	Qen =20-80 l/min
Operating distance:	L = 100-300 mm
Irradiated time:	t = 8 - 30 s

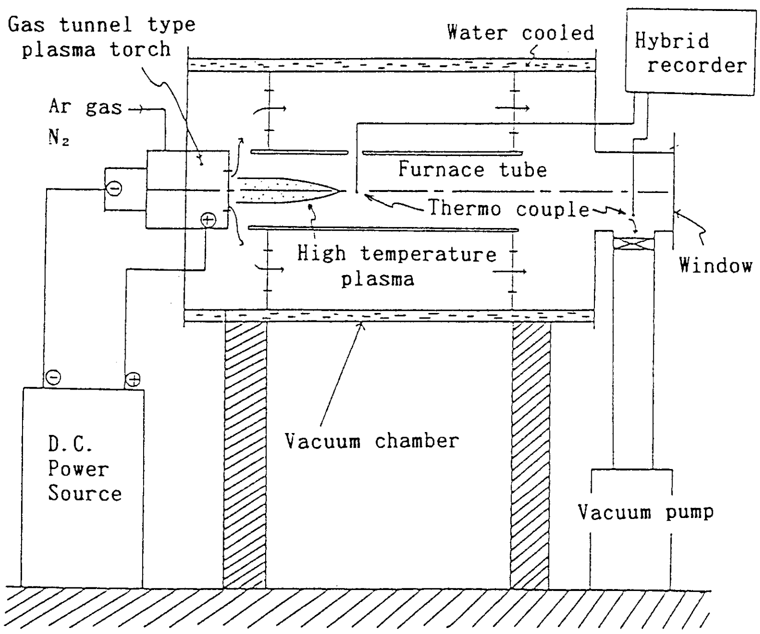

Fig.1 Block diagram of the high temperature plasma furnace using the gas tunnel type plasma jet.

RESULTS AND DISCUSSION

Thermal Efficiency of Plasma Furnace

Figure 2 shows the results of measurements of thermal efficiency of the Ar plasma furnace. The experimental conditions were: input power to plasma torch of P = 21 kW, and working gas flow rate of Q = 200 l/min. In this experiment, the pressure in the furnace was changed from atmospheric pressure to low vacuum (about 40 hPa).

The thermal efficiency of the plasma furnace increases slightly as a pressure in the furnace is decreased. The value of the efficiency is about 80% at the pressure less than p = 100 hPa. This value is much higher than that of the conventional type of plasma jet which is about 50%.

The dependence of the efficiency on the power input was also measured, and it was proved that the thermal efficiency of this furnace increased gradually with an increase in power input. It achieved a thermal efficiency of 84% at P = 30 kW.

Figure 3 shows the thermal efficiency of the plasma furnace, for the case that the working gas was changed from argon (Ar) to nitrogen (N2). The thermal efficiency was measured at various nitrogen mixing rates: ***R***. Input power to the plasma torch changed from P = 21 kW to 18 kW. The working gas flow rate was Q = 150 l/min, and the pressure in the furnace was p = 30-40 hPa.

This result shows that the thermal efficiency of the plasma furnace increases slightly as the nitrogen mixing rate increases.

In the case of argon plasma, the value of the efficiency was about 80% at a pressure of p = 40 hPa with P = 20 kW. The efficiency was not changed at low nitrogen mixing rates, less than R = 50%.

As the nitrogen mixing rate increased beyond R = 70%, the thermal efficiency was increased a little. In the case of a full nitrogen plasma, the value of the efficiency reached a high value of about 82% at a pressure of p = 40 hPa with P = 20 kw. The reason was thought to be that the thermal pinch effect of nitrogen gas increased as an increasing nitrogen mixing rate.

Temperature Distribution in Ar Plasma Furnace

Figure 4 shows the distribution of temperature in the Ar plasma furnace, which was obtained by using the high temperature materials. In this case, the melting points of those high temperature materials were respectively 1953 K for Ti, 2903 K for Mo, 3263 K for Ta, and 2323 K for alumina.

In this figure, (a) shows the result at p = 177 hPa and (b) shows, p = 39 hPa. The power input was constant at P = 21 kW. The diameter of furnace tube was 50 mm.

