Effects of pulsing parameters on production and distribution of macroparticles in cathodic vacuum arc deposition

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The effects of pulsing parameters such as the duty cycles, frequencies, and arc currents on the production and distribution of macroparticles (MPs) were studied. A tunable pulsed arc power supply that could provide either direct current (dc) or pulsed current plus dc was used in the experiments. Copper and titanium were used as the cathodes, and glasses were used as the substrate. Optical microscopy, scanning electron microscopy, and special image processing were utilized to investigate the MPs deposited onto the substrate. Our results illustrate the general trend that the MP density increases with higher dc but decreases with increasing pulsing frequency. There is no obvious relationship between the MP density and the duty cycle at high dc but the MP density obviously increases with the duty cycle at low dc. © *2006 American Vacuum Society.*
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I. INTRODUCTION

The cathodic vacuum arc produces a highly ionized, energetic, plasma stream and is widely used in the deposition of films such as TiN, TiC, and diamondlike carbon (DLC).[1–4] However the generation of macroparticles (MPs) has hindered the use of this method in more demanding areas such as optoelectronics and microelectronics. These macroparticles arise from the plasma-solid interactions at the cathode spot. A cathode spot is necessary in order to provide a sufficient energy density for the formation of the plasma, electron emission, and current between the cathode and anode.[5] The cathodic arc current is localized in minute, nonstationary, cathode spots. The heat generated by the high current density and ion impact induces melting of the cathode materials, resulting in violent evaporation of the locally melted cathode materials as well as appearance of MPs.[6] The sizes of these macroparticles are generally in the range of 0.1–10 μm and there also exist smaller particles called nanoparticles.[7] In order to reduce the number of MPs deposited on the substrate or eliminate the particles from the plasma, many methods have been adopted, such as mechanical filters or electron-magnetic filters. The 90° curved magnetic filter is one of the most successful filters and has been widely researched.[8] It should be noted that although such a magnetic filter can successfully remove the particles from the plasma, plasma loss is inevitable leading to low deposition rate. Therefore, the improvement of the transport efficiency of these filters is important.

In order to decrease the amount of MPs while keeping a high deposition rate, the parameters affecting the production of MPs such as cathode material, arc current, distance, and angle between the cathode and substrate must be well under-

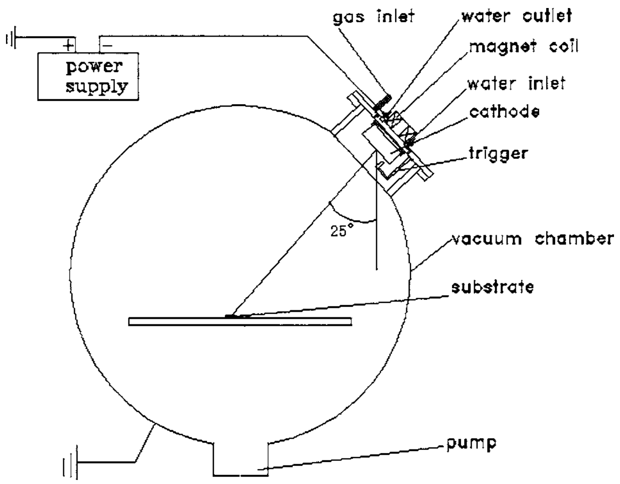

FIG. 1. Schematic of cathodic vacuum arc deposition system.

