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Optimizing the triggering mode for stable operation of a pulsed cathodic arc deposition system

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Abstract
In order to deposit fine structures such as nanoscale multilayers using a pulsed cathodic arc, it is necessary to ensure that the deposition per pulse is stable over a large number of pulses. We compare the deposition rate using centre and edge triggering in a pulsed cathodic arc system by determining the rate of change of thickness of a growing film. Three arc currents were used and the results indicated that the centre triggering configuration provides a constant deposition rate when compared to edge triggering. It was also observed that the highest arc current in the centre mode showed the most uniform deposition rate. The erosion profile of the cathodes for the two different triggering types were examined and used to explain the differences in terms of uniformity of erosion. We also measured the discharge voltage and found that there was an increase with increasing arc current.

1. Introduction

The vacuum arc plasma in the pulsed mode is initiated by a high voltage discharge across the surface of an insulator and sustained by a high current pulsed power supply. This discharge can be created using different triggering mechanisms as summarized by Anders *et al* [1]. The most common triggering mechanism used for low arc currents (up to 300 A) is edge triggering because it is relatively easy to achieve as well as being simple to manufacture, particularly for cylindrical geometry cathodes. In this mode, the plasma is established by a high voltage surface flashover between the cathode material and trigger electrode across an insulator. This type of trigger can fail due to excessive deposition of cathode material onto the insulator, thus creating a short between the cathode and trigger electrode.

Siemroth *et al* [2], on the other hand, report the use of a trigger located at the cathode centre to trigger a high current (>1 kA) pulsed vacuum arc. They reported that the high current pulse enables the cathode spots to run radially across the surface of the cathode at high velocity, producing a well defined erosion area of the cathode material.

The aim of this work is to compare these two triggering mechanisms in relation to the stability of the deposition rate in a pulsed cathodic arc system for currents up to 220 A. This is central to the deposition of structured materials such as nanoscale multilayers, in which fine control of the layer thickness is required. The work was conducted using a MEVVA type vacuum arc plasma source [3–5], whereby the common mode of operation is edge triggering. Tests were performed in both types of configurations, edge and centre, to compare the deposition rates between the two modes and their performances were explained in terms of the erosion of the cathode. We used a range of operating currents to assess the effect of the current on the stability of operation.

2. Experimental details

A schematic of the filtered pulsed cathodic arc set-up is shown in figure 1. The cathode used was a 10 mm diameter titanium rod of purity 99.5%. The anode consisted of a copper ring, diameter 75 mm, length 15 mm, positioned 10 mm above the

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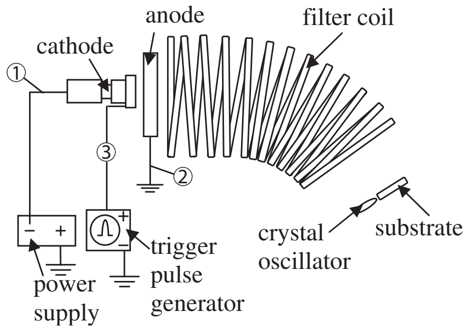

Figure 1. Schematic diagram of the pulsed cathodic arc deposition system. Edge triggering of the arc is shown. ① and ② are connection points for the voltage probe used to measure discharge voltage. ③ is the location of the current loop used to measure arc current.

cathode. The curved magnetic filter coil was made from copper tubing of 6.2 mm diameter with 28 turns and ran on power supply different from that of the pulsed arc power supply. The filter coil was floating and the applied current through the coil was 40 A. The magnetic field measured at the middle of the filter coil was 2.1 mT.

All experimental runs were conducted using a pulsed mode with a pulse length of 0.5 ms and a frequency of 4.5 Hz. Three arc currents were used: 80, 150 and 220 A, with 220 A being the maximum current achievable on the pulsed cathodic arc system used. In each case, the current quoted represents the average value of the pulse. New titanium rods were used for each arc current in both centre and edge triggering and one face of each rod was carefully machined to a flat finish prior to each experiment. The machined face was then used as the exposed front surface of the cathode. A trigger power supply providing an open circuit voltage of 10 kV and a maximum current of 40 A over a period of 50 μs was used to ignite the arc.

A substrate holder was positioned 100 mm from the last turn of the filter coil. At this distance the thickness uniformity over 40 mm $\times$ 40 mm area is approximately 10% (the percentage of the thickness deviation from the total thickness). A quartz crystal oscillator was placed next to the substrate holder to monitor the mass of the material deposited. These numbers were converted to a nominal thickness assuming a titanium bulk density of 4.5 g cm^{-3}. As the crystal oscillator is sensitive to plasma and electronic interference, the arc power supply was stopped for a fixed time of 1 min before each crystal oscillator reading.