In the case of (a): p = 177 hPa, the furnace temperature was about T = 2000 K at the axis of l = 100 mm judged from the melting point of Ti. Moreover, in the case of (b) : p = 39 hPa, it was found that the furnace temperature at the center is more than 3000 K. For the comparison this value is indicated as a black circle in Fig. 4.

At p = 39 hPa, even the temperature at l = 200 mm is more than 2000 K. In this case, the high temperature region is expanded to much longer distance. The estimated plasma flame is shown in the same figure.

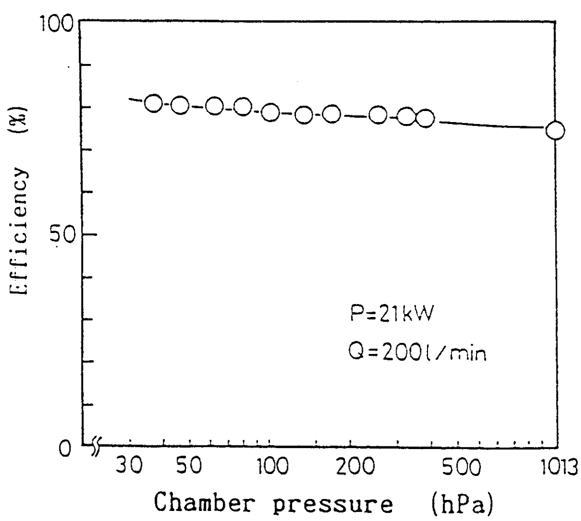

Fig.2 Dependence of thermal efficiency of the Ar plasma furnace on pressure in the furnace.

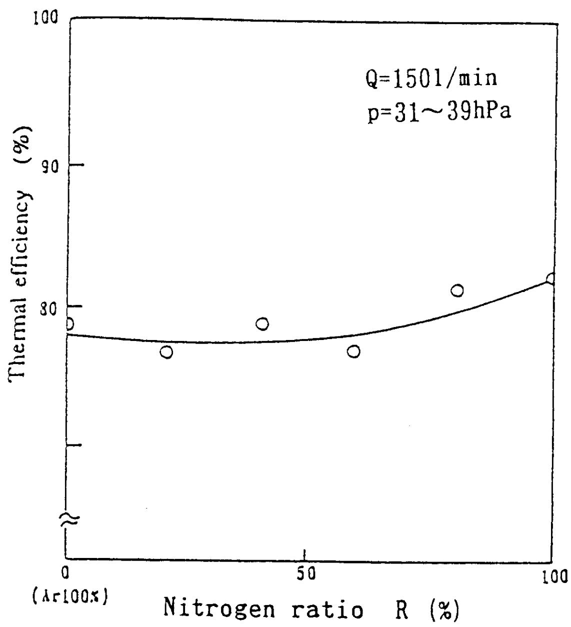

Fig.3 Thermal efficiency of the plasma furnace at various nitrogen mixing rates: ***R***.

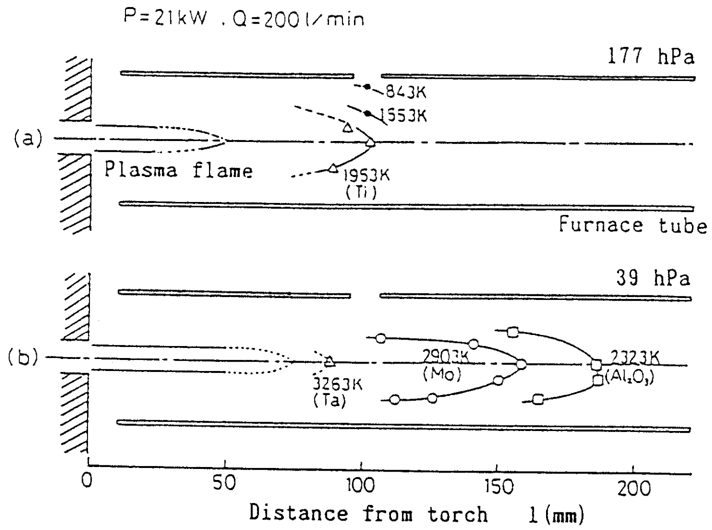

Fig.4 Distribution of temperature in the Ar plasma furnace at different pressures.

