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100 kW DC Arc Plasma Jet CVD System for Low Cost Large Area Diamond Film Deposition

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In the present paper, a new type of DC arc plasma torch is disclosed. The principles of the new magnetic and fluid dynamic controlled large orifice long discharge tunnel plasma torch is discussed Two series of DC Plasma Jet diamond film deposition equipment have been developed. The 20 kW Jet equipped with a Φ70 mm orifice torch is capable of depositing diamond films at a growth rate as high as 40 μm/h over a substrate area of Φ65 mm. The 100 kW high power Jet which is newly developed based on the experience of the low power model is equipped with a Φ120 mm orifice torch, and is capable of depositing diamond films over a substrate area of Φ110 mm at growth rate as high as 40 μm/h, and can be operated at gas recycling mode, which allows 95% of the gases be recycled. It is demonstrated that the new type DC plasma torch can be easily scaled up to even higher power Jet. It is estimated that even by the 100 kW Jet, the cost for tool grade diamond films can be as low as less than $4/carat.

Key words : Diamond films, DC Arc Plasma Jet, Torch, Economics

I. Introduction

Large scale production of CVD diamond wafers at low cost is the key issue for industrial applications of diamond films. Of the very many deposition methods, high power DC Arc Plasma Jet is generally considered as the most promising technique.[1] However, the conventional design of plasma torches based on the technologies of plasma thermal spray or high power industrial arc-heaters suffer the disadvantages of high gas consumption, low heat efficiency, the complicity and high investment of the equipment, and the most of all, the difficulties for large area uniformity of diamond deposition. In the present paper, a new type of CD arc plasma torch is disclosed. The principles of the new magnetic and fluid dynamic controlled large orifice long discharge tunnel plasma torch is discussed. Preliminary results of large area diamond deposition and the cost of tool grade diamond wafers using the new torches are presented.

II. Principles of the New DC Arc Plasma Torch

1. Principles of DC Arc Plasma Jet CVD diamond deposition

DC Arc Plasma Jet CVD diamond deposition is schematically shown in Fig. 1,[2] where the torch consists of a cathode which is usually made of W-Ce alloy rod, and an anode which is usually made of oxygen free copper. In the early work, the design of the most plasma torches used for diamond deposition was simply copied from that for plasma thermal spray and plasma cutting and welding which is very similar in principle to that shown in Fig. 1. Apparently the carbon source can not be introduced from the top of the torch (which is required for chemical uniformity of the plasma jet), otherwise deposition of carbon onto the inner surface of the discharge tunnel will cause serious problems to the contamination of the growing film and the instabilities of the arc discharge. Therefor, the carbon source is usually introduced at the lower part (or even outside the anode nuzzle) of the torch.[3] However this will in turn result in serious problem in dynamic mixing of the cold carbon source stream with the hot high speed plasma jet, particularly when the diameter of the nuzzle orifice is large. According to the principles of fluid dynamics, the cold carbon source stream will not mix with the hot jet immediately but to first form a cold sheath surrounding the hot plasma jet and make the jet to shrink. Besides, plasma torches for thermal spray and plasma cutting are usually operated at low voltage and high current. On scaling up to high power jet, extremely high current will eventually make the design technically impractical, and or cause excessive consumption of the W-Ce cathode, which in turn cause serious contamination problems to the growing diamond films.

One way to overcome this obstacle for large area deposition of diamond films by DC plasma Jet is to simply

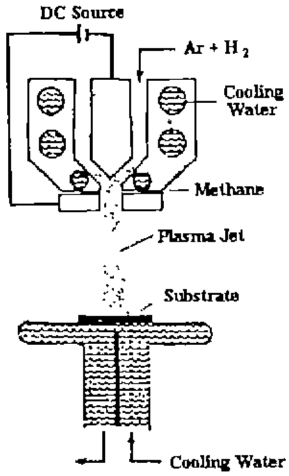


Fig. 1. Schematic diagram of DC Plasma Jet CVD diamond deposition system.

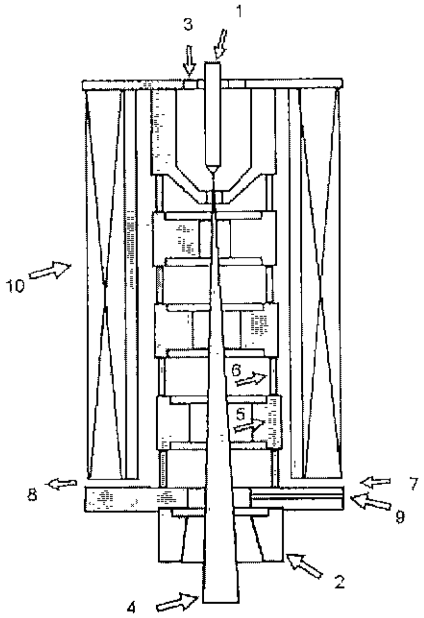


Fig. 2. Schematic diagram for a magnetically stabilized DC arc plasma torch operating at higher voltage. The numbering denotes: 1-cathode, 2-anode, 3-inlet for Ar+H_2, 4-the plasma jet, 5-spacer ring, 6-insulator ring, 7-water in, 8-water out, 9-inlet for carbon source (CH_4), 10-magnetic coil.

