REVIEW ARTICLE

Vacuum arc deposition devices

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The vacuum arc is a high-current, low-voltage electrical discharge which produces a plasma consisting of vaporized and ionized electrode material. In the most common cathodic arc deposition systems, the arc concentrates at minute cathode spots on the cathode surface and the plasma is emitted as a hypersonic jet, with some degree of contamination by molten droplets [known as macroparticles (MPs)] of the cathode material. In vacuum arc deposition systems, the location and motion of the cathode spots are confined to desired surfaces by an applied magnetic field and shields around undesired surfaces. Substrates are mounted on a holder so that they intercept some portion of the plasma jet. The substrate often provides for negative bias to control the energy of depositing ions and heating or cooling to control the substrate temperature. In some systems, a magnetic field is used to guide the plasma around an obstacle which blocks the MPs. These elements are integrated with a deposition chamber, cooling, vacuum gauges and pumps, and power supplies to produce a vacuum arc deposition system. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2169539]

I. INTRODUCTION

The vacuum arc is a high-current electrical discharge in which current is conducted by a plasma consisting largely of material emitted from the electrodes. This plasma can subsequently condense on internal parts of the apparatus or on substrates placed therein, thus forming a deposition. Vacuum arc deposition was probably observed by Wright[1,2] in the 1870s and was used by Edison[3,4] as part of a process to form master molds for duplicating wax phonograms.[5] Commercial industrial vacuum arc deposition devices were developed in the former USSR in the 1970s,[6,7] and in the last decade vacuum arc deposition has become the predominant technology for depositing hard coatings on cutting tools.

The vacuum arc itself has fascinated physicists and engineers alike. A natural concentration of current at minute "cathode spots" which move randomly or directed by a magnetic field across the cathode surface produces ultrasonic jets of fully ionized (and often multiply ionized) vapor of the cathode material, while most of the power in the arc is dissipated at the anode. Unfortunately, in addition to the plasma jets which act as a highly desirable deposition source, the cathode spots also produce a spray of droplets, known as macroparticles, which are deleterious in some applications.

The objective of this article is to review briefly the physics of the vacuum arc, the design principles for vacuum arc deposition devices, and their implementation in both laboratory and industrial deposition devices. First the physics of the vacuum and the plasma it produces will be described briefly, as they ultimately determine the device design requirements. Then the design of the arc electrodes will be described, with emphasis on controlling the cathode spots, heat removal, and arc ignition. Next the components for transporting the plasma from the electrodes to the substrates (while in some cases removing macroparticles) and for holding the substrates will be described. And finally ancillary components, including vacuum hardware and power supplies, together with system integration will be discussed.

II. THE VACUUM ARC AND ITS PRODUCTION OF PLASMA AND MACROPARTICLES

The electrical arc is a high-current discharge which operates at low voltage due to the high efficiency of collective electron emission processes such as thermionic and field emission at the cathode.[8–10] The electron emission processes distinguish the arc from other forms of discharges such as the glow, where meager secondary electron emission processes from bombardment of the cathode by ions, excited atoms, and photons predominate, and high voltage is required to accelerate these electrons to produce an ionization cascade capable of supplying electrons sufficient for the device current. Arcs are further classified according to pressure range. The vacuum arc does not require any background gas to operate but rather produces vapor by evaporation of the electrodes. This vapor is ionized by the discharge, forming a plasma which conducts the arc current. Furthermore, this plasma will form a coating of the electrode material, or, if a reactive background gas is present, of a compound of the electrode and gas materials, upon condensation on a substrate. The primary source of evaporation may be the cathode or the anode, and these discharges are sometimes referred to as cathodic or anodic arcs, respectively.[9]

A. The cathode spot and cathode spot plasma jets

In most vacuum arcs, there is a natural concentration of the current at one or more minute spots on the cathode surface, known as cathode spots.[8–13] The number of these spots

N_{cs} is proportional to the current I, i.e. $N_{cs} \cong I/I_s$, where I_s is a characteristic cathode spot current which depends on the material, ranging from ~0.4 A for very volatile cathode materials (e.g., Hg) to 300 A for very refractory materials (e.g., W).[10] The cathode spots are not stable; rather they tend to continually divide into two spots, spontaneously extinguish, and reignite at adjacent (or even remote) locations. The cycle of spontaneous extinction and reignition at adjacent locations gives the spot the appearance of having a random-walk motion. In the presence of a magnetic field, however, ordered motion is observed primarily in the "retrograde" $-\mathbf{I}\times\mathbf{B}$ direction.[10–25] Cathode spot motion is particularly important in the design of arc deposition cathodes.

The cathode spot temperature over a minute area (a few micrometers) is extremely high, i.e., significantly exceeding the atmospheric pressure boiling temperature, even though the bulk temperature of the cathode might be close to room temperature. As a consequence, there is intense evaporation from the cathode spot surface directed approximately normal to the cathode surface with an approximately Lambertian (cosine) distribution,[26,27] and in addition liquid metal droplets, known as macroparticles[28,29] (MPs) are sprayed from the cathode spot, usually close to the cathode plane. Almost all of the vapor is ionized, and the ratio of ion current which may be extracted from the arc to the arc current is a fixed fraction[27,29–31] $f=I_i/I=(0.08-0.15)$ for a wide range of materials. Thus the ion erosion rate, which sets the upper bound for the productivity of deposition systems, is given by $G_i = m_i f/(Ze)$, where m_i is the ion mass, Z is the average ionization stage, and e is the electron charge. G_i is in the range of 20–220 μg/C. The total erosion includes MP emission and may range from 30 to 660 μg/C. The MP erosion will generally decrease with the melting temperature of the cathode material and increase with the cathode surface temperature.[10]

The plasma emitted from the cathode spot is highly ionized, and the ions have a high directed energy and velocity. The ionization fraction is close to 100%, and multiple degrees of ionization are common, particularly with the more refractory cathode materials. The average degree of ionization ranges from 1 for Li, C, and Sb to 3 or more for Nb, Mo, W, and U. The average directed energy of the ions ranges from 14 to 120 eV.[10] This translates to a high flow velocity, e.g., ~10 km/s for Cu. The temperature of the ions, and hence the random component of its velocity, is much more moderate, e.g., 1–8 eV, and thus the plasma flow is hypersonic.[10,32]

