Plasma Jet Technology and CVD Diamond

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Introduction

The DC arc plasma jet provides a brute force approach to CVD diamond coating; the gas pressures and flow rates are higher, and the power input is larger, resulting in diamond film grows at rates 10 -100 times greater than with the microwave reactor. The high diamond growth rate achievable with DC arc jet reactor is most likely attributable to the high C and H atom densities present in the plume, thought it is recognized that the predicted C$_2$ concentrations in the plume is such that the C$_2$ contribution to film growth$^1$ cannot be excluded too. Moreover, it is likely that other more abundant carbon containing radical species (i.e. C$_2$H$_2$, C, CH and C$_3$), also contribute to diamond growth$^2$.

The first serious attempt to commercialize the diamond coating technology using the DC arc plasma technique was the joint venture project conducted from 1992 – 1995 by Westinghouse Electric Corporation and SGS Toll Co. Researchers from the University of Minnesota, Department of Mechanical Engineering, were, also, brought into this project with their expertise in plasma torch modeling and plasma chemistry experimentation. The project lasted 3 years, for a total project budget of USA $5.748 millions. The project succeeded in increasing the power of “hot-cathode” plasma torch from 15kW to 100kW, and also developed an integrated gas recycling process that should have eliminated the need for gas replacement$^3$. The JV project team failed, however, in its overall goal to develop a cost-effective process for coating the rotary tools with diamond film. It also failed to increase torch power over 100kW. As a result, Westinghouse discontinued its work on arc plasma CVD for diamond film deposition in 1995. Then General Electric took over the Westinghouse plasma torch design for diamond coating for its own R & D on CVD plasma diamond synthesis, and is probably ahead of other in using the DC arc plasma for diamond coating.

Where is the problem

The basic problem relates to the cost issue of the CVD diamond coating is what if we increase the power of the plasma torch, to activate the CH$_4$/H$_2$ gas mixture we must progressively increase the gas flow rate too. Even if we disregard the difference in the cost of active/reactive gas mixture (cheaper or costly one) it is the shear waste of efficiency if gases pass only once through the plasma gun and than exits the reaction chamber. Being the methane is the only consumable reactant, which contributes to diamond mass yield, and because the overall conversion of methane into diamond carbon does not exceed 1%, the successful solution for gas recirculation is of great

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3 Westinghouse and SGS Tool; “Plasma Technology for Production of Low-cost Diamond Film” in Advanced Materials and Chemicals, 2000, pp. 53-56.

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importance for the overall economy of diamond coating. A 100% of gas recirculation in commercially developed plasma diamond coating technology is mandatory for any further decreasing of the cost of diamond coating.

To make such a recirculation possible, a hot cathode design for a powerful plasma torch is required. Such a commercial solution is not yet available on the market. The problem is in the construction of the very cathode, which would enable the arc to work in a specific hot regime. Obviously it wasn’t Westinghouse hot cathode design, neither is the METCO or Taffa plasma torch design that use different principle to increase the power of plasma plume, and haven’t been used for diamond coating. They suffer from the same shortcoming the Westinghouse design does. They cannot provide the genuine hot cathode condition for creating the high energy plasma plume, required for faster diamond coating, and therefore cannot bring the substantial cost saving. The cost saving in diamond deposition should, also, come from a much efficient use of Methane through a fully integrated recirculation of the reaction gas through the reaction chamber and plasma gun system. Such an integrated system hasn’t been developed yet because no powerful plasma torch is available to test the operative parameters of the proposed principles for gas recirculation.

Why Plasma Jet technology stands out of others

*Plasma Jet Co* has developed an originally designed plasma torch for the diamond deposition, which implies considerable technological advantages in comparison to all other technical designs that have been developed in last two decades, aiming diamond coating.

The construction of the plasma gun for diamond coating is quite different than construction of the gun for plasma spray coating. In the case of diamond coating it must be specific hot cathode designed torch. This design is also preferable in plasma spray coating, for some coating materials, while all other technological characteristics are different than those applied in diamond coating. On other words, the gun for plasma spray coating cannot be used for diamond coating. Therefore, the construction of plasma gun for diamond coating requires further R&D. However, *Plasma Jet Co* has got the heart for such a gun construction, and it is the unique hot cathode design concept applied in construction of PJ -100 plasma spraying gun⁴.