Prior to deposition, the chamber was evacuated to a vacuum base pressure of 3×10^{-6} Torr. Experiments were conducted for a total time integrated current of 4000 A s. The integrated current for each pulse is the area under the current (I_{arc}) versus time curve. Given that the magnetic field configuration was held constant, the time integrated current could be expected to be roughly proportional to the total ion charge reaching the substrate during the pulse time interval.

Figure 2 shows the set-up of the two trigger types: (*a*) centre and (*b*) edge triggering. In the centre triggering configuration, a hole was drilled through the centre of the titanium cathode through which a 0.3 mm diameter tungsten wire (purity 99.9%) was inserted and acted as the trigger electrode. The tungsten wire was raised 2.0 mm above the surface of the cathode and was surrounded by an alumina tube (inner diameter, ID = 0.6 mm; outer diameter, OD = 1.9 mm). This alumina tube was positioned 1.0 mm below a larger alumina tube (ID = 2.0 mm, OD = 3.0 mm) which was placed flush with the surface of the cathode. This arrangement of the tungsten wire with two alumina tubes was found to be crucial for the centre triggering set-up at low arc currents as it prevented the coating of the alumina spacer from causing a short between the tungsten wire and the cathode. An additional outer alumina insulator shielding the top section of the titanium cathode was used to prevent the arc from running over the edge of the cathode.

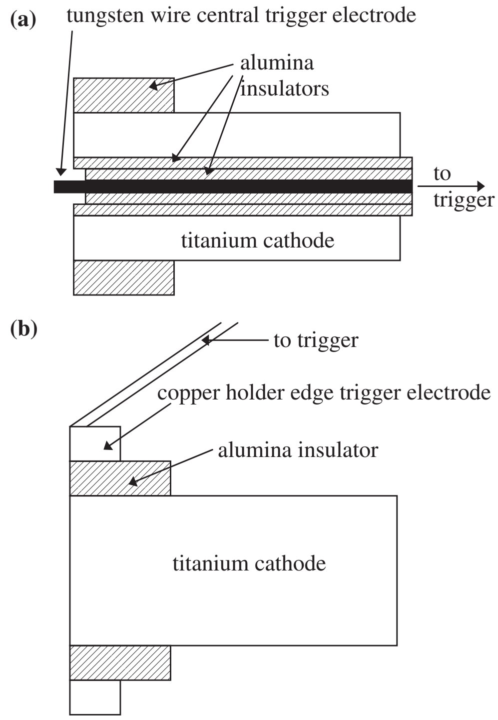

Figure 2. Schematic diagram of the cathode configuration for (*a*) centre and (*b*) edge triggering in the pulsed cathodic arc (side view).

For edge triggering, the titanium cathode was surrounded by an alumina spacer that was in turn encased in a copper ring, which acted as the trigger electrode. The arc was then triggered by surface flash-over from the copper ring to the cathode across the alumina spacer. This set-up is similar to that used by Brown [6].

In addition to measuring the mass of the material deposited, the discharge voltage for the three different arc currents was measured to ascertain if there was a difference in the total power dissipated. The discharge voltage or the arc voltage, in our experiment, was measured as the potential difference between the external connection to the cathode and the earthed anode when the arc is alight (connection points shown in figure 1 as ① and ②). In a review article by Brown [6], he remarked that the burning voltage depends on the cathode material used and typical values lie in the range 10–30 V, averaging around 20 V. He also reported that an increase in the arc current would increase the burning voltage, albeit only slowly. Anders *et al* [7] measured the burning voltages for 54 cathode materials. They compared their results with those published in the literature using either dc continuous or pulsed cathodic arc equipment. They remarked that there was generally a correlation between the cohesive energy of the cathode material, the arc current and the burning voltage. In our experiment, the discharge voltage was measured using a high voltage probe with a 1000 : 1 ratio and then recorded using a digital oscilloscope, whereas the arc current profile was recorded on another channel (connection point shown in figure 1 as ③).

3. Results and discussion

The results for the thickness as a function of time integrated current for the two types of triggering are shown in figure 3 at various current levels. The centre triggering results shown in figure 3(*a*) indicate that there is a linear dependence of thickness on time integrated current for the three different arc currents. The data were well fitted by straight lines with regression coefficients, R^2, of 0.9999 for 220 A, 0.9995 for 150 A and 0.9998 for 80 A. In the 80 A experiments, the tungsten wire shorted across the cathode towards the end of a run. However, the situation was rectified by flashing the tungsten wire with the maximum current of 220 A for several seconds and then reducing the current back to 80 A. By flashing the tungsten wire in this way, the majority of material build-up on the tungsten wire and alumina tubes was cleaned off the surface and the experiment could continue to the desired end point.