It should be noted that the properties of the cathode spot and the plasma which it produces are very much dependent on the surface condition, and, in particular, the presence of a gas layer or compound can profoundly influence the properties. In general, the cathode spots usually preferentially locate themselves on "contaminated" regions of cathode surface unless that area has become so insulating (e.g. if an oxide layer forms) that it cannot support an arc. Cathode spots on contaminated regions generally have a smaller I_s, lower erosion, and higher random spot velocity than cathode spots on clean metallic surfaces.[10]

The mechanism of cathode spot operation is still enthusiastically debated, and two schools of thought have emerged. One characterizes the cathode spot process as a succession of explosions in adjacent locations, in which a small protrusion on the cathode surface is instantly vaporized and ionized. Each explosion produces conditions in adjacent locations conducive to triggering a further explosion.[33] The other characterizes the cathode spot process as being quasistationary. The cathode surface in a minute region is heated by backflowing ions and electrons and Ohmic heating within the cathode but concentrated near the surface. The cathode spot surface is cooled by thermal conduction into the surrounding regions of the cathode, radiation, evaporation, and electron emission. The electrons are emitted by some combination of thermionic and field emission (known as TF emission). The electrons are accelerated by a local electric field, colliding with the evaporated metal ions, exciting them, and ionizing them, forming a dense plasma. The electrons have a tendency to diffuse away from this concentrated plasma ball faster than the more massive ions, and thus a local positive space charge is formed within the dense plasma, which assists in the emission of electrons from the cathode and their acceleration as well as the acceleration of ions in all directions. However, the primary mechanism for accelerating the ions to the high velocities and directed energies observed experimentally is akin to the mechanism occurring in a jet engine; as the hot gas expands, there is a conversion of random or thermal energy to directed energy. In the case of the cathode spot plasma jet, as the plasma expands, it is further heated Ohmically by the electrical current passing through it, thus providing further thermal energy which can be converted to directed energy.[10,34]

B. Plasma production at the anode

A concentration of the arc at the anode surface, known as an anode spot, can also occur under suitable conditions. The anode spot differs in many respects from the cathode spot: Generally it is not essential for the operation of the arc and thus only occurs in particular circumstances, and usually only a single anode spot (if any) is present.[35,36] The anode spot plasma is desired in certain pulsed plasma sources with small anodes,[37] while great effort is made to avoid anode spot formation in large switching devices used in high-power circuit breakers, known as vacuum interrupters, which use the vacuum arc as a switching medium.[38] Anode spots are not generally used in deposition devices.

More controlled anodic evaporation, often without MP production, can be obtained in the hot anode vacuum arc (HAVA), in which a moderate current arc is used to heat a thermally isolated anode to significant temperature until significant evaporation or sublimation occurs.[39,40] The emitted material may be (a) the anode itself, (b) a second more volatile material placed on or in the anode (e.g., constructing the anode in the form of a crucible), or (c) material condensed from the cathode plasma jets, in a configuration known as the hot refractory anode vacuum arc (HRAVA).[41]

Minute anode spot formed in pulsed devices with small anodes produces hypersonic highly ionized plasma jets with properties similar to cathode spot jets.[37] On the other hand, the vapor produced in the HAVA and HRAVA is usually

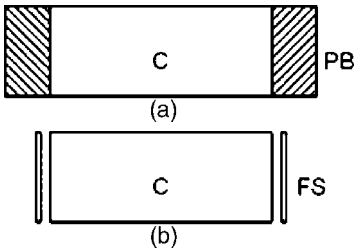

FIG. 1. Shields for cathode spot control, showing the cathode C, (a) passive border PB, and (b) floating shield FS.

emitted from a much broader area, only some fraction of the vapor is ionized as it passes through the discharge, and the ion energies are less than in the cathode spot plasma jet.[42,43]

III. CATHODE DESIGN

In most vacuum arc deposition apparatus, the cathode serves as the plasma source electrode, and thus its design is the most critical element in the success of the apparatus. The most critical issue in the design is controlling the location and motion of the cathode spots, while other issues include arc ignition, removing excess heat, and allowing for periodic replacement.

A. Cathode spot control

Given the mobility of the cathode spots, it is generally necessary to control the spot motion, so that they are on the "front" surface of the cathode, i.e., facing towards the substrates, both so that the deposition device will be efficient and also to prevent destructive erosion from occurring on support structures. It is also desirable to control the spot motion in order to spread out the heat flux to the cathode surface and thus prevent local overheating and to erode the cathode relatively uniformly.

Generally two methods are used to control the location and motion of the cathode spots. The first method deploys a shield around those surfaces where arcing is undesirable (Fig. 1). The shield may be an insulator applied directly to the surface[44] and is sometimes called a passive border.[45] In laboratory devices, often simple glass tubes or ceramic paste suffice. Machinable ceramics and BN (Ref. 46) have also proved to be very useful. The main advantage of this method is its simplicity. Disadvantages include formation of conductive coatings from material evaporated from the cathode and thus the establishment of a "cathode extension" on the insulator. Generally this coating will be "cleaned" by occasional cathode spot activity on the coated surface, but this may damage the generally brittle insulator, evaporate part of it, and thus possibly contaminate the coating. Alternatively, the shield may be either an insulator or an insulated conductor, with a small gap between it and the surface.[47] This structure resembles a dark space shield used in sputtering apparatus but in vacuum arc applications it is usually at floating potential. If a cathode spot slips into the region under the shield, a direct line of sight between the cathode spot and the anode will be lost, much of the plasma produced by the spot will condense on the shield, and hence the electrical impedance between the spot and anode will be greatly increased, decreasing current to this spot in favor of spots more favorably situated and extinguishing the spot, which is less stable at low currents. Both types of shield prevent cathode spot activity under the shield.

