Parametric Effects on the Substrate Temperature Profile in Oxy-Acetylene Flames

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In the oxy-acetylene combustion method, the quality and morphology of the diamond film depends on a variety of factors, including the substrate surface temperature, gas flow rates and their ratio, and substrate position. Due to the nature of the oxy-acetylene flame, surface temperature of the substrate varies in the radial direction. The substrate temperature profile, in turn, is influenced by the coolant flow rate, nozzle size, substrate position on the heat sink, substrate position in the combustion flame, and the total flow rate of mixed gas (acetylene and oxygen). In this article, temperature measurements using fine-gauge thermocouples were made to characterize the influence of these parameters on the substrate temperature profile.

INTRODUCTION TO CVD DIAMOND SYNTHESIS

Diamond is a technologically fascinating material. It has many unique properties, including highest hardness (Knoop hardness ~8000 kg/mm^2), high wear resistance, low coefficient of friction (0.1 in air), high thermal conductivity (20 W/cm K, five times that of copper), chemical inertness, high electrical resistivity (10^{16} Ω cm), optical transparency (at wavelengths > 320 nm), and high sonic speed (7200 m/s), and consequently its synthesis has been for centuries a great scientific challenge.

The unique properties of diamond have enabled its use in a variety of manufacturing applications. Diamond (both natural and synthetic) has long been used to cut, drill, mine, and mill everything from the hardest rock to the softest aluminum. Now synthetic diamond films are rapidly taking on new roles that have the potential to coat aircraft turbine blades, microprocessor chips, surgical instruments, and light-emitting diodes. Potential new uses for diamond films range from supercomputer heat sinks and heat-seeking missile windows to such mundane things as gourmet knives and scratchproof sunglasses.

The growing demand for this unique material has fueled efforts to produce diamond synthetically. The modern era of low-pressure diamond synthesis under metastable conditions began in the 1980s using activated chemical vapor deposition (CVD) techniques. However, the CVD process was limited commercially by its low growth rates (~1 μm/h). Excellent reviews of the synthesis of diamond under metastable conditions have been presented by DeVries [1] and Angus and Hayman [2].

During the past decade a number of activated CVD methods for low-pressure diamond deposition have been developed with the aim of increasing the growth rate [3]. This is accomplished by (1) high-temperature activation [hot filament, laser, arc discharge, arc plasma jet, combustion (oxy-acetylene)]; (2) electric or electromagnetic gas discharge (microwave, radiofrequency, DC and AC); and (3) combined methods (hot filament + microwave, hot filament + DC discharge).

Among the three activated processes for CVD diamond synthesis, the oxy-acetylene combustion approach is particularly exciting in view of its simplicity and low cost of equipment. This method, originally developed by Hirose of Japan in 1988, uses an oxy-acetylene welding torch with a slightly fuel-rich (acetylene) mixture (see Fig. 1 for schematic of the apparatus). The oxy-acetylene flame sketched in Fig. 1 shows three regions: the inner cone bounding the O_2-C_2H_2 flame front; the C_2H_2 feather zone, where excess C_2H_2 burns with O_2, which diffuses into the flame from the surrounding air; and the outside flame, where the CO and H_2 produced in the inner cone and acetylene feather zone are burned to produce CO_2 and H_2O. The flame temperature in the inner cone varies with the ratio, R, of O_2 to C_2H_2 gas flow, from 3162°C for $R = 1.5$ to 2960°C for $R = 0.8$ [4]. The length of the inner cone depends on the total flow rate and nozzle size, and the length of the acetylene feather depends on the flow ratio and total gas flow rate. Diamond growth on the substrate was observed only in the second zone, the acetylene feather. The acetylene feather envelopes the substrate and shields the diamond film from oxidation. As the flame temperatures are very high ($\sim$3000°C), the substrate is cooled by mounting it on a water-cooled copper block in order to provide the appropriate conditions for diamond nucleation and growth. This technique offers a very simple and economical means of synthesizing diamond films. As the diamond growth takes place under atmospheric conditions, expensive vacuum chambers and equipment are not required. The flame provides its own environment for diamond growth, and the quality of the film depends largely on the substrate temperature profile, the gas flow ratio of oxygen to acetylene, and the substrate position. The substrate temperature profile, in turn, is influenced by such process variables as coolant flow rate, nozzle size, substrate position on the heat sink, substrate position in the combustion flame, and total flow rate of mixed gas (oxygen and acetylene). The influence of these parameters on the substrate temperature profile and consequently the morphology and quality of diamond films for this interesting new technique has yet to be fully exploited. In this article the influence of these parameters on the substrate temperature profile will be characterized.

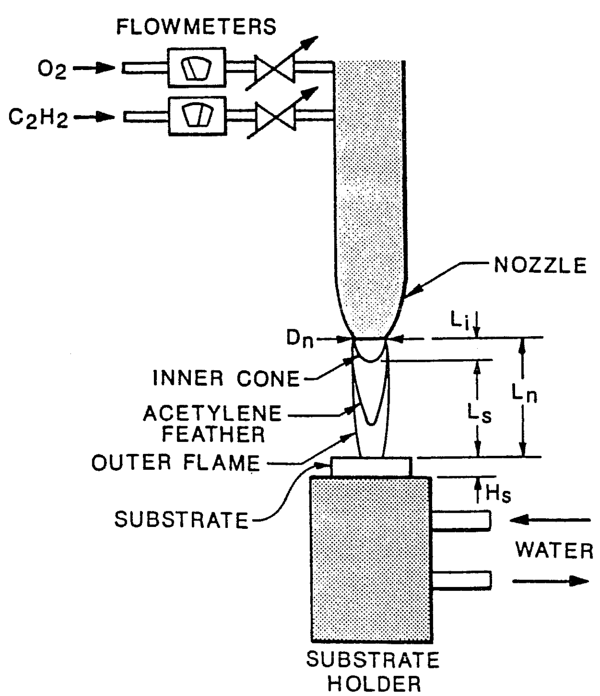


Figure 1 Schematic of the oxy-acetylene experimental setup.