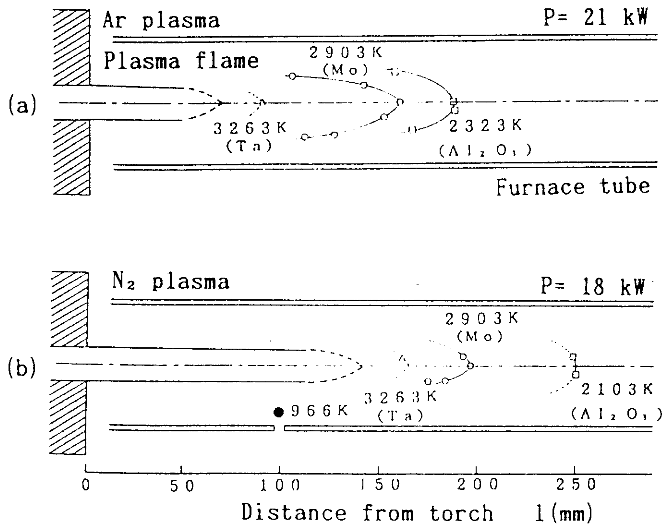

Fig.5 Distribution of temperature in the furnace at p = 39 hPa. (a): argon plasma furnace, (b): nitrogen plasma furnace.

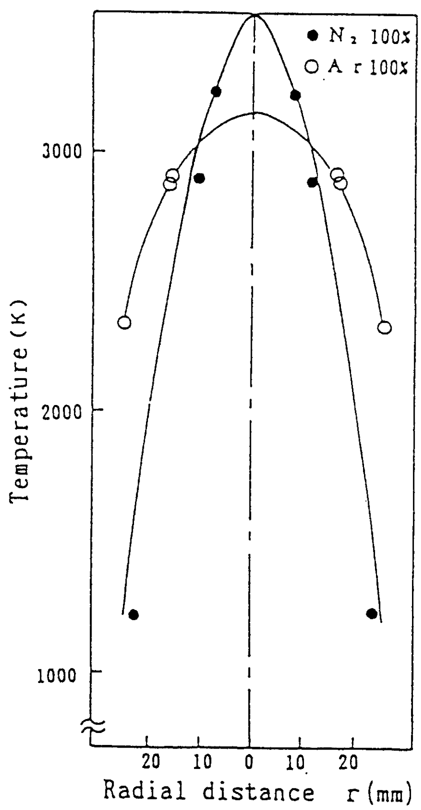

Fig. 6 Radial distribution of temperature in the furnace at l = 120 mm.

At the distance l = 100 mm, r = 10 mm, the temperature is 1500 K in the case of p = 177 hPa, but T = 2900 K in the case of 39 hPa. This confirms that, the high temperature region also expands in the radial direction.

Temperature Distribution in N2 Plasma Furnace

Figure 5 shows the distribution of temperature in the N2 plasma furnace. It was obtained by using the high temperature materials, Ti, Mo, Ta, and alumina.

In this figure, (a) shows the result for the argon plasma furnace and (b) that for the nitrogen plasma furnace in the case of pressures of p = 39 hPa. The power input was P = 21 kW for (a), 18 kW for (b).

For both cases, the temperature in the plasma furnace was more than 3000 K at l = 100 mm on the furnace central axis. (The temperature was more than the melting point of Mo.)

In the case of the nitrogen plasma furnace : (b), the temperature was much higher than for the argon plasma furnace. Consequently, the temperature at l = 150 mm on the furnace axis exceeded the melting point of Ta : 3263 K.

Moreover, in the case of the nitrogen plasma, the temperature was nearly 3000 K at l = 200 mm on the furnace central axis,. And the high temperature region was expanded to longer distances. The plasma flame of nitrogen appeared to become longer as is shown in this figure.

The radial distribution of the temperature in the furnace at l = 120 mm is shown in **Fig. 6**, measured under the same conditions as Fig.5.

At the axis, the temperature was more than 3000 K for both argon and nitrogen. The temperature of the nitrogen plasma was about 3500 K, which was 400 K higher than the argon plasma (T = 3100 K).

However the diameter of temperature distribution of the nitrogen plasma was much smaller than for the argon plasma. For instance, in the case of argon plasma the diameter of the region of T = 2000 K in argon was 48 mm, which was 25% larger than in the case of nitrogen plasma.