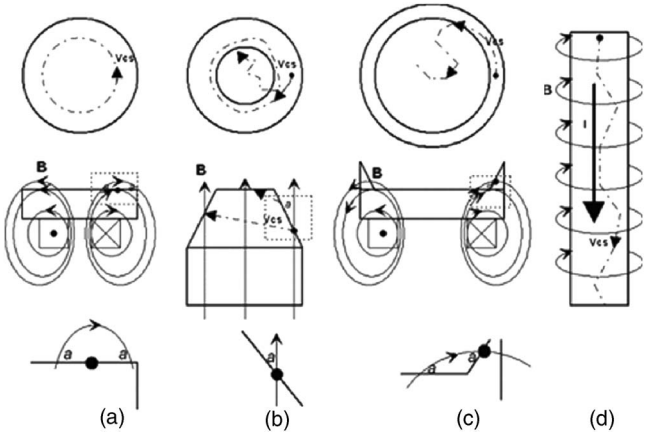

FIG. 2. Configurations for magnetically controlling cathode spot motion and location showing magnetic-field lines **B**, acute angle a between the field lines and the cathode surface, and the velocity vector V_{cs} of the cathode spot. (a) Race track, (b) conical cathode in axial magnetic field, (c) dished cathode in axial magnetic field, and (d) central cathode rod (showing the current flow direct **I** in the cathode). (a)–(c) include top and side views and an enlargement of the side view for better visibility of the acute angle a.

A magnetic field, however, can provide more definitive control on the desirable part of the cathode surface. Two phenomena are often exploited, often together: (1) retrograde motion—the cathode spots will have an apparent motion in the $-\mathbf{J}\times\mathbf{B}$ direction,[6,8,10–14,19,22–24] with a velocity approximately proportional to $|\mathbf{J}\times\mathbf{B}|$ up to a saturation value on the order of 50–150 m/s (the minus sign should be noted—i.e., the motion is in the opposite direction to what might be intuitively expected from the magnetic force on a currently carrying element), and (2) "acute angle rule"—if the magnetic-field lines cut the cathode surface obliquely, there will be a second-order tendency of the cathode spots to drift in the direction of the opening of the acute angle between the magnetic-field line and its projection on the cathode surface.[6,48–52] Four popular configurations using these principles are illustrated in Fig. 2.

(a) *Race track.* In the race-track configuration, an arched circular field with a radial component parallel to the cathode surface is produced by a magnetic coil[53–56] or permanent magnet[57–59] under the cathode [Fig. 2(a)]. The radial field forces the cathode spots to move in the azimuthal, i.e., retrograde, direction. However, given that the field cannot be perfectly "flat", i.e., radial, but rather will have an arched shape containing an axial component, the acute angle law indicates that the cathode spots will have a preferred azimuthal trajectory at the radial position of the apex of the "arch," where the axial component is zero. If the cathode spot drifts either towards the center of the cathode or towards the outside from this preferred radius, the acute angle of the field lines will encourage it to return to the preferred trajectory. This will erode a groove into the cathode surface, which becomes increasingly narrow with stronger fields. In practice, the location of this groove is somewhat outside that predicted by the above description. The location of the

groove can be controlled by superimposing an axial magnetic field, e.g., created by an external coil. If the current in the internal and external coils are in the same sense, the radial groove will be shifted outwards and vice versa.[54–56] If the external coil is operated with ac current, the radial position will shift according to the instantaneous value of the current, and the erosion pattern can be broadened. The principle of the arched field configuration can be extended to rectangular cathodes[60,61] or in general to arbitrary closed path motion of the cathode spots. If the field is created by current flowing in a conductor under the cathode surface, it can be shown that the preferred cathode spot motion will be parallel to and in the direction of that current. An advantage of the race-track configuration is that the cathode spot motion can be controlled over large area cathodes, which are often desired in order to obtain uniform deposition over large areas and to have long cathode life.

(b) *Conical cathode in an axial field*.[6,52,62–66] If a cathode with an approximately conical shape, including a truncated cone or a hemisphere,[67] is placed in an axial magnetic field, the retrograde motion of the cathode spots on the slanted surfaces will be in the azimuthal directions, and the secondary drift of the cathode spots will be towards the apex [Fig. 2(b)]. This encourages the cathode spots away from the base of the cathode structure. The advantages of this configuration are that relatively small, inexpensive cathodes can be used, and the design is simple in that the coil is removed from the vicinity of the cathode rear, which is generally crowded with mechanical support, high-current connections, and water cooling structures.

(c) *Dished cathode*.[68–74] This configuration is conceptually the inverse of the above. A generally flat cathode is provided with a shallow recess at its front surface surrounded by a beveled rim and placed in a generally axial magnetic field, which, however, diverges outward and thus has some radial component [Fig. 2(c)]. Cathode spots are initially ignited on the flat surface. These spots will have a generally azimuthal motion,[70,72] but the acute angle formed by the diverging field lines will give them an outward drift as well. However, the intersection angle on the beveled rim is such that any cathode spots on the rim will drift back onto the flat portion.

(d) *Central rod cathode*.[75–77] In this configuration a central rod cathode runs almost the entire length of a cylindrical deposition chamber [Fig. 2(d)]. The arc is ignited at one end of the rod, and the azimuthal self-magnetic field of the current flowing in the rod itself will cause slow retrograde motion of the spot along the rod. The addition of an external axial magnetic field, or asymmetry of the current flow in the immediate vicinity of the spot, can give the spot motion an azimuthal component, so that the resulting total motion is helical. A device is provided to detect the arrival of the cathode spot at the opposite end of the rod, at which time the arc current is momentarily interrupted, and a new arc is ignited at the original end of the arc. Water cooling can be provided along the length of the cathode if it is fabricated in the form of a hollow pipe or the rod can be cooled radiatively and by solid conduction along its length, if the current is limited. A variation,[78,79] with the central rod divided by an insulator into two cathodes of different materials, with each supplied with interior water cooling, and with an axial magnetic field to induce azimuthal cathode spot motion, was used to deposit superhard nanocomposite coatings of $(Al_{1-x}Ti_x)N/Si_3N_4$.

A problem with the magnetic control approach is that if a cathode spot does succeed in "escaping" from the areas where the magnetic field controls it, i.e., to a side surface in configurations (a) and (c) or to the straight cylindrical region of configuration (b), the fields in these regions might not be configured to return the cathode spot to its desired location. Thus often the magnetic-field control is supplemented with shielding, as described earlier.