BACKGROUND

A brief review of the results of some of the important previous investigations on growth of diamond films by oxy-acetylene combustion method will be presented here.

Kosky and McAtee [5] found that formation of solid carbons from gaseous carbons by condensation is dependent on the ratio, R, of O_2 to C_2H_2. Figure 2 is a graph of the maximum substrate temperature locus at which solid carbon can form. In fuel-rich flames, that is, where $R \leq 1.0$, carbon (solid state) will deposit on substrate from low to high temperatures. The etching–deposition boundary is very steep near $R = 1$, and for a given flame stoichiometry, relatively small substrate temperature changes will control whether a deposit is produced or an existing deposit is etched. The experimental results of [6–12] showed that the optimal range of R for diamond film deposition was 0.83–1.0.

Hirose et al. [12] made a map of carbon deposition with the oxy-acetylene combustion method in terms of temperature versus gas ratio (O_2/C_2H_2), as shown in Fig. 3. This figure shows a wide temperature range (370–1200°C) and gas ratio range (0.7–1) for diamond deposition. However, for the deposition of transparent diamond films (high-quality diamond film, HQD), the gas ratio

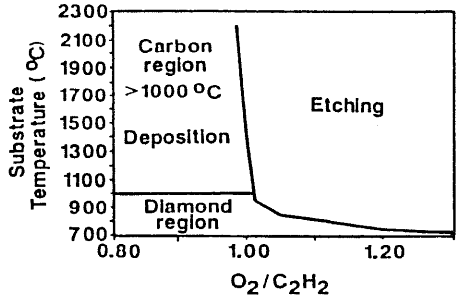


Figure 2 Maximum temperature for carbon deposition at 1 bar as a function of the flame stoichiometry [5].

range is from 0.85 to 0.98 and the temperature range (500–750°C) is much smaller.

The morphology of diamond films and crystals is strongly dependent on the substrate temperature, T_s. Ravi and Joshi [10] found that the deposition of diamond films with cubic morphology (transparent diamond films) occurs when $T_s >$ 1000°C. This result is contradictory to Hirose et al.'s [12] conclusion that the optimal substrate temperature is in the range of 500–750°C for the deposition of transparent diamond films.

Hanssen et al. [7] studied the dependency of morphology on substrate temperature and gas flow ratio ($R = O_2/C_2H_2$). From Raman spectra analysis, they described the conditions of substrate temperature and R for producing facet growth of crystals. No diamond growth happens at $R > 1.1$, regardless of substrate temperature. Based on their results, the limit of substrate temperature for producing diamond crystals increases as R increases.

Oakes et al. [13] measured the substrate surface temperature profile under typical growth conditions using a thermal imaging camera (see Fig. 4), and compared it with the observed inhomogeneities in the diamond crystallite quality. They concluded that the temperature profile on a substrate is one physical property that could contribute to this inhomogeneity. More recently,

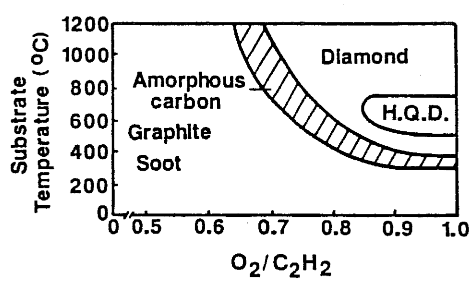


Figure 3 Map of carbon disposition with the oxy-acetylene combustion method [12].

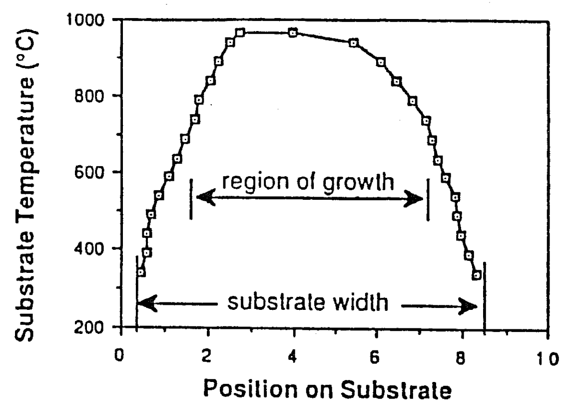


Figure 4 Substrate temperature profile measured with thermal imaging camera [13].

Nandyal [14] observed that the morphology of the produced diamond film varies in the radial direction from the center of the film, as shown in Fig. 5. This figure shows four distinct radial zones of a diamond film, with each zone having a different morphology. However, the substrate temperature profile in the radial direction for these observations was not reported. It may be noted that prior to the present work, Fig. 4 was the only information available in the literature on the substrate surface temperature distribution.

The mole fractions of species in the feather zone of the oxy-acetylene flame are dependent on the distance from the nozzle as well as the radial direction [10, 11, 15]. The cross-sectional area of the diamond film is also dependent on the distance from the nozzle tip. Therefore, substrate position in the flame decides the diamond film deposition area and growth rate.