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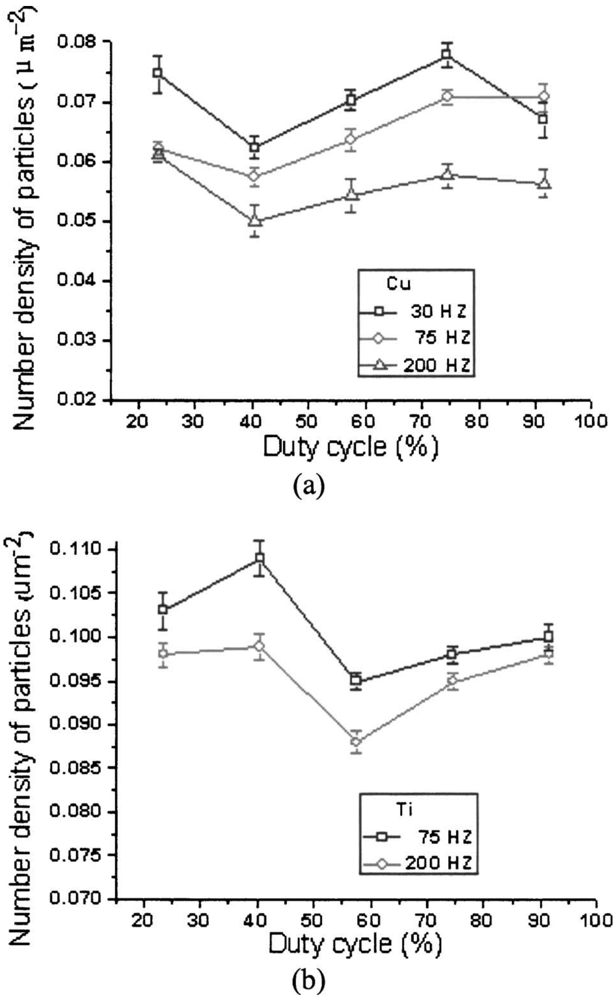


FIG. 2. Number density of particles as a function of duty cycles (peak value of pulsed current=40 A, dc current=70 A). The cathode materials are (a) copper and (b) titanium.

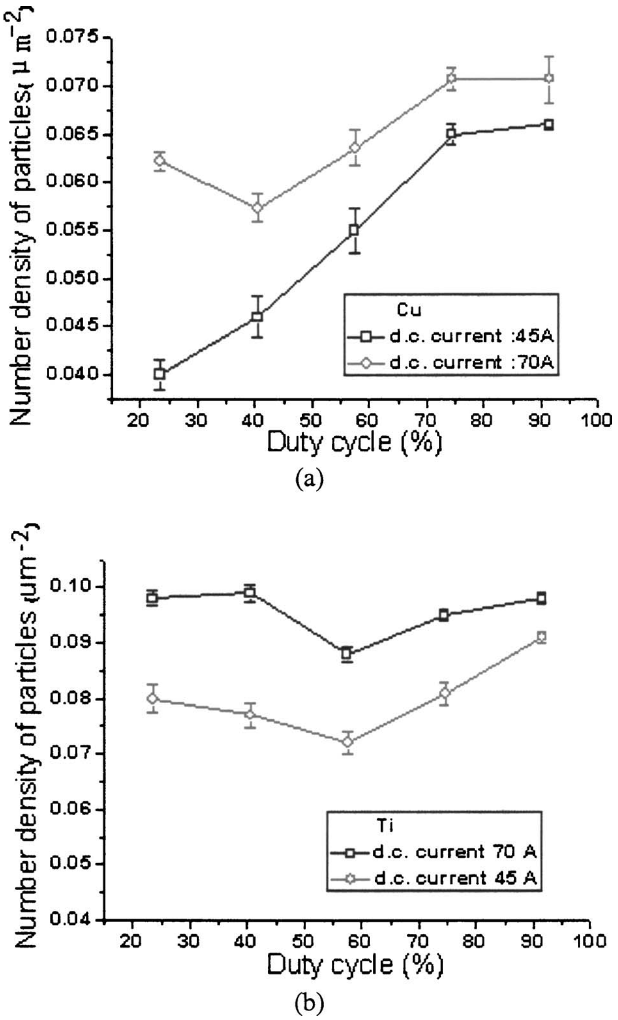


FIG. 3. Number density of particle vs duty cycle for two different dc currents (peak value of pulsed current=40 A): (a) copper, frequency=75 Hz and (b) titanium, frequency=200 Hz.