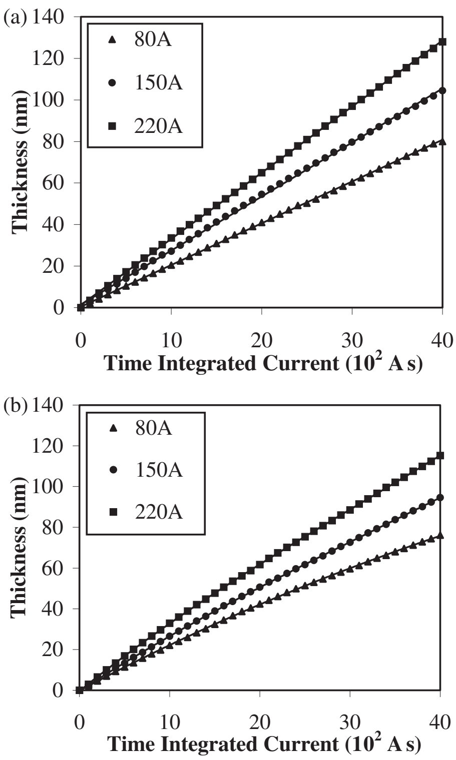

Figure 3. Thickness as a function of time integrated current using (*a*) centre and (*b*) edge triggering, for arc currents of 80, 150 and 220 A. Solid lines in (*a*) are linear fits and in (*b*) polynomial fits to the data.

Figure 3(*b*) shows the results from the edge triggering set-up. The most obvious difference to that of the centre triggering in figure 3(*a*) is that the curves in the edge triggering set-up did not show a linear dependence, but instead showed a progressive decrease in incremental thickness with increasing time integrated current. They have been fitted with a polynomial of order 3. For comparison purposes, we also fit the data in figure 3(*b*) to linear fits. The R^2 obtained using linear fits were 0.9951 for 220 A, 0.9963 for 150 A and 0.9893 for 80 A. This indicates that edge triggering does not produce constant deposition rates when compared to centre triggering, regardless of the arc current used. It is, therefore, advisable to use a centre trigger if constant deposition rates are required such as in the deposition of thin-film multilayers.

To achieve a time integrated current of 4000 A s, a time of 3 h was required running at 220 A and 6.5 h was required running at 80 A. Note that in both centre and edge trigger operation, the thickness versus time integrated current shows a variation with arc current. This demonstrates that the ion flux is not simply proportional to the arc current as is often assumed. If this was the case the curves in figure 3 would overlap. To investigate this effect further, we measured the discharge voltage for each arc current.

Figure 4 shows the discharge voltage and arc current profile for a single 80 A pulse, which is similar for both trigger types. The discharge voltage was taken as the average value in the region where the voltage has settled down to a quasi-steady-state value, in this case about 150 μs after the beginning of the pulse. Results of the discharge voltage obtained for the three different arc currents are shown in table 1.

The results showed an increase in the discharge voltage with arc current, even though the increase in the voltage was small when compared to the increase in the current. A rise of approximately 30% in the discharge voltage was observed with each increase of 70 A in the arc current.

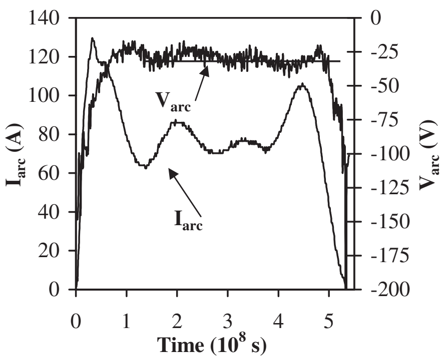

Figure 4. Discharge voltage and current pulse profile for an arc current of 80 A, using a centre triggering set-up. Note that the discharge voltage scale is on the right-hand axis and the voltage magnitude increases in the downward direction.

Table 1. Discharge voltage for the three arc currents.

Arc current (A)	Discharge voltage (V)
80	31 ± 6
150	41 ± 12
220	50 ± 18

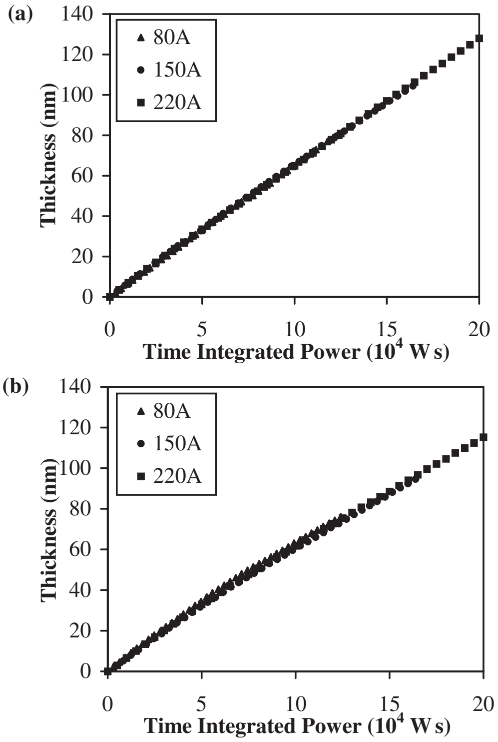

Figure 5. Thickness data from figure 3 replotted against time integrated power.

By replotting the thickness data in figure 3 as a function of time integrated power, i.e. each time integrated current was multiplied by the appropriate discharge voltage, we obtained the results given in figure 5. For both centre and edge triggering, the data for the three different arc currents overlapped, indicating that the thickness deposited depends only on the time integrated power and the trigger mode.

The thickness against time integrated power plots are a measure of the efficiency of the process in delivering material for energy expended. This efficiency was found to be independent of the arc current. This means that there are no gains in efficiency for high current operation and that the same fraction of the input energy appears as energy of ablation irrespective of the current in the cathode spots.

The erosion profiles of the cathodes are shown in figure 6. Comparisons were made between 80 and 220 A, centre and edge triggered cathodes. It was observed that in edge triggering, there was a preferred region where the arc tended to run, i.e. always on the edge of the cathode which represents a path of least resistance between the cathode, insulator and trigger. The region of cathode erosion was more extensive for 220 A compared to 80 A. This is because the 220 A arc used more energy and ran across a larger area of the cathode surface. It is obvious that as the edge triggered cathode erodes, the outside edges of the cathode wear more than the centre producing a curved edge region. An arc running on such a curved region projects plasma normal to the worn surface and hence at an angle to the filter duct axis. This reduces the efficiency of injection into the filter duct and accounts for the observed fall in deposition rate with time in the edge triggering mode.

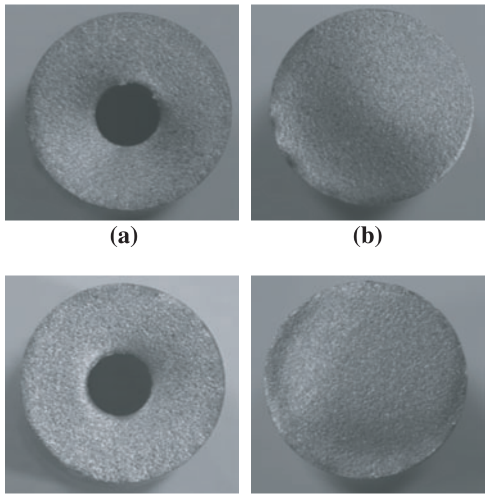

Figure 6. Erosion profile after 4000 A s time integrated current for (*a*) centre, 80 A; (*b*) edge, 80 A; (*c*) centre, 220 A and (*d*) edge, 220 A.

In contrast, centre triggered cathodes showed fairly uniform erosion across the surface of the cathode. The 220 A cathode had the most uniform erosion profile, indicating that the arc spots travelled radially from the centre across the entire cathode surface. There was also no shorting observed between the tungsten trigger electrode and the cathode at this high arc current. It is, therefore, recommended that the highest arc current possible should be employed when using a centre triggering arrangement. This observation of the uniform erosion profile of the cathodes in the centre triggering set-up provides further evidence that centre triggering is the more reliable triggering mode, in terms of the deposition rate, when compared to edge triggering.

4. Conclusions

Our results show that centre triggering is preferred over edge triggering for pulsed cathodic arc systems when constant ion fluxes per pulse are required over time. The results show that centre triggering gives a uniform erosion rate of the cathode material for all arc currents studied, with the highest arc current providing the most uniform erosion profile spatially. A constant deposition rate per pulse was achieved by centre triggering and is a requirement when fabricating multilayer stacks with homogeneous and reproducible layer thicknesses. The measurements of deposition rate as a function of time integrated power showed that there was a universal curve for each triggering set-up, independent of arc current, with the amount of material deposited depending only on the total energy time integrated power (*VI* product) dissipated by the arc system. The highest arc current used in this work (220 A) with centre triggering was found to be the most reliable.

Acknowledgment

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