From the results of investigations discussed here, it is evident that there are at least three apparent primary parameters that influence the

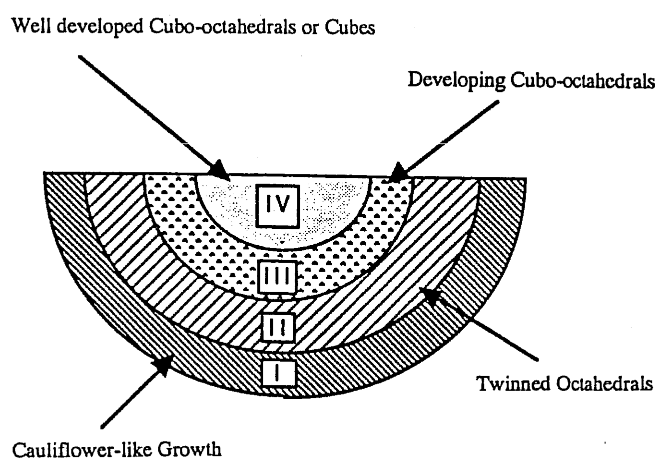


Figure 5 Morphology distribution on a diamond film produced by the oxy-acetylene combustion method [14].

deposition and growth rate of good-quality diamond films. These parameters are the substrate temperature, the gas ratio ($R = O_2/C_2H_2$), and the distance between the nozzle and the substrate. Although there is agreement among investigators on the role of these parameters, there is disagreement on the range of them. The variation in the reported range of these parameters is quite large, considering the fact that the experimenters basically used the same type of experimental setup and had the same objective (deposition of good-quality diamond films). The reasons behind these differences could be attributed to inaccurate substrate temperature profile measurement (as will be discussed later) and lack of consideration of the role of some secondary parameters. For example, the coolant flow rate, the flow rate of oxygen and acetylene mixture, the substrate position in the heat sink, and the nozzle size also play important roles in the oxy-acetylene combustion method. The coolant flow rate plays an important role in controlling the shape of the substrate temperature profile. The gas mixture flow rate (oxygen + acetylene) influences the growth rate of diamond films. An increase in the gas mixture flow rate increases the diamond growth rate due to a large amount of diamond growth (hydrocarbons) and etching (atomic hydrogen) components. Additionally, different flow rates of gas mixture changes flame propagation (length and shape) due to a different gas flow velocity [16]. Nozzle size decides the flame shape. As nozzle size increases with the same pressure of gas mixture at the nozzle exit (flow rate also increases), the shape of the flame becomes wider and longer.

It may also be noted that the parameters (primary and secondary) discussed above are dependent on each other, and only the partial roles of these parameters have been presented in the previous works. Moreover, full information about the experimental conditions (the values of primary and secondary parameters) is not available in the works reported in the literature. This type of information is essential for correct application of the oxy-acetylene combustion method.

SUBSTRATE TEMPERATURE

The majority of investigators using the oxy-acetylene combustion method have used a noncontact temperature-measurement instrument (pyrometer) to measure the substrate temperature. From the operation of a pyrometer, it is clear that the accuracy of the instrument is associated with the emittance calibration of the object whose temperature is being measured. Also, the temperature measurements by a pyrometer are influenced by the target size, area focused, changes of target emissivity with deposition of diamond film, distance between the target and the pyrometer, and the surroundings. Choi et al. [17] reported temperature measurement error from pyrometers during diamond deposition. They observed that temperature measurement error was induced by emittance variation with film thickness change during film growth process. In addition, a pyrometer, due to its inherent limitations, can only detect the temperature of the target area (i.e., the average temperature of the area), not the temperature of a specified point. Most investigators have assumed the measured temperature to be the center temperature of the substrate surface. Furthermore, the area detected by a pyrometer varies with the working distance from the pyrometer to the target. For a typical pyrometer used in most of these experiments (Williamson 8000 series), the smallest target diameter is about 0.64 cm at a distance of 46 cm from the pyrometer. Thus the reported temperatures are actually the average surface temperature of the detected area and not the temperature at a point and could have been influenced by a number of uncontrollable external factors. Moreover, the flame temperature varies with the radial direction as well as with the propagation direction (axial direction). Therefore, the single substrate temperatures reported by almost all of the investigators cannot be the representative substrate surface temperature as long as temperature gradients exist on the substrate surface.

As discussed earlier (see Fig. 5), the radial temperature variation of the substrate surface influences the morphology of diamond films. Therefore, it is necessary to measure accurately the radial temperature distribution of substrate surface to study the radial morphology distribution in diamond films produced by the oxy-acetylene combustion method. This can be accomplished by using thermocouples mounted at various locations on the substrate. Use of thermocouples will reduce the influence of uncontrollable factors on the recorded temperatures.

EXPERIMENTAL SETUP

Figure 1 is a schematic diagram of the oxy-acetylene experimental setup used by most investigators (after [18]). The apparatus consists of asubstrate (molybdenum), a water-cooled substrate holder (copper block), and an oxy-acetylene welding torch fitted with a brazing nozzle. The substrate was mounted on a substrate holder to be cooled via conduction heat transfer through copper block and convection heat transfer by continuous coolant (water) flow. Mass flow controllers (MKS type 2259C) were used to meter the gas flow rates of oxygen and acetylene. A mass flow programmer (MKS type 147B) was used to program the flow rates desired and control the individual mass flow controllers with an accuracy of $\pm 0.8\%$ of full scale. Welders-grade acetylene (99.6% purity grade) and high-purity oxygen (99.9% purity grade) were used as the reactant gases. The torch was mounted on a translation stage for accurate and repeatable positioning of the torch relative to the substrate.