stood and optimized.[9–12] It has been found that an additional magnetic field can decrease MP production[13] and an appropriate substrate bias can reduce the quantity of MPs impacting the substrate.[14] Siemroth *et al.* have also observed that the number of droplets in high-current pulsed arc (HCA)-deposited films is noticeably lower than that in dc arc-produced films, and the number of large droplets is strongly reduced in HCA deposition.[15] The arc pulse duration time also affects the density of the particles.[9] Ellrodt and Meche have described a pulsed arc evaporation process combining both dc and pulsed cathodic arcs that can provide enhanced stability at low currents and increase the spot velocity.[16] Keutel *et al.* have also observed that the modified pulsed arc source can decrease the MP number and roughness of the films,[17] but the effects of other processing pulsing parameters such as duty ratio and frequency in pulsed arc source (including pulsed and modified pulsed arc source) have not been investigated in details. In this work, the modified pulsed arc source combining the dc and pulsed arcs was used to study the influence of the duty ratio, frequency, and current (dc and pulse) on the production and distribution of MPs and possible reasons are discussed in this article.

II. EXPERIMENTAL DETAILS

The experiments were performed in a cylindrical vacuum chamber 80 cm in diameter and 120 cm in length as shown in Fig. 1. The cathodes with a diameter of 84 mm were composed of 99.99% copper or titanium. The length of the copper and titanium cathodes were 60 and 30 mm, respectively. The substrates were 20×20 mm^2 glass slides placed at about 45 cm from the arc source. The argon partial pressure was about 1.7×10^{-1} Pa. The films were deposited for about 600 s. The power supply was capable of generating independent dc and pulsed currents at the same time. The pulse signals were monitored by an oscilloscope. The deposition was conducted using different currents (dc and pulsed), duty ratios, and frequencies.

These films were analyzed by optical microscopy and scanning electron microscopy (SEM, JSM6460). The number

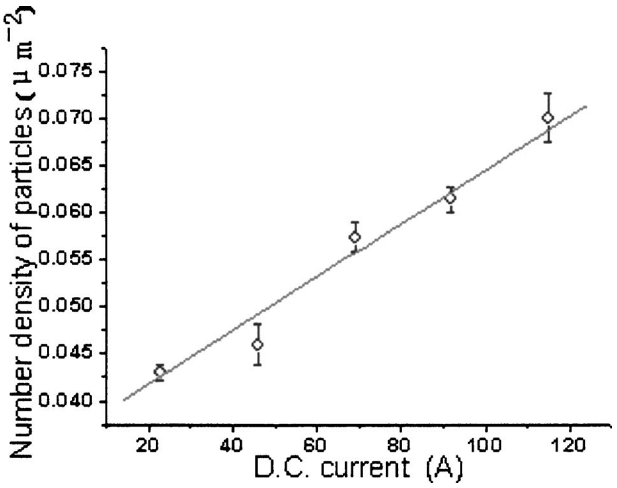


FIG. 4. Number density of copper particle as a function of dc current (peak value of pulsed current=40 A, frequency=75 Hz).

density of the particles was determined by counting the average number of particles over six locations on each substrate. Particles smaller than 0.2 μm or larger than 10 μm were not counted in our algorithm. It is due to the resolution of the equipment used to image the particles smaller than 0.2 μm and that the number of particles with sizes larger than 10 μm is relatively rare.

III. RESULTS

A. Effects of frequencies and duty cycles

The dc and peak values of the pulsed current were kept at 70 and 40 A, respectively, and three different frequencies, 30, 75, and 200 Hz, were used. At each frequency, the duty cycle was varied from 23.5% to 94.5%. Figure 2 shows the number density of particles for the copper cathode [Fig. 2(a)] and titanium cathode [Fig. 2(b)] using different deposition parameters. For both cathodes, the particle density decreases with increasing frequency but exhibits no obvious correlation with the duty cycle although there are minimum values. It should be noted that for the copper cathode, the lowest particles density appears at a duty ratio of 40.5%, whereas the lowest particle density appears at a duty ratio of 57.5% for the titanium cathode.