An interesting part of talk the inventor of PJ-100, conducted with Russian scientist and inventor Spitsyn during his visit to Belgrade in 1996 is quite reflective of the nature of the PJ-100 plasma torch design. This heart-to-heart conversation illuminates, also, the passion that both inventors shared for the R&D work on CVD diamond deposition. While they chatted about Mr. Vilotijevic PJ-60 plasma torch design, and its capacity for further plasma power increase, distinguished Russian suggested: “Migi (the nick name of Mr. Vilotijevic) you have to make it revolutionary, do not go in it evolutionary”. It sounded to me as he already sensed that I just was doing that. Yet, it wasn’t clear to Spitsyn how I was able to make the PJ-60 plasma torch, and only when I explained that I had to start from the very scratch, he became less suspicious, and explained how he himself, while he was pioneered CVD diamond deposition process in the sixties, had to do the same; starting from almost nothing.

⁴ Comparative outline of the PJ-100, the Sulzer-METCO and TAFA gun
The construction of new PJ -100 plasma gun enables the designing of more powerful torches that will be able to work with the voltage up to 500V and amperage up to 600A, with the ascending U – I characteristics. Such a powerful PJ-200 or PJ-300 would work with the OHMic regime; when cathode became a true hot cathode. The hot cathode design embodied in the PJ-100 plasma torch gives an excellent stability to the plasma plume emanating from the simplified technical and engineering solution for a powerful torch.

A massive commercially viable synthesis of CVD diamond from a gas mixture in which, usually, Argon counts for approx 94% of gas mixture, while only 10% of Methane in Hydrogen counts for the rest of 6% in the gas mixture, is impossible. Furthermore, within such plasma gas–active gas system, where the Hydrogen and Methane are injecting into Argon’s plasma plume, there is no possibility for any gas recirculation. And all these constraints are due to the lack of the plasma power produced by existing plasma gun designs, which simply do not allow a richer gas mixture to be processed into deposited diamond.

In the case of PJ-100, and needless to say it for PJ-200 or PJ-300 torches, for the powered U - I guns, the ratio of Argon : Hydrogen : Methane in the input gas mixture is quite different from the gas mixture that all other DC-arc plasma guns can employ. The ratio of Argon : Hydrogen : Methane, which Plasma Jet Co gun can utilize for CVD synthesis of diamond is conducive for much higher diamond deposition rate, than it has been processing-able by other plasma torch designs. On other words, the situation is quite different in the case of the PJ -100 specific hot cathode design. Characteristics of this design principle are as following:

- The length of the arc is fixed, and cannot be shorter than the predetermined.
- The considerably higher working voltage up to 500V and the current up to 600A.
- The gas flow is co-linear with the arc trajectory, all the time, enabling very homogeneous heating of the active/reactive gas mixture (CH₄ and H₂), providing the best condition for synthesis.
- The plasma speed and temperature are higher than with any other DC arc plasma torch. Speed measured at the end of plasma plume is 1,800m/s.
- Plasma torch runs under the rising U/I feature (OHMic mode), giving excellent working stability and lower power loss in the leads, and therefore gives an engineering simplification as a bonus.

Those major improvements are conducive to a plasma gas mixture much richer in active – reactive (Methane – Hydrogen) mixture to be processed in the carrying Argon plasma gas. This favors much higher diamond deposition rate.

**Economy of diamond coating**

The important commercial niches have been clearly shown for diamond film application, and diamond coating technology has matured to the point at which exploitation will depend on individual companies and investment capital. A wider use of diamond coating in a range of commercial applications, including optics, acoustics, medicine, electronics, tooling and hard coatings hasn’t been so far

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5 Sulzer-METCO, TAFA and Westinghouse versus PJ-100 Gun – What potentiality others do not have?
successful because of rather high cost for diamond coating. To make the process cost
effective, increased torch power is mandatory. Increased torch power would allow
diamond deposition over a larger area, with each run of the plasma torch, thereby
increasing the production rate. Therefore, the cost per carat of diamond film would be
reduced considerably, because the coating process would need to be repeated fewer
times to coat the same surface area and amount of diamond film. It is achievable by
implementation of an integrated active gas recirculation system, which is enabled by
working with the carrying plasma Argon and active/reactive gas mixture far richer in the
latter components.

Fig. 1 The XRD of diamond deposited at 1100 K and its fracture
Fig. 2 Diamond deposits at different substrate temperatures
Figs 1 to Fig 4 are taken from: M. Vilotijevic and B. Dacic, “Quality of Diamond films dependence on Temperature and Concentration in the DC-Arc Plasma assisted CVD from Ar/H₂/CH₄" The material would be submitted for publishing.
Fig. 4 Raman spectroscopy of diamonds deposited for different concentration of active/reactive gas mixture.