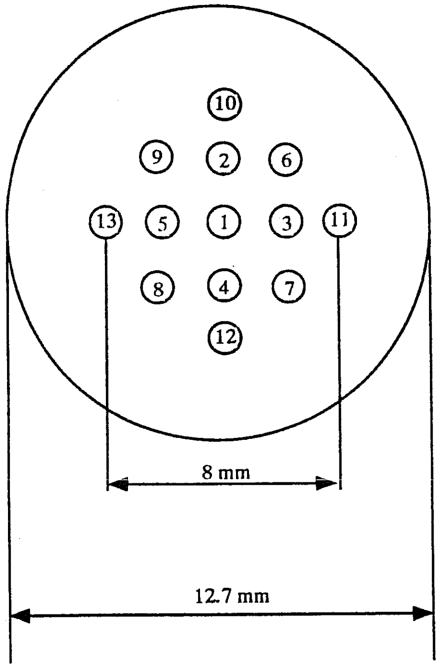
To meet the objectives of this study, the substrate temperature profile, the coolant flow rate and its inlet and exit temperatures, the substrate position on heat sink, the surface temperature of copper block, and the usual parameters for the combustion synthesis method had to be carefully monitored. This required redesign of the substrate and substrate holder (heat sink).

In selecting a proper substrate material for our study, the following aspects were considered: (1) repeatability of experiments (substrate characteristics should not change with each heat cycle); (2) high thermal conductivity (relatively uniform temperature distribution); (3) ease of installation of thermocouples (material hardness); (4) high melting point (substrate should withstand temperatures up to 1400°C for diamond film deposition); and (5) good carbide former.

From the first aspect, a rod type of substrate was chosen because sheet types cause thermal resistance at the interface between the sheet and the contacting substrate holder. Thermocouples were used for substrate temperature measurements. To install a set of thermocouples in the substrate, drilling a number of small-diameter holes (about 1.7 mm) was required. Thus, for drilling purposes, metal materials would make better substrates than nonmetallic materials. Among metals with high melting point, high thermal conductivity, good affinity for carbon, and relatively low hardness, molybdenum was chosen. The size of molybdenum rod used as substrate in these experiments was 12.7 mm in diameter and 31.75 mm in height. These dimensions are consistent with those reported in the literature.

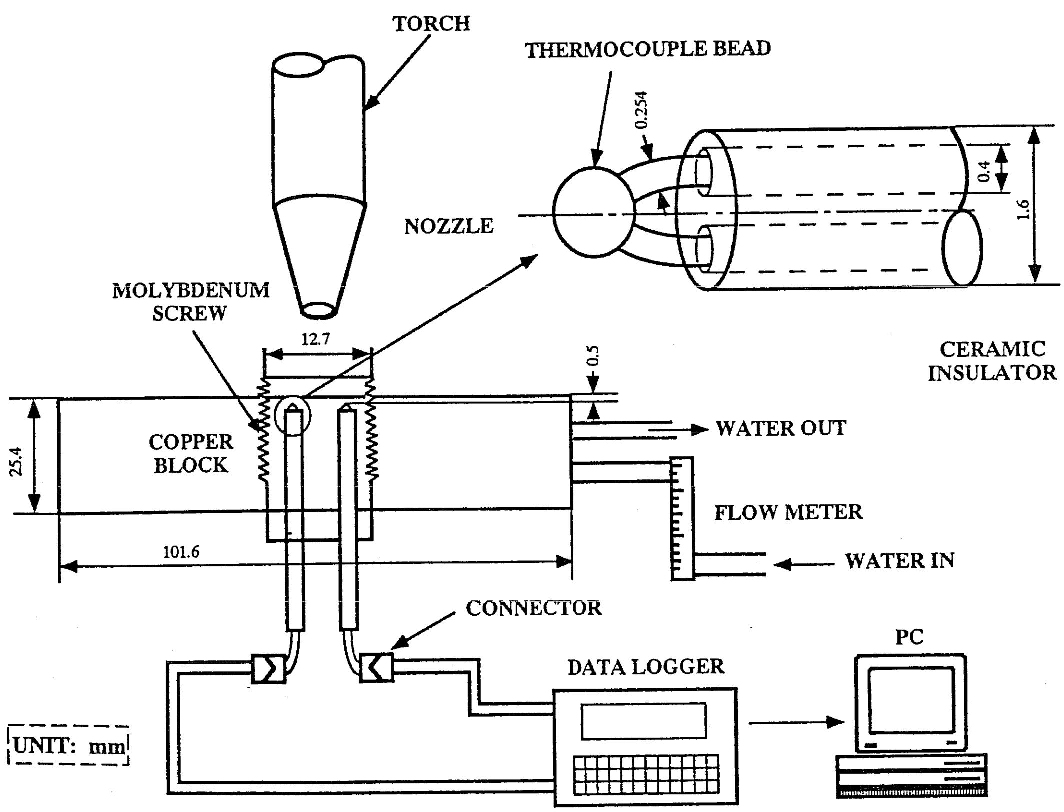
One of the primary objectives of this study was the accurate determination of substrate temperature distribution. As discussed in the previous section, pyrometers do not provide an accurate and realistic temperature distribution of the substrate surface. Therefore, for this study 13 thermocouples with the distribution shown in Fig. 6*a* were used. A numerically controlled milling machine (Bridgeport model Interact 412 with controller Heidenhain TNC 151) was used to drill thirteen 1.7-mm-diameter holes on the back of the molybdenum substrate to a depth of approximately 0.5 mm below the substrate surface. A control program for drilling was developed using a language called DIALOGUE. This program moves the substrate as a workpiece to each hole center, and controls the rpm and the drilling feed rate. Cobalt and high-speed steel drill bits (size #51, 1.7 mm diameter) were used for drilling holes. Unsheathed fine-gauge thermocouples with a bead diameter of approximately 0.63 mm and a wire diameter of 0.254 mm placed in 1.6-mm ceramic insulators (Omega TRX 164116) were inserted through the drilled holes in the back of the substrate. To maintain good contact between the thermocouple beads and the substrate, a specially designed spring-loaded thermocouple holder plate was used. The temperature at stations #1 to #9 (refer to Fig. 6*a*) were monitored with B-type thermocouples (Omega P30R-010), which have a temperature limit of 1650°C and a response time of about 4 s. For the remaining stations, which are near the outer edge of the substrate, if the temperatures were below 350°C then T-type thermocouples (SPCC-010) were used. The thermocouples were monitored with a 40-channel Electronics Controls Design datalogger interfaced with a personal computer. Steady-state temperature readings were taken at 30-s intervals. The measured temperatures were then divided by the run time (usually about 30 min) to give the average temperature for each thermocouple station. Calibration of the thermocouples showed an accuracy of $\pm 1\%$ of the reading for the B-type and ± 0.5°C for the T-type thermocouples.