Surface Nitriding of Titanium Material

The surface nitriding of titanium material was carried out using nitrogen plasma furnace. TiN film was formed in a short time of 30 seconds. **Figure 7** shows the photomicrograph of the cross section of a titanium nitride (TiN) film observed by an optical microscope. The experimental condition was as follows: P =24 kW, p = 42 hPa, l = 150 mm, and t = 25 s.

This TiN film was 5 μm in thickness. And the surface color was gold color. The Vickers hardness on this surface was about Hv=1000, which was much higher than the original hardness of the titanium substrate (Hv=300).

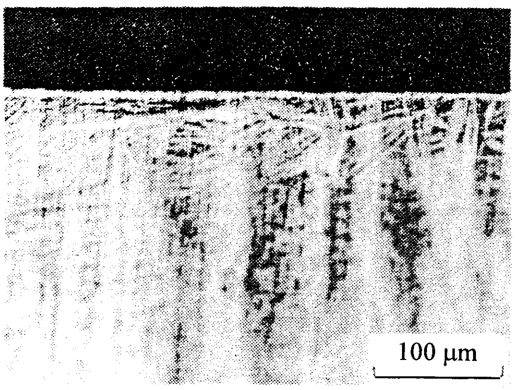

Figure 7 photomicrograph of the titanium nitride (TiN) films.

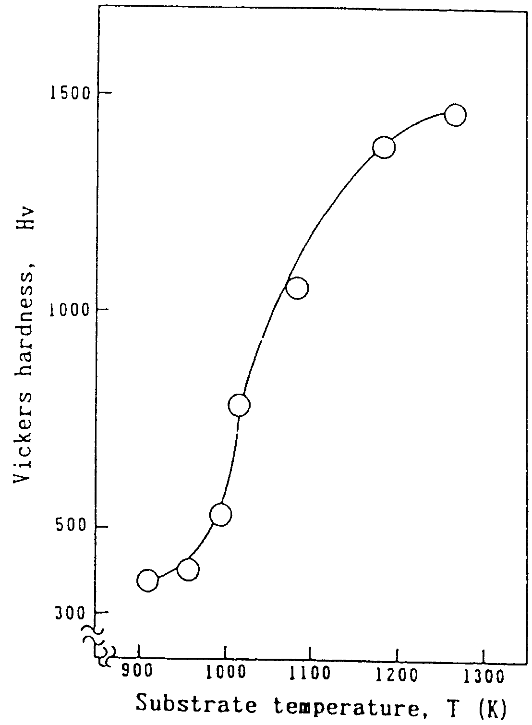

Figure 8 Vickers hardness of the titanium nitride (TiN) films.

Figure 8 shows the dependence of Vickers hardness of the titanium nitride (TiN) films on the substrate temperature. In this case, the temperature was measured on the back surface of the stainless steel substrate.

The Vickers hardness on this surface was more than Hv=1500 at 1300 K of the substrate temperature. The thickness of the TiN film was about 10μm. This condition was achieved at the radiation distance of l = 100 mm and irradiation time of t =30 s.

CONCLUSION

In this study, the high-energy plasma jet: gas tunnel type plasma jet was used as a heat source of the furnace and a new type of high temperature plasma furnace was developed as a furnace for multi purpose use. The performance of this plasma furnace was investigated and the following results were obtained.

(1) The thermal efficiency of the Ar plasma furnace increases slightly as a pressure in the furnace is decreased. The value of the efficiency is about 80% at the pressure less than p = 100 hPa.

The thermal efficiency increased slightly with increase in the nitrogen mixing rate. The efficiency for nitrogen plasma was about 82%; a little higher than the case of argon plasma.

(2) The Ar plasma furnace temperature at the center axis of l = 100 mm is more than 3000 K at the pressure of p = 40 hPa. The radial distribution of argon plasma was broader than the case of nitrogen plasma.

(3) In the case of nitrogen plasma furnace, plasma flame was longer than the case of argon plasma. For nitrogen plasma the maximum temperature was about 4000 K at the center of furnace tube within l = 100 mm.

(4) As an application of this nitrogen plasma furnace, the experiment for the surface nitriding of titanium materials was carried out in order to form a TiN coating. It was proved that TiN film of 10 μm thickness could be formed in a short time within 30 seconds. The Vickers hardness on this surface was more than Hv=1500, which was much higher than the original hardness of the titanium substrate (Hv=300).

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