B. Arc ignition

The vacuum arc in principle can be ignited by applying a sufficiently high voltage to break down the gap between the anode and the cathode. In vacuum, however, this voltage may be in the range of 13–26 kV per millimeter of gap length[80] and thus would require a power supply with very high voltages and would generally require care not to cause breakdown along undesirable paths and not to damage electronic equipment attached to the system. Much lower breakdown voltages, typically a few hundred volts, can be obtained if the product pd of the pressure p and anode-cathode gap d in the chamber is adjusted to the "Paschen minimum," typically[81] on the order of 1 Torr cm. This introduces operational complications, however.

Most commonly the arc is ignited using an auxiliary trigger electrode, operated either in a breakdown mode or more commonly in a "drawn arc" mode.[6,80] By placing the trigger electrode close to the cathode, a lower breakdown voltage can be realized than between the cathode and arc anode. The breakdown voltage can be lowered even further by placing the surface of a thin ceramic insulator between the trigger and cathode, so that the breakdown is by "surface flashover" along the insulator surface rather than by breakdown across a vacuum gap. A disadvantage of this method is that a conducting coating may form on the trigger insulator, thus short circuiting it. Triggering may still be possible, but generally a much higher current pulse will be required in order to evaporate the conducting film.

The most common arc ignition method is the drawn arc, in which the trigger electrode, sometimes called a "striker" in this configuration, is brought into momentary contact with the cathode and then is withdrawn. Current begins to flow when the trigger is in contact with the cathode, and an arc is "drawn", i.e., ignited, as the contact is broken. This is attributed to the thermal explosion of the narrow metallic bridge forming the last contact point between the two contacting electrodes. Only low voltage is needed for drawing an arc, and thus often the arc power supply itself can be used for powering the trigger discharge. Often a resistor is inserted in series with the trigger electrode to limit the current and thus avoid overheating the trigger, which is often a Mo or W wire or thin rod. The trigger motion is commonly energized by a solenoid. The trigger mechanism and its solenoid are sometimes located inside the vacuum system and sometimes outside. Internal mounting avoids the need for a motion

feedthrough, while external mounting allows simpler maintenance and the application of "first aid" additional force if the trigger welds to the cathode.

A further triggering method is the application of a focused laser pulse onto the cathode surface,[52,82,83] thus causing local evaporation and the ignition of a cathode spot which can be sustained by the main arc power supply. Laser triggering can be particularly effective if the arc is operated in a repetitively pulsed manner. The cathode erosion pattern can be controlled by sweeping the location of the laser beam. Alloy coatings with different compositions can be deposited by alternatively aiming the laser at one of several adjacent cathodes. The disadvantages of this method are the expense of the laser and the complications in the design caused by coating accumulation on any optical component within the vacuum chamber (e.g., the interior surface of the window through which the laser beam enters the chamber).

C. Control of the cathode temperature

Roughly 1/3 of the power supplied to the arc, $P_{\text{arc}} = V_{\text{arc}} I_{\text{arc}}$, is dissipated as heat in the cathode,[84,85] and in most cases this heat must be removed to prevent cathode damage. The exception is where the total energy dissipated in the cathode, $E_{\text{cath}} \cong (1/3) P_{\text{arc}} \tau_{\text{arc}}$, where τ_{arc} is the arc duration, is sufficiently small and the cathode is sufficiently massive that the energy can be absorbed in the cathode safely, i.e., when $T = T_0 + E_{\text{cath}}/(cm_{\text{cath}}) < T_{\text{damage}}$, where T is the cathode temperature after the arc, T_0 is the initial cathode temperature, c is the heat capacitance of the cathode material, m_{cath} is the cathode mass, and T_{damage} is a damage threshold temperature, e.g. the melting point of the cathode material. The above expression assumes instant equalization of the temperature within the cathode (i.e., a thermal diffusion time much shorter than τ_{arc}) and thus in practice some safety margin must be allowed.

In most apparatus, the cathode is water cooled either directly, i.e., water contacts the back of the cathode itself, or indirectly, i.e., the cathode is mounted on a holder which is water cooled. A typical indirect water scheme is shown schematically in Fig. 3. The average surface temperature of the cathode, T_s, i.e., disregarding the extreme temperatures in the vicinity of the minute cathode spots, may be estimated by $T_s = T_w + P_{\text{cath}} R_{\text{th}}$, where $P_{\text{cath}} \cong (1/3) \mathrm{P}_{\text{arc}}$ and the thermal resistance of the cathode is given by $R_{\text{th}} = R_c + R_i + R_h + R_w$. The thermal resistance of the cathode and cathode holder bodies are easily estimated as $R_c = L_c/(k_c A_c)$ and $R_h = L_h/(k_h A_h)$ for the cathode and cathode holder, respectively, where L, A, and k are the lengths, cross-section areas, and thermal conductivities of the respective bodies. The thermal resistance of the water interface R_w is complicated and will depend on the surface condition at the holder-water interface and the water flow parameters. The thermal resistance of the interface between the cathode and the cathode holder, R_i, is very complicated and difficult either to estimate or to measure. The difficulty arises from the generally unknown topology of the contact surface. Generally, any real solid surface is highly textured on the microscopic level, even after the best possible grinding and polishing. Contact between two rigid bodies is only at a finite number of discrete contact points, i.e., where the residual protrusions on the two bodies first touch each other when the two bodies are brought into contact. The contact area increases if the two bodies are pressed together, as the contacting protrusions are deformed elastically and plastically, and additional points come into contact. Solid thermal conduction is only through these relatively small contacting protrusions. The total conductance of the interface may be supplemented, however, by radiative heat transfer and by conduction through whatever gas fills the voids between the contacting surfaces, if the interface is not in vacuum. The resulting thermal resistance of the contact interface thus depends on the contact mounting pressure, is difficult to estimate, and may, in fact, be the dominant term in the total thermal resistance.