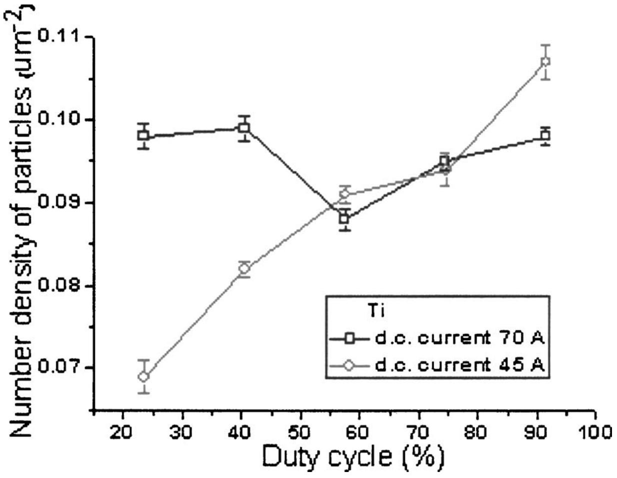


FIG. 5. Number density of titanium particle vs duty cycle for different pulsed currents (dc and pulsed currents are individually adjusted to have the same total current; frequency=200 Hz).

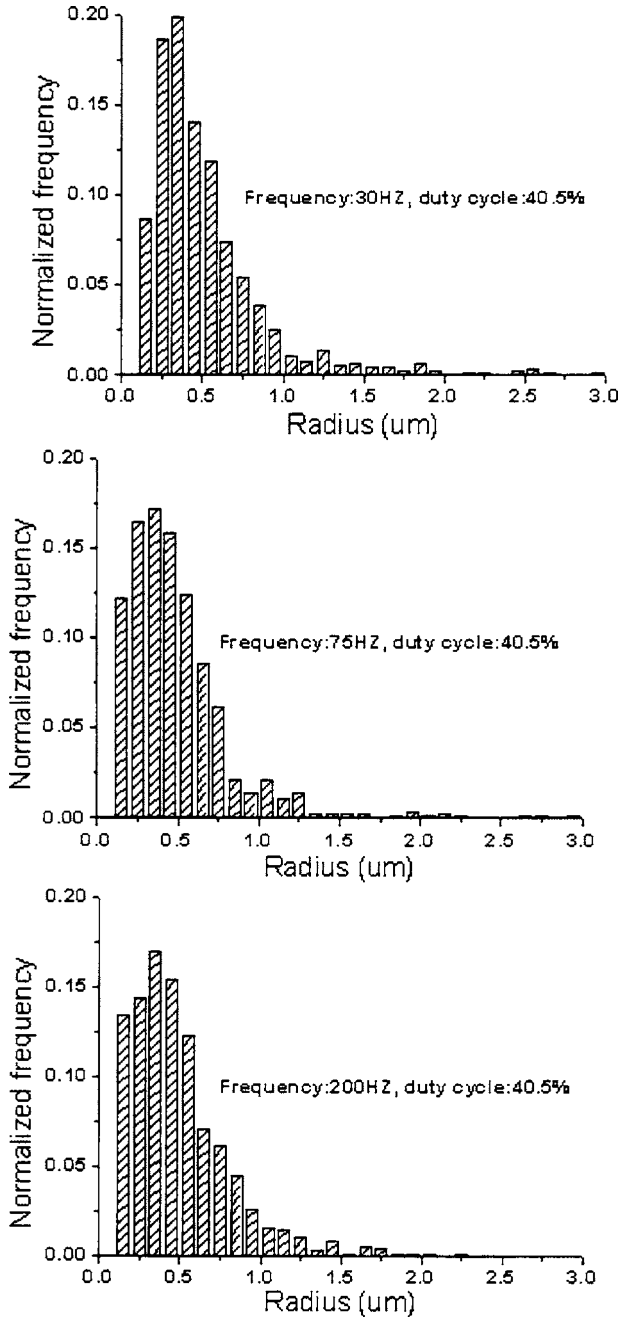
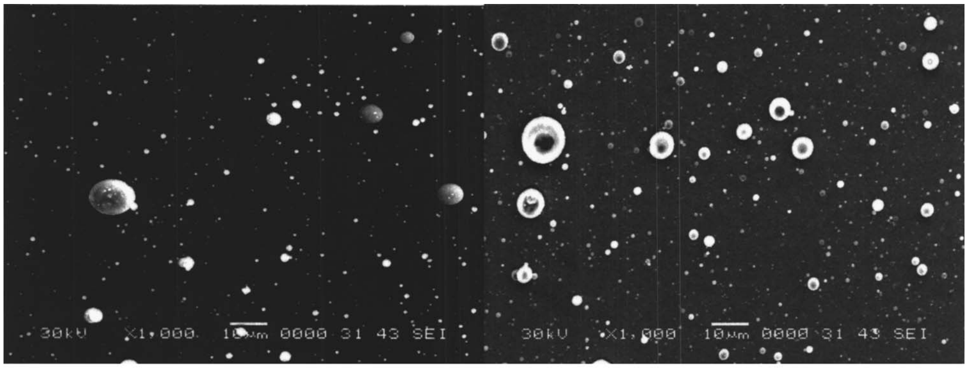