The molybdenum substrate described above was threaded and mounted at the center of a water-cooled copper block; refer to Fig. 6*b*. The copper block was 10.16 cm in diameter and 2.54 cm in height with a threaded center hole diameter of 12.7 mm (same as the substrate rod). Coolant (water) flowed inside the copper block to dissipate heat from the substrate and upper surface of copper block. The coolant flow rate was moni-



DISTANCE FROM CENTER, mm	THERMOCOUPLE STATION NO.
0.0	1
2.0	2, 3, 4, 5
3.0	6, 7, 8, 9
4.0	10, 11, 12, 13

(*a*)



(*b*)

Figure 6 (*a*) Distribution of thermocouples in substrate. (*b*) Schematic of the overall experimental setup.

tored using a calibrated rotameter with full-scale accuracy of ±2% and full-scale repeatability of ±1%. The inlet and exit temperatures were monitored with two T-type thermocouples. The schematic diagram of the overall experimental setup is shown in Fig. 6*b*.

Table 1 Sample Thermocouple Temperature Data

Distance from center (mm)	Thermocouple station no.	Temperature (°C) for each station
0.0	1	560.3
2.0	2, 3, 4, 5	542.5, 541.5, 543.3, 543.7
3.0	6, 7, 8, 9	537.2, 538.7, 539.0, 538.3
4.0	10, 11, 12, 13	524.4, 524.3, 523.1, 524.6

RESULTS AND DISCUSSION

Table 1 shows a sample of the temperature readings, obtained by the data acquisition system, from the 13 thermocouples used in the substrate for a typical oxy-acetylene combustion experiment. For distribution of the thermocouples, refer to Fig. 6*a*. From the tabulated data it is evident that the substrate temperature profile is symmetric about the center of the surface, and the four temperature readings obtained at the same radial distance from the center but at different locations are very close to one another. For this reason, only seven of the 13 thermocouples were chosen for reporting the substrate surface temperature distribution under different experimental conditions. The remainder of the thermocouples were used for checking the symmetric nature of the profile. The temperature profiles presented in this section (see Figs. 7–12) are based on the thermocouples at stations 1, 2, 4, 7, 9, 10, and 12; refer to Fig. 6*a*.

As discussed in the previous sections, the substrate surface temperature distribution is influenced by a variety of factors, including the oxygen and acetylene flow rates, the substrate position in the combustion flame, the substrate position on the heat sink, the coolant flow rate, and the nozzle size. The influence of these parameters on the substrate temperature profile is shown in Figs. 7–11. The reported experiments were conducted with the centerline of the combustion flame perpendicular to the substrate surface (see Fig. 1), constant ratio of oxygen to acetylene flow rates ($R = 0.98$), and constant oxygen and acetylene cylinder pressures ($P_{O_2} = 10$ psig and $P_{C_2H_2} = 5$ psig). Other experimental conditions specific to a particular experimental run are shown on the figures. The heat transfer rate ($\dot{q}$) labeled on each temperature curve (see Figs. 7–11) needs further explanation. The term expresses the rate of heat transfer to the cooling water from the threaded molybdenum rod (substrate) and copper block (substrate holder). This heat transfer rate was determined from an enthalpy balance on the cooling water.

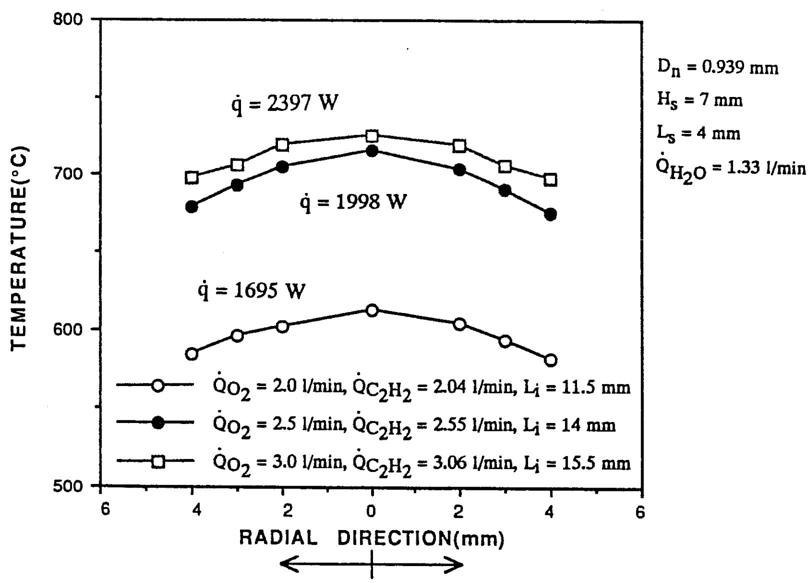


Figure 7 Effect of O_2 and C_2H_2 flow rates on the substrate temperature profile.