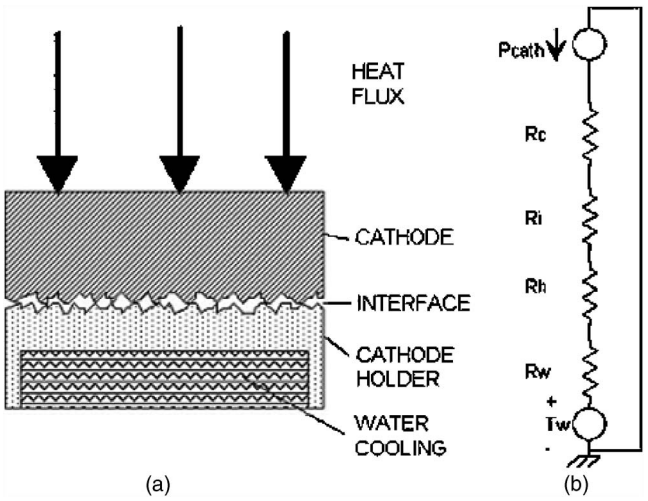

FIG. 3. (a) Schematic diagram of heat flow in an indirectly cooled cathode and equivalent electrical circuit for the heat flow. The roughness of the interface between the substrate holder and the substrate is exaggerated in the diagram. (b) Equivalent electrical circuit for calculating the heat flow, where P_{cath} is the net thermal power transferred by the arc to the cathode, R_c is the thermal resistance of the cathode, R_i is the thermal resistance of the cathode-cathode holder interface (which generally depends on the surface condition of both bodies and the clamping force), R_h is the thermal resistance of the cathode holder, R_w is the thermal resistance of the holder-water interface (which depends on the flow conditions), and T_w is the input water temperature.

Thus the disadvantage of indirect cooling is a higher average surface temperature for a given current or, conversely, a lower current rating for a given allowed temperature. The advantages of indirect cooling include a lower cost for replacement cathodes and a relatively short time required to change the cathodes.

The average temperature of a directly cooled cathode may be estimated using the same formulas, with R_i and R_h set to zero. The advantage of direct cooling is more effective cooling, and thus higher current densities can be sustained. However, the cathodes will generally be more complicated and more costly and time consuming to replace.

In some cases, specifically when it is desired to use semiconducting cathode materials such as Si and B whose room-temperature resistivity is very high, the cathode must be heated (e.g., to ~600–700 °C) to reach sufficient conductivity to sustain a vacuum arc. The cathode design should provide some means for preheating the cathode to the desired temperature, such as resistive or radiative elements.[86–89]

Small commercial halide lamps placed within the cathode body have proven to be effective for this task.[86,87] The requisite temperature may often be sustained during arcing if the cathode is thermally isolated from the surroundings.

D. Cathode materials, fabrication, and location

Cathodes may be fabricated from any material sufficiently conductive to conduct the arc current without excessive voltage drop. This includes pure metals and metal alloys and in some cases semiconductors. If the material is readily machinable, the cathode can be fabricated to be directly or indirectly cooled. In many cases the cathode material can be fabricated by sintering of powders. However, in some cases results were poor, e.g., excessive erosion in the form of very large macroparticles. Hard to work materials are usually prepared in some simple form, e.g., a flat disk, and the cathode design must allow for some form of bonding or clamping to a cathode holder. Low-melting-temperature metals (e.g., Sn and Zn) can be cast into a cup-shaped cathode holder, often using simple heating means (e.g., a toaster-oven or Bunsen burner), and the holder can be reused for many refill cycles.[55,60,61,90–94] In most systems the cathode is fixed in position, and arc erosion can change the cathode-anode gap length and the strength of the magnetic field at the receding face of the cathode. Furthermore, in some applications, exceedingly long deposition runs are required, and provisions must be made for having cathode material available without interrupting the run. These problems can be solved by having a long cathode rod or bar which may be fed into the arc at a rate commensurate with the cathode erosion. In this case the cathode must either be relatively immune to thermal damage (e.g., graphite)[67] or cooling means must be provided which allow for the cathode feed.[95]

The location of the cathode must be appropriate for its design, e.g., cathodes (a)–(c) in Sec. III A are usually mounted on the wall or door of the deposition system, while cathode (d) is mounted in the center of the chamber. To obtain sufficient uniformity in large industrial batch coating systems using cathodes (a)–(c), either very long cathodes or multiple cathodes at staggered heights are deployed.

IV. ANODE DESIGN

In the most widespread arc deposition mode, "cathodic" arc deposition, the anode plays a relatively passive role, merely completing the electrical circuit. However, a coating may form on its surface, which may disturb the electrical connection, and there may be some degree of reemission of the coating material through sputtering, sublimation, or evaporation (or emission of the anode material by these means). In contrast, the anode may serve as the principal source of vaporized coating material in "anodic" arc deposition systems. Design principles for these two cases will be described separately in the following paragraphs.

A. Passive anodes

In the most widespread cathodic arc deposition systems, the anode merely needs to complete the electrical circuit. The anode design must first of all fulfill that role, while allowing for good plasma transmission to the substrates and providing for heat removal, given that approximately $1/2-2/3$ of the arc power is dissipated as heat in the anode[84,85].

The simplest arrangement is to use the wall of the deposition chamber as the anode.[96] This maximizes the solid angle subtended by the anode on any given point on the cathode surface and thus minimizes the arc voltage[97,98] and maximizes the stability of the arc. The disadvantages are (1) that there is no control of the distribution of the current, and hence heat flux, to the anode and (2) in some cases it is desired to positively bias bodies connected to the chamber wall, e.g., to maximize plasma transmission through magnetic filters, which is not possible if the wall is the arc anode. In some cases the chamber wall is cooled by the surrounding air and no special cooling means are provided, while in other cases the chamber is provided with water cooling coils or ducts or a water jacket. The cathode must somehow or other be mounted on the chamber, and the design of the insulator separating the cathode from the chamber is critical. It must be shielded to prevent the accumulation of a conductive coating on its surface.