FIG. 6. Copper particle size distribution for different frequencies.

B. Effects of dc current

When the peak value of pulsed current was kept at 40 A, the dc was adjusted to 45 and 70 A. The density of MPs as a function of duty cycle (20.5%–91.5%) at a constant frequency is exhibited in Fig. 3. For a copper cathode when the



(a)

(b)

FIG. 7. SEM micrographs showing particles deposited on glass: (a) Ti particles and (b) Cu particles.

dc current is kept at 45 A, the number density of MPs increases rapidly with increasing duty cycles from 23.5% to 74.5%, then rises more slowly upon further increase in the duty cycles. In contrast, the MP density shows no obvious relationship with the duty cycle at higher dc [Fig. 3(a)]. For the titanium cathode, the relationship between the MP density and duty ratio is similar with that of different dc [Fig. 3(b)]. The MP density as a function of dc for copper is depicted in Fig. 4. The results show that the MP density increases approximately linearly with the dc current.

C. Effects of pulsed current

Using titanium as the cathode and keeping the dc value at 70 or 45 A, the peak pulse current was adjusted to maintain the same average current. The MP density as a function of the duty cycle is displayed in Fig. 5. When the dc is 70 A, the MP density does not fluctuate appreciably with the duty cycle. However, it increases with increasing duty ratio at lower dc (45 A). When the duty cycle is below 57.5%, the MP density at a lower dc is much less than that at a higher dc. However, when the duty cycle exceeds 57.5%, the number density shows no obvious differences in either case.

IV. DISCUSSION

The power applied to the cathode affects the temperature of the cathode spot and consequently determines the volume of melted materials. Therefore, particle emission can be correlated with the estimated heat load Q in this zone. The heat load in the cathode spot area can be approximated by the arc power delivered to this zone during a pulsing time t employing the following relationship:

$$Q=\int_{t_0}^{t_f} IVdt=\int_{t_0}^{t_f}(I_d+I_P)Vdt=\int_{t_0}^{t_f} I_dVdt+\int_{t_0}^{t_f} I_PVdt, \tag{1}$$

where t_0 is the pulse beginning time, t_f the ending time of an individual pulse, I_d the dc arc current, I_p the pulse arc current, and V the total voltage drop. When the heat load rises, the volume of melted materials formed at the cathode spot increases, and so does the number of particles emitted from the cathode. Increasing the arc current leads to a greater number of spots or a larger spot size,[18] and the MP density goes up with increasing current,[9] as illustrated in Fig. 4.