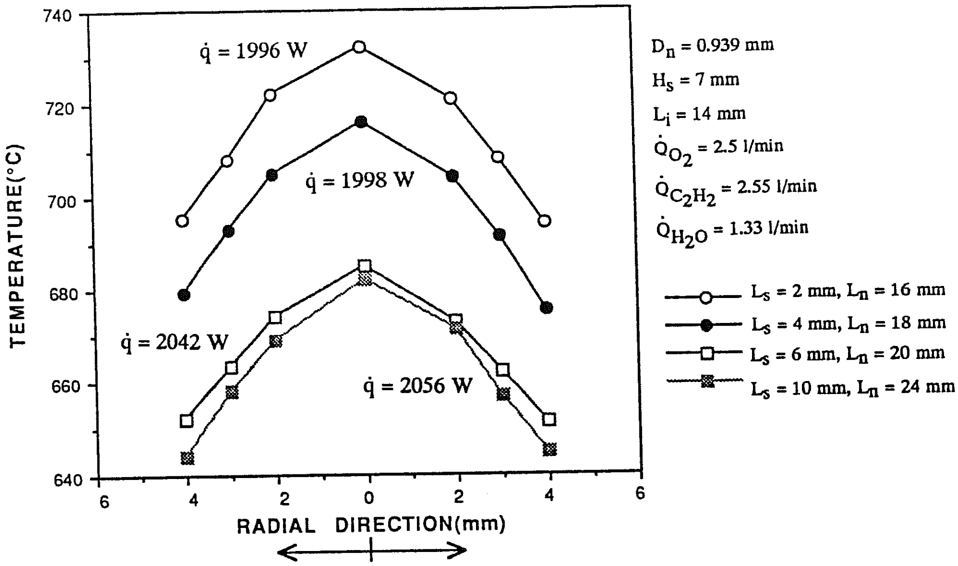


Figure 8 Effect of substrate–inner cone distance on the substrate temperature profile.

The effect of oxygen and acetylene flow rates ($\dot{Q}_{O_2}$ and $\dot{Q}_{C_2H_2}$) on the substrate surface temperature distribution for three different gas flow rates is shown in Fig. 7. An increase in the gas flow rate increases the length of the inner cone (L_i), and results in a higher rate of heat transfer from the flame to the substrate surface. This high rate of heat transfer to the substrate surface causes an increase in the substrate temperature distribution and is supported by the increase in the rate of heat transfer to the coolant ($\dot{q}$), as indicated on Fig. 7. From the results shown, a 50% increase in the gas flow rates is accompanied by roughly a 120°C increase in the substrate surface temperature. However, the resulting temperature profiles are all fairly similar in shape. In these experiments the substrate height (H_s) and the distance between the substrate surface and the inner cone (L_s) were fixed. However, the distance between the surface of the substrate and the tip of the nozzle (L_n) had to vary due to variation in L_i.

Figure 8 shows the influence of substrate–inner cone distance (L_s) on the substrate temperature profile for four different cases. The resulting tem-

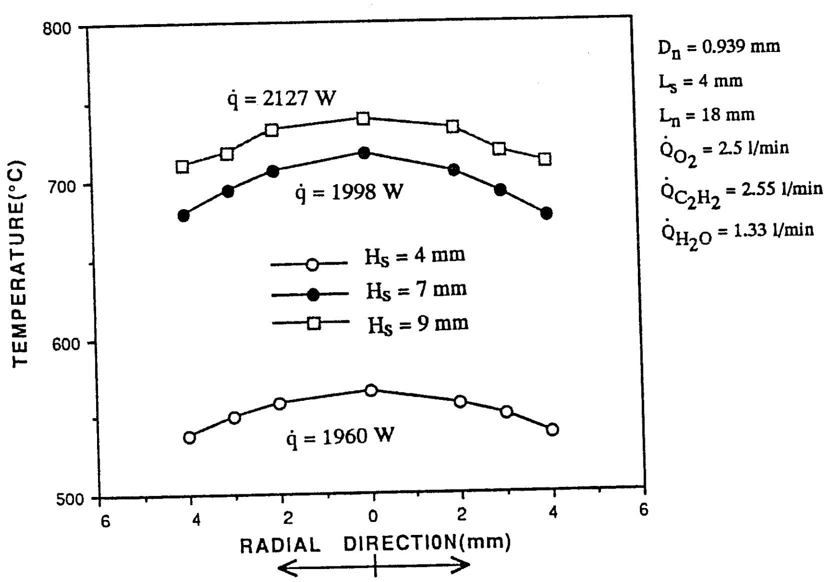


Figure 9 Effect of substrate–heat sink distance on the substrate temperature profile.

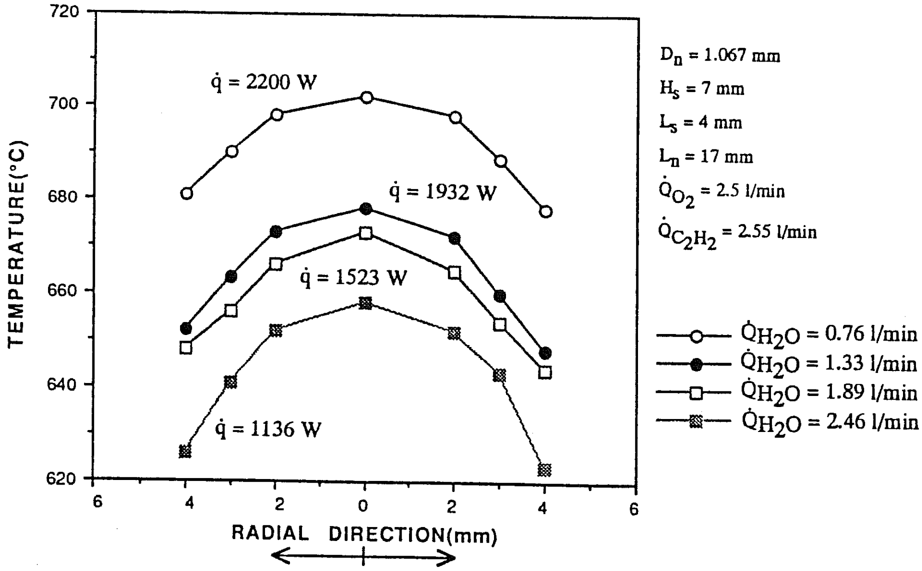


Figure 10 Effect of coolant flow rate on the substrate temperature profile.

perature profiles are very similar in shape. However, the magnitude of the temperature decreases with an increase in the substrate–inner cone distance. That is, the smaller the distance, the higher are the surface temperatures. These higher substrate surface temperatures are due to the closer contact of the substrate surface with the acetylene feather zone of the flame (see Fig. 1). The feather zone temperature is a function of both the radial direction and the flame propagation direction. As the substrate is moved away from the feather zone, the substrate surface temperature decreases. However, from the results presented, it appears that there is a limit to this decrease of substrate surface temperature. The temperature drop from L_s = 6 to 10 mm is very small, indicating that for the conditions of Fig. 8 any further increase in L_s would not change the temperature levels significantly.

Another interesting aspect of results presented in Fig. 8 has to do with the values of rate of heat transfer to the coolant ($\dot{q}$). These values behave opposite to what was reported for the results of Fig. 7. In this case, the coolant heat transfer rates

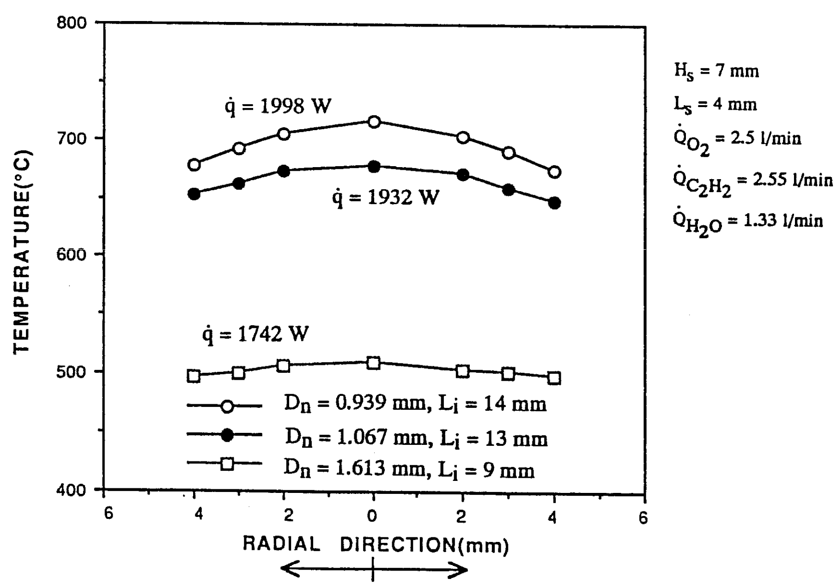


Figure 11 Effect of nozzle diameter on the substrate temperature profile.

increase with decreasing substrate surface temperature. This is due to steep temperature gradients in the radial direction, which gives rise to heat transfer by conduction in the radial direction. This large radial conduction causes an increase in the rate of heat transfer by convection from the heat sink (copper block) to the surroundings. Therefore, for small substrate–inner cone distances, there is less transfer of energy between the substrate and the cooling water.

The effect of substrate–heat sink distance (H_s) on the substrate temperature distribution is shown in Fig. 9 for three different cases. An increase in the distance between the substrate and the heat sink results in an increase in the substrate surface temperature. This increase in temperature is due to less heat conduction through the copper block (substrate holder) because of reduced contact area between the substrate and the heat sink. The shapes of the temperature profiles shown in Fig. 9 are generally similar. However, the comparison of the two close temperature profiles at $H_s = 7$ and 9 mm show considerably less radial temperature gradient for the case with $H_s = 9$ mm. This flatness of the temperature profile is due to additional heat transfer from the exposed threaded surface area of the substrate rod by convection to the surroundings. As the distance H_s decreases, the temperature gradient in the radial direction should increase.

Figure 10 shows the influence of coolant flow rate ($\dot{Q}_{H_2O}$) on the substrate temperature profile for four different cases. As shown, higher coolant flow rates produce lower substrate surface temperatures. The temperature profiles presented in the figure show an increase in the radial temperature gradient with an increase in the coolant flow rate. The reported rates of heat transfer to the coolant ($\dot{q}$) behave similar to those reported in Figs. 7 and 9. That is, the rates of heat transfer to the coolant decrease with decreasing substrate surface temperature. This is due primarily to large radial temperature gradients at high coolant flow rates, which gives rise to large radial conduction along the substrate. Therefore, less energy would be available to be exchanged between the substrate and the cooling water.

The effect of nozzle diameter (D_n) on the substrate temperature distribution for three different nozzle diameters is shown in Fig. 11. An increase in the nozzle diameter is accompanied by a decrease in the length of the inner cone (L_i) and a widening of the feather zone. Thus, for a small-diameter nozzle the heat flux distribution from the flame is more concentrated on the center region of the substrate surface, causing higher substrate surface temperatures. For the largest nozzle diameter used in these experiments, the resulting substrate temperature is fairly uniform. This is due to wide and relatively uniform distribution of flame heat flux over the entire substrate surface.

The results presented in Figs. 7–11 show clearly that changes in the rates of heat transfer from the substrate and the copper block, caused by variations in several parameters, influence the shape and the magnitude of the substrate surface temperature distribution. The synthetic diamond crystals (films) produced by the oxy-acetylene combustion method should have uniform morphology in the radial direction. For this purpose, a relatively uniform temperature distribution across the substrate surface is desirable. That is, the radial temperature gradient across the substrate should be minimized. Another requirement for a successful application of this method is the magnitude of substrate surface temperature. For well-faceted diamond films, substrate surface temperatures greater than 500°C are required [12]. Figure 12 shows that by appropriate combination of the parameters that influence the substrate surface temperature distribution, the desired conditions for producing good-quality diamond films with uniform morphology (i.e., uniform substrate temperature profile at temperatures greater than

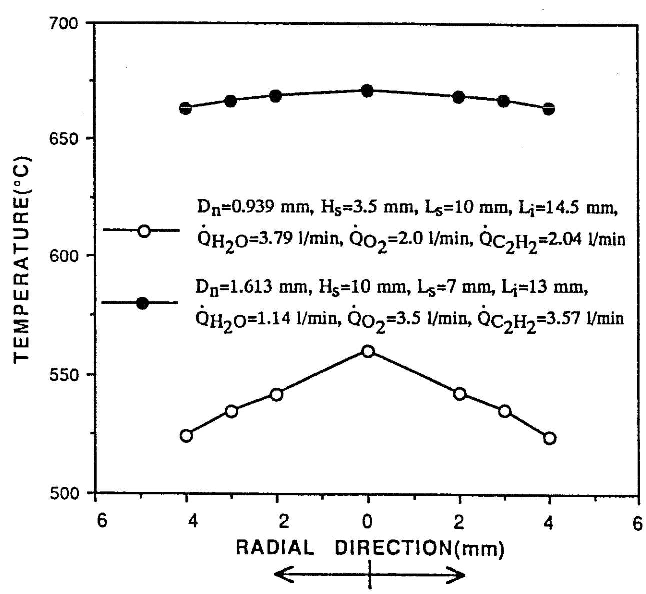


Figure 12 Effect of several parameters on the substrate temperature profile.

500°C) can be developed. The second temperature profile in Fig. 12 shows that only one of the conditions for successful application of diamond synthesis was met. In this case, the temperature levels are high enough to produce transparent diamond films [12]. However, the substrate surface temperature distribution is not uniform. Therefore, because of large radial temperature gradients, the morphology of the diamond film would not be uniform in the radial direction. This emphasizes the importance of the knowledge of radial distribution of the substrate surface temperature for correct application of this method.

It should be noted that there are other means by which the uniformity and levels of substrate surface temperature profile can be controlled—for example, by insulating the exposed threaded surface area of the substrate rod. During the experiments it was observed that large temperature gradients exist at the outer edge of the substrate rod (similar to Fig. 4). Reducing the heat losses from the substrate should help in improving both the uniformity and levels of the substrate surface temperature.

Our future plans are to develop an experimental database on the temperature distribution of the substrate surface as it affects the quality and morphology of the diamond films. The database will be used for development of the necessary relationships between substrate temperature distribution and the parameters that influence the morphology, quality, and deposition of diamond films. The morphological characteristics of diamond films will be examined under a scanning electron microscope, and their quality will be assessed using μ-Raman spectroscopy. The temperature database will also be used for development and verification of a computer model for prediction of substrate surface temperature profile under a variety of operating conditions.

CONCLUSIONS

The experimental technique used in this study established the radial variation of the substrate surface temperature under a variety of operating conditions. The reported results indicate clearly that the shape and the magnitude of the measured substrate temperature profiles were influenced by several parameters. These parameters were the oxygen and acetylene flow rates, the substrate–inner cone distance (substrate position in combustion flame), the substrate–heat sink distance, the coolant flow rate, and the nozzle size. All of these factors contributed to the uniformity or nonuniformity of the substrate temperature profile and the temperature levels at the surface of the substrate. For a desired substrate surface temperature level and shape, it was found that a proper combination of these parameters should be used.

The results of this study are unique in the sense that it is the first attempt at reporting how and why certain parameters influence the substrate surface temperature distribution by the oxy-acetylene combustion method. The ability to control the substrate surface temperature distribution through proper choice of experimental variables is essential to successful application of this method for diamond synthesis.

NOMENCLATURE

c_p	specific heat of water evaluated at the average of inlet and outlet temperatures
D_n	nozzle diameter (see Fig. 1)
H_s	substrate height (see Fig. 1
L_i	length of the inner cone (see Fig. 1)
L_n	distance between the substrate surface and tip of the nozzle (see Fig. 1) ($= L_s + L_i$)
L_s	distance from the substrate surface to the inner cone (see Fig. 1)
$\dot{m}$	mass flow rate of water
$P_{C_2H_2}$	pressure of acetylene in the cylinder
P_{O_2}	pressure of oxygen in the cylinder
$\dot{q}$	rate of heat transfer to the coolant [$= \dot{m}c_p(T_{co} - T_{ci})$]
$\dot{Q}_{C_2H_2}$	volume flow rate of acetylene
$\dot{Q}_{H_2O}$	volume flow rate of water
$\dot{Q}_{O_2}$	volume flow rate of oxygen
R	ratio of volume flow rates of oxygen to acetylene
T_{ci}	cooling water inlet temperature
T_{co}	cooling water outlet temperature

ACKNOWLEDGMENT

Support for this research was provided by the Oklahoma State University Center for Energy Research under grant number 1150748.

A version of this paper was presented at the 1992 ASME Winter Annual Meeting, session on Heat Transfer in Materials Processing, held in Anaheim, California, November 8–13, 1992.

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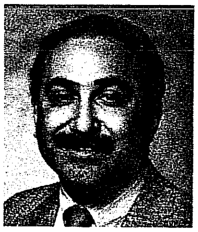

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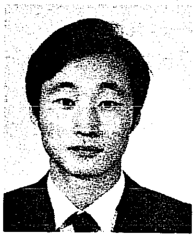

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