Often it is desired to have a separate anode, e.g., to facilitate biasing the duct walls or to minimize arc heating of the chamber wall. Often an annular anode,[53–56,67] generally surrounding the cathode, is used. In this case there is an engineering tradeoff between the desire to have an anode intercepting as much of the cathode spot plasma flux as possible in order to minimize arc voltage and maximize arc stability and the desire to minimize the intercepted plasma so as to maximize the flow of plasma to the substrate and thus maximize deposition rate and productivity of the deposition system.[99,100] Thus, increase of the anode aperture and decrease of its length, on one hand, increases the deposition rate and productivity of the system, while on the other hand, it leads to unstable arcing.[99–101] As a minimum for arc stability and low arc voltage, the anode must be arranged such that

$$\iint_A eN_e v_{e\text{-th}} da > I_{\text{arc}},$$

where e is the electron charge, N_e is the electron density, $v_{e\text{-th}}$ is a characteristic electron thermal velocity, and the integration is over the area A of the anode. Under these conditions, the random electron current to the anode exceeds that which is required for maintaining current continuity, and the anode potential is negative with respect to the adjacent plasma, thus repelling the excess electron flow.[102] As a rule of thumb, a minimum of about 10% of the plasma flow must thus be intercepted.

Separate anodes usually must be cooled if operated continuously. In some cases, the anode is constructed from copper tubing, through which cooling water flows. Water connections within the vacuum system should be avoided. In practice, there is a high probability that at some time in the operational life of the system, there will be a water leak from such a connection, which will require a long downtime (several days) for repair, cleaning, and drying.

B. Active anodes

1. HAVA

The hot anode vacuum arc (HAVA) has the advantage that a distributed attachment of the arc to the anode surface is possible, avoiding the production of droplets which can degrade the coating quality. In laboratory apparatus, simply holding a small wire or foil sample of the desired coating material on a refractory anode may be sufficient.[103] During operation, the sample material melts, and an evaporating liquid droplet forms which may cling to the anode during evaporation.

Industrial application, however, generally requires loading the system with a larger quantity of coating material. This may be accomplished by designing the anode in the form of a crucible, which may be loaded with the coating material. System efficiency is optimized if most of the power input to the anode is removed by evaporation of the coating material rather than by radiation or conduction. Radiation is minimized by surrounding all of the crucible except for its opening by a series of "heat shields," which reradiate incident radiation back to the anode surface. Thermal conduction is minimized by supporting the anode and connecting to it electrically by a long thin rod. Crucible anodes, just like sources used in other evaporative physical vapor deposition (PVD) techniques, must be mounted such that their contents do not spill and hence are located under the substrates. Metallurgical interaction between the molten coating material and the crucible is also an issue. The molten coating material may dissolve material from the crucible, thus damaging it and contaminating the coating material.

2. HRAVA

A recent innovation called the hot refractory anode vacuum arc (HRAVA) combines some of the advantages of cathodic and anodic arc deposition. In this arc mode, plasma and droplets emitted by the cathode spots are intercepted by a refractory anode heated to high temperature by the arc and reevaporated without droplets. Thus not having any molten reservoir, the HRAVA electrodes may be mounted in any orientation.[41,104]

V. MACROPARTICLE CONTROL

The major disadvantage of vacuum arc deposition, particularly in the cathode spot arc mode, is the coproduction of molten droplets, which may be incorporated into the coating as macroparticles (MPs),[10,28,105] contaminating the coating and causing growth defects in overlying layers. The MP problem may be addressed by several approaches.

(1) *Neglect.* In some applications, e.g., where a matt surface is desired, MP incorporation may be beneficial,[106] while in others the MPs may not be deleterious, or the cost of doing anything about them is greater than the perceived benefit, and/or good results are obtained in spite of the MPs. In these cases, the MP issue is simply ignored.

(2) *Minimizing MP production and incorporation by adjustment of the operating conditions.* MPs are produced by the reaction force of the cathode spot plasma jet on the molten surface in the vicinity of the cathode spot and are emitted preferentially close to the cathode plane. As a rough approximation, all molten material in the cathode spot vicinity is removed;[107] thus all measures which reduce the amount of molten material can be effective in reducing MP production. These measures include (a) effective cooling of the cathode; (b) minimizing the average arc current density to the cathode, i.e., minimizing the current and using large area cathodes;[108] (c) using a magnetic field to cause rapid retrograde motion ("steered arc") of the cathode spots over the cathode surface[109,110] and thus minimizing the temperature peak experienced by regions outside of but adjacent to the cathode spots; (d) in the most common industrial applications, namely, production of nitride coatings, operating at a sufficiently high nitrogen pressure so that the cathode surface becomes nitrided, thus forming a surface layer with a higher melting point and decreasing the current per cathode spot;[108,111,112] (e) in addition, the substrates may be placed where the desirable cathode vapor plasma flux is maximized and the MP flux minimized, i.e., directly in front of the cathode; (f) another technique is to pass the MPs through a high-density plasma, e.g., by magnetically collimating the plasma ("intensified arc")[113] or by operating the arc in high-current short-duration pulses ("high-current arc"),[114] and thus vaporizing a portion of the MP mass in-flight; and (g) finally, negatively biasing the substrate tends to decrease MP incorporation[108,115,116] for reasons which are not entirely clear.

(3) *Hot anode modes.* The use of the HAVA or HRAVA arc modes, rather than conventional "cathodic" arc deposition, can eliminate or greatly reduce MP production, albeit in some applications there are operational disadvantages.

(4) *Filtered vacuum arc deposition (FVAD).* In FVAD, an obstacle is placed between the cathode and the substrate[58,69,73,117] blocking any direct path, both for the undesirable MPs and the desirable metal ions or atoms. A background gas may scatter some metal ions towards the substrate, though generally at a low deposition rate. More effectively, the plasma beam may be bent by the application of an appropriate magnetic field. An apparatus combining an obstacle and some magnetic field to bend the plasma around the obstacle is referred to as an MP filter and effectively filters the MPs out of the plasma flux. The remainder of this section will describe various arrangements utilizing this concept.