The cathode spot speed has important effects on the production of particles. The melted region on the cathode moves outward by joule heating and the ion pressure results in the ejection of molten materials forming a crater.[19–22] These are responsible for the appearance of MPs on the deposited films. Microprotrusions formed at the crater edge provide more favorable conditions for the cathode spot to exist, and so the spot moves with a step size on the order of the crater radius. Swift[13] has suggested the following relationship between cathode spot speed and size of cathode spot on a clean cathode:

$$v_s \propto 1/r_s, \tag{2}$$

where v_s is the speed of the cathode spot and r_s is the elementary step size that can be set equal to the cathode spot radius. This relationship shows that the expansion front of the cathode spot necessarily slows down due to the increase in the amount of materials melted as the spot expands.

The MP density exhibits no obvious correlation with the duty cycle at high dc values, but there is a low value for different duty ratios and different materials as shown in Figs. 2 and 3(b). It can be considered as the result of combined effects of the heat load and spot speed as a larger duty cycle increases the heat load as well as spot speed. This in turn reduces the resident time of the cathode spot giving rise to a smaller cathode spot. When the effect of the latter is dominant, the MP density decreases with increasing duty cycle and there is also a minimum. If the dc values are low, increasing the duty cycle produces relatively larger changes in the heat load. In other words, the effects of the heat load are predominant in this situation inducing larger cathode spots and more particles. Here, the MP density increases noticeably with larger duty cycles, as shown in Figs. 3(a) and 5. With increasing frequencies, the MP density is reduced. The increase in the frequency not only decreases the density of MPs but also the relative amount of particles with bigger sizes, as illustrated in Fig. 6. However, this effect is not as obvious when the duty cycle is very low or high (Fig. 2).

This is reasonable because the current is close to dc at very low or high duty cycle and the influence of the frequency is greatly reduced.

It has been shown that the MP density is related to the melting point of the cathode materials. A cathode material with a high melting point produces less MPs for the same current, pressure, and distance.[12] Our results are different. Figure 2 shows that the MP density produced by the copper cathode is less than that of the titanium cathode (melting point of pure copper is 1356 K, melting point of pure titanium is 1901 K). It should be attributed to the shape of the cathode. The MP emission is indisputably influenced by the shape of the cathode including the cathode's length and emitting surface.[23] The applied magnetic field on the cathode surface has two components, namely, a normal component and another component parallel to the cathode surface. The strength of the components has different effects on the motion of cathode spot.[24,25] In our work, the length of the copper cathode is twice that of the titanium cathode. The variable magnetic field components that are normal and parallel to cathode surface further impact the motion of the cathode spot and MP emission. We have also noticed that particles deposited from the copper and titanium cathodes have different behavior (Fig. 7). The larger particles deposited using the copper cathode are flat whereas those deposited from the Ti cathode are more spherical. A possible reason is that the larger Cu particles are deposited onto the substrate in the molten state whereas the Ti particles solidify during transit to the substrate surface.

V. CONCLUSION

The effects of pulsing parameters such as the duty cycle, frequency, and arc current on the production and distribution of macroparticles were studied. The MP density has no apparent correlation with the duty cycle at high dc values. The lowest density is obtained at a duty cycle of 40.5% for the copper cathode and 57.5% for the titanium cathode. In comparison, the MP density increases with the duty cycle at low dc current values. The current (dc or pulsed) and frequency also have an important effect on the production of the particles. The particle density increases approximately linearly with increasing dc current. Increase in the frequency not only decreases the MP density but also yields a larger amount of big particles. The influence of the frequency diminishes at very low or high duty cycles. The state of the particles is also found to depend on the cathode material.

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