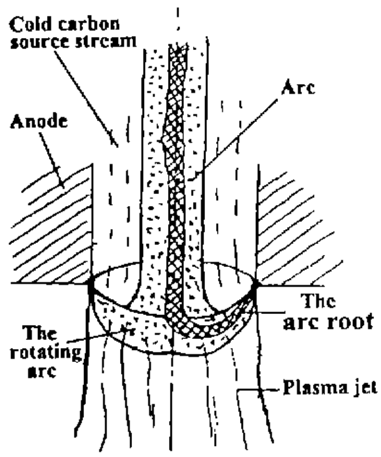


Fig. 3. Schematic of rotating are which can offer good large area uniformity both for composition and temperature distribution of the plasma jet.

scan the jet over the substrate by using a X-Y specimen stage.[4] However, this is detrimental to high quality diamond growth, since the conditions for steady state growth can not be satisfied. And, in order to obtain high mass deposition rate, high power plasma torch is still needed.

The novel design of one cathode three anode DC plasma torch by Yoshikawa *et. al*[5] offered better solution both in higher operation voltage and better mixing of the carbon source. However, the complexity of the design will probably limit its scale up capability.

2. *Principles of the new magnetic and fluid dynamic control DC Arc Plasma Torch*

One way for constructing high power DC plasma jet is to increase the operation voltae and maintain the current in the reasonable level. This can be easily realized by our previous design schematically shown in Fig. 2,[6] which, in principle, is similar to the conventional high power industrial arc heaters, but having the advantages of low gas consumption and high heat efficiency. Because the arc discharge tunnel is relatively long, in order to stabilize the arc, an externally magnetic field must be applied. However, for large outlet orifice, the problem of dynamic mixing of the cold carbon source stream to the hot plasma jet still remain unsolved.

We have successfully solved this technical problem by proper control of the externally applied magnetic field and the characteristics of fluid dynamics as shown schematically in Fig. 3. Where it can be seen that the cold carbon source stream forms a cold sheath surrounding the hot plasma jet before passing through the outlet orifice of the anode. If we can exactly locate the root of the arc at a fixed position and rotate the arc steadily at a fixed loci and at a proper speed, then the cold stream will be heated rapidly to very high temperature and the expanding of the cold gas will result in dynamic mixing with the central hot plasma, and further more, the rotating arc will effectively stir the hot gas mixture, so as to markedly improve the composition uniformity of the plasma jet passing through the orifice. By our experience, this is achievable, and what is more, we can also exactly control the shape of the rotating arc, so that to achieve large area temperature uniformity as well. The above mentioned technology has already been patented.[7]

III. The 20 kW DC Arc Plasma Jet CVD Diamond film Deposition System

The 20 kW DC plasma jet CVD diamond deposition system equipped with the new type of plasma torch is shown in Fig. 4. The novel design of the torch is compared to the conventional torch for plasma cutting of steel sheets in Fig. 4(b), whilst the typical 'W' shaped rotating arc is shown in Fig. 4(c), by which large area uniformity of temperature distribution can be achieved.

The overall performance of this system is as follows:

Plasma torch:

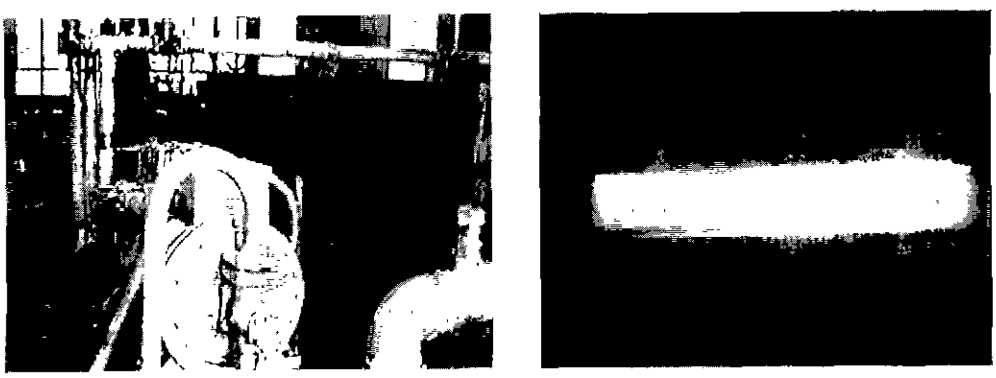
Output power:	10-15 kW
Operation voltage:	90-140 V
Anode orifice:	30-80 mmΦ
Gas consumption:	Ar: 15-20 l/min
	H_2: 9-14 l/min
	CH_4: 50-800 ml/min
Heat efficiency:	~70%
Substrate size:	70 mmΦ miximum
Deposition rate:	300 mg/h (1.5 carat/h)
Thickness uniformity:	≤±15%
Carbon conversion rate:	~10%
Safety:	protection for power, water and vacuum failure
Power requirement:	AC 240V, 3 phase, 20 KVA
Cooling water:	20-40 l/min
Weight:	~700 Kg

*Heat efficiency is defined as the ratio of the heat flow from the torch nuzzle to the deposition chamber to the

(a) 20 kW DC plasma jet CVD diamond deposition system (b) new type plasma torch (left) as compared to conventional torch for plasma cutting (right) (c) 'W' shaped rotating arc, a dark filter was used for taking the photograph

Fig. 4. The 20 kW DC plasma jet CVD diamond deposition system.

(a) the main system (b) part of the gas recycling system



(c) part of the cooling water recycling system (d) plasma jet (the substrate is Φ110 mm)

Fig. 5. 100 kW DC Arc Plasma Jet CVD diamond deposition system.

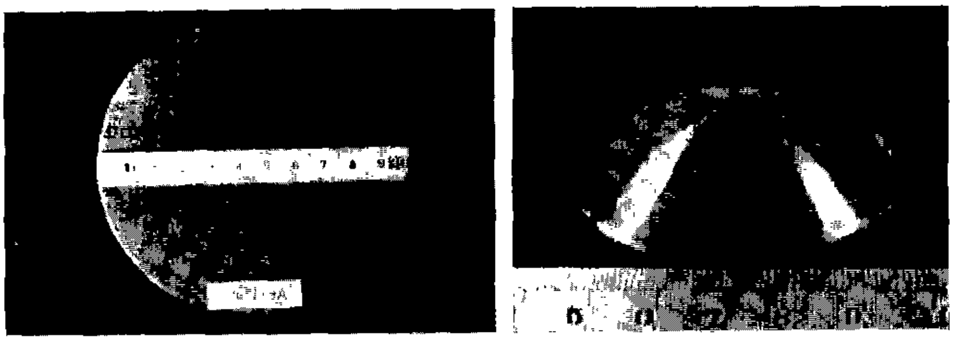


Fig. 6. Left: a Φ110 mm diamond wafer; Right: a Φ60 mm dome produced by the 100 kW Jet.

power consumption of the torch.

IV. 100 kW High power DC Arc Plasma Jet Diamond fiom Deposition System

Based on our experience on the 20 kW system, we have successfully developed an 100 kW high power DC Plasma Jet CVD system recently (seee Fig. 5). The 100 kW system is equipped with a plasma torch of a large orifice of Φ120 mm in diameter capable of depositing diamond films over a substrate area of Φ110 mm at a growth rate as high as ~40 μm/h (~8.3 carat/h) with a thickness uniformity less than ±15%. Unlike the 20 kW system, the newly developed 100 kW high power Jet can operate at gas recycling mode by which 95% of the gases can be recycled. In order to reduce the requirement of purification of the recycled gases, oil free pumps are used. And, according to the local law of water resources in Beijing, a cooling water recyling system is also installed. By proper control of the magnetic field and the characteristics of the fluid dynamics it is possible to control the shape and position of the rotating arc so that to achieve the uniformity both in composition and temperature of the plasma jet (see Fig. 5(d)).

A diamond wafer of Φ110 mm and a dome of Φ60 mm are shown in Fig. 6. The 100 kW system is still under trial operation However, the following overall performance is guaranteed:

Plasma torch:

Output power:	10-50 kW
Operation voltage:	90-150 V
Anode orifice:	120 mmΦ (maximum)
Gas consumption at recycling mode:	
	Ar: 6~10 l/min
	H_2: 8~12 l/min
	CH_4: 0.04~1.2 ml/min
Heat efficiency:	>50%
Substrate size:	110 mmΦ miximum
Deposition rate:	~1,7 g/h (8.3 carat/h)
Thickness uniformity:	≤±15%
Carbon conversion rate:	~10%
Safety:	protection for power, water and vacuum failure
Power requirement:	AC 240V, 3 phase, 120 KVA
Cooling water:	fully recycled

V. Cost Analysis

Simple analysis based on the principles described by Bush et. al.[8] showed that the production cost of tool grade diamond wafers can be as low as below $4/carat, even though the capital recovery rate is taken as in 3 years.

Besides, our new type torch can be easily scale-up to even higher power jet, as long as the principles of magnetic field control and fluid dynamics control are properly designed so as to allow stable arc discharging and the exact control of the shape and position of the rotating arc.

VI. Summary

In the present paper, we have disclosed a new type of DC arc plasma torch suitable for low cost large area deposition of diamond films. Magnetic field is absolutely necessary for stabilize the arc discharge when the orifice of the anode is large and the discharge tunnel of the torch is long. In order to achieve both temperature and compositional uniformity of large diameter arc jet, proper control of the magnetic field and the characteristics of the fluid dynamics are of vital importance.

Based on our experience on the 20 kW DC plasma arc jet CVD system, we have built an 100 kW high power DC arc plasma jet, which can be operated at gas recycling mode, and can be used for production of diamond wafers (tool grade) at a low cost below $4/carat

The new type torch can be easily scale-up to even higher power jet as long as the principles of magnetic field control and fluid dynamic control are properly designed.

Acknowledgment

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