Several review papers were devoted to magnetic filtering.[62,66,69,118–124] Various MP filter arrangements are shown in Fig. 4. The first arrangement [Fig. 4(a)], known as the "straight filter," applies an axial magnetic field to collimate the plasma and thus direct it towards the substrate,[99,125–128] while it lacks an obstacle which blocks MP transmission. The magnetic field has little effect on the MP trajectories, and thus the ratio of plasma to MPs increases and the density of MPs per unit volume of coating material is decreased.[129]

Aksenov *et al.*[123] described a MP filtering system combining a straight magnetized duct and an obstacle situated on the duct axis [Fig. 4(b)]. Field coils outside of the duct and coaxial with it provide a generally axial magnetic field. By

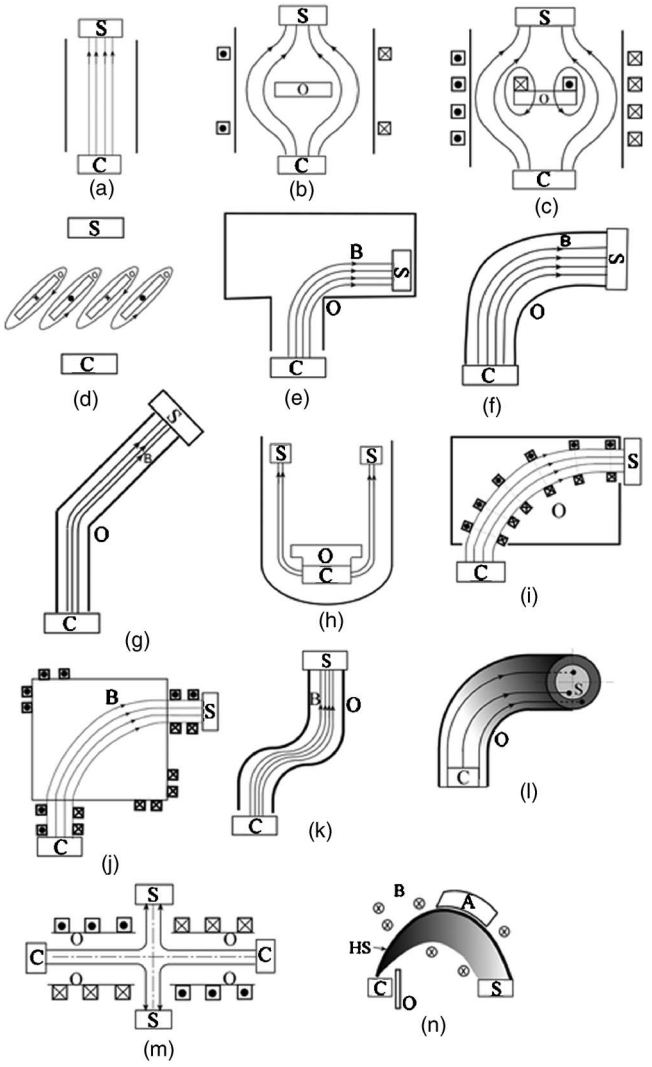

FIG. 4. MP filter configurations showing the cathode C, obstacle O, and substrate S, and magnetic-field lines **B** are indicated by arrows. The plasma flows along the field lines [except in configuration (n)]. In most cases the field coils or magnets are omitted for simplicity; where shown, the coil current flow direction is indicated. (a) Straight duct, (b) straight duct with axial obstacle and diverging-converging axial field, (c) magnetic island, (d) Venetian blind—current flow in the vanes is indicated, (e) straight duct with offset substrate and bent field, (f) 1/4 torus, (g) knee, (h) dome, (i) open torus,(j) plasma magnetically bent between two flanges of chamber, (k) S, (l) twist, (m) axial to radial flow conversion, and (n) Hall stratum (HS).

applying less current per unit length in the vicinity of the obstacle, the field lines diverge around the obstacle and then reconverges and thus guide the plasma around the obstacle while it blocks the direct path of MPs. An alternative magnetic-field arrangement with a similar plasma flow is known as the magnetic island [Fig. 4(c)].[62,66,130] Here an external field coil produces a generally uniform axial field while an additional field coil placed behind the obstacle and also aligned coaxially with the duct is energized in the opposite sense, so that the superposition of the two fields diverge around the obstacle and reconverge as in the previous example.

An alternative filtering concept which maintains a generally axial flow is the "Venetian blind" [Fig. 4(d)]. Here the direct straight-line path is blocked by a series of thin louvers.[62,66,122,131,132] Current flow through the louvers produces a magnetic field which guides the plasma through the slits between the louvers.[6] High substrate current to arc current ratios for such filters were reported ($I_s/I_{arc} \sim 7\%$) however, as was mentioned by authors,[6,122] this number needs to be confirmed. Also, Aksenov[6] noted that the problem of MP reflections is not solved in such filters, and the solution is not clear.

A slight variation of the straight filter arrangement is shown in Fig. 4(e). Here the plasma is magnetically directed through a duct into a deposition chamber as in the straight filter, but the substrate is located off axis such that chamber and duct wall act as a MP obstacle, and the magnetic field is bent to direct the plasma to the substrate.[62,133–135]

MP filtering systems where a plasma flux is bent by a magnetic field are known for more than 25 years from first publications of Aksenov and co-workers.[136,137] The most popular MP filter is a toroidal plasma duct with various angular sections of a torus and, in particular, the 90° section or "1/4 torus" [Fig. 4(f)].[6,62,66,118,119,121–123,136–138] Here, the portion of the toroidal duct wall on the inside of the curve serves as the obstacle. Other angular toroidal sections were also used, including 60° ,[139,140] 30°, and from one to six cascaded 30° sections.[141,142] In addition, a combination of straight and curved duct sections can be used.[143] A variation of this concept is to use a bent duct, rather than a straight duct, forming a "knee filter" [Fig. 4(g)].[138,144] A further variation is the dome filter [Fig. 4(h)].[144,145]

While the MPs are initially molten and may even be superheated by the plasma close to the cathode, usually they solidify in-flight, and MP bouncing in the duct walls is a major concern. One approach is to minimize reflections by minimizing the surface area close to the plasma path by using an "open" torodial filter[88,122,146–148] [Fig. 4(i)] in which the toroidal magnetic field is produced by an open coil located inside a large vacuum chamber or by using an arrangement wherein input and output plasma ducts are attached to a large chamber, and an external coil produces a magnetic field which connects from the input duct through the chamber and into the output duct [Fig. 4(j)].[6,123,149–151] This arrangement can have a large radius of curvature R to aperture radius a ratio ($R/a \approx 1.3$) and I_s/I_{arc} reaching $\sim 6.5\%$, higher than that of any other filtering system known. The alternate approach for addressing the bouncing MP problem is to provide baffle plates or corrugation along the duct walls[6,60,122,123,152] to minimize the probability of specular MP reflection in the direction along the duct wall. Another approach is to use filters with larger angular sections (e.g., 180°) or designs with multiple duct sections. One example is the "S filter"[122,153–156] [Fig. 4(k)], which has two 1/4-torus sections cascaded in opposite directions. This has the advantage of correcting off-axis plasma drift (in the **G** and $\mathbf{B} \times \mathbf{G}$ directions,[92,157,158] where **G** represents a vector in the "centrifugal" direction) produced in the first section off of the duct axis, in the second section, where the direction of **G** is reversed. The S filter may be thought of as starting with two 1/4-torus section mounted together to form a 1/2- torus and then rotating the second section about its interior axis by 180° . If the second section is rotated by only 90° , an out-of-plane twist filter is formed[156,159,160] [Fig. 4(l)]. If the

plasma beam center is displaced from the duct axis, its location may be corrected using beam deflection coils located near the duct output or in the deposition chamber, oriented such that their field is perpendicular to the system axis.[92] If an ac component is added to the excitation of these coils, they may be used to sweep the plasma beam over the substrate surface and thus improve uniformity.[137] Various toroidal-like filter designs can be generalized to a rectangular cross section to provide filtered plasma flux over a wide area.[60,61,161–165]

Usually the magnetic-field strength in the duct is sufficient to "magnetize" the electrons (i.e., cause the Lamor radius to be smaller than the duct width) but not the ions.[125,136,137] The ions are confined electrostatically by the field generated by the drift of the ions away from the electrons. However, the plasma transmission through a toroidal-like filter increases when the field is sufficiently strong to also magnetize the ions. However, strong fields lead to increased arc voltage and to an unstable arc if the arc power supply cannot supply the requisite voltage.[53,54] Special care should be exercised in the design of the magnetic field near the cathode surface to prevent the toroidal field from forcing the cathode spots off of their preferred location on the cathode surface. In addition, the duct transmission can be improved if it is positively biased, typically by 15–25 V.[136,166,167]

The filters described above typically produce a narrow plasma beam, whereas coverage over a wide area is desirable in some applications. In an alternative approach[6,123,168,169] one or a pair of cathodes is mounted on the axis of cylindrical chamber and two opposing magnetic-field coils are arranged to produce a cusp field, which bends the initially axial plasma flow to the radial direction and thus provides deposition over a broad band around the circumference of the deposition chamber [Fig. 4(m)]. A cylindrical shield with a midplane gap blocks MP transmission. Using this concept, I_s/I_{arc} reaching $\sim 8.4\%$ (Refs. 123 and 169) were achieved, higher than any other filtering scheme and approaching values achieved in unfiltered systems.[30]

A rather different filtering concept was proposed by Bender and Krivenko,[170] in which a transverse magnetic field is imposed in the cathode-anode gap. A "Hall stratum" forms in the interelectrode space on the retrograde side of a vacuum arc plasma, which will electrostatically reflect ions impinging on it [Fig. 4(n)]. Substrates are positioned such that they are exposed to the reflected ions but shielded from the cathode spots (and hence the MPs). In this configuration no plasma duct is required, and the design can be compact. Recently Bender *et al.*[171] experimentally demonstrated bending of the cathode spot produced plasma beam in a transverse magnetic field applied in the interelectrode gap.

VI. SUBSTRATE CONTROL AND FIXTURING

The substrates must somehow or other be held within the vacuum chamber in some location which receives depositing plasma flux. In some laboratory experiments, merely taping the substrates to a convenient wall of the deposition chamber may be sufficient, particularly for thin films. However, often a substrate holder is desired which also provides for controlling the substrate temperature, allowing for substrate bias, shielding of unwanted surfaces from deposition, moving the substrate to provide uniform coatings over large areas, multiple substrates or convoluted shapes, and/or accommodating quick loading and unloading from the vacuum system.

Obtaining good film adhesion to the substrate is critically dependent on substrate cleaning, which is usually accomplished in two stages: (1) *ex situ* chemical cleaning before mounting in the vacuum system and (2) pre-deposition *in situ* ion cleaning in the vacuum chamber. In most cases, the ion cleaning uses energetic metal plasma ions produced by the vacuum arc by applying a high negative bias voltage V_b to the substrate before deposition and a lower voltage during deposition.[172] The pre-deposition ion bombardment also heats the substrate. Substrate temperature is the most important parameter determining the coating structure,[173,174] and usually wear-resistant coating deposition on cutting tools requires heated substrates. In most cases, the temperature must be carefully controlled to prevent thermal damage and annealing of the substrate material. Nonconducting substrates, e.g., polymers and ceramics, may be ion cleaned in a glowdischarge established in a low-pressure background gas between the substrate which serves as the cathode and the chamber wall which serves as the anode.[175,176]

In some cases of VAD, especially of diamond-like carbon (DLC) deposition, an additional gas ion-beam source is used for ion bombardment cleaning. High-energy (up to 50 keV) repetitively pulsed gas ion beams are used for ion implantation or at lower energies (1–3 keV) for predeposition ion cleaning.[177–181]

Control of the substrate temperature and bias is important, as these can have very significant influence on the film properties. Controlling substrate temperature can be a significant issue, particularly in laboratory systems which can often be arranged to have very high deposition rates and hence high heat flux to the substrate.[29,175,182–184] Temperature control requires temperature measurement, which may be accomplished either by using some contact temperature sensor, such as a thermocouple, or with an infrared radiation monitor. Each has advantages and disadvantages. Contact sensors are generally the simplest to use and install, particularly on stationary substrate holders. However, they basically measure their own temperature and thus can measure the substrate temperature only if they are in good thermal contact with the substrate.[185] This is a nontrivial problem, and the thermal conductance considerations discussed in Sec. III C are also relevant here. Often such sensors are in good thermal contact only with the substrate holder and not with the substrate itself. When contact can be arranged between the sensor and substrate, it usually must be at the back surface to prevent plasma heat flux directly to the sensor. However, the temperature of significance for film growth is the front surface, and in the face of a high heat flux there can be significant temperature gradients across the substrate, particularly in the case of substrates with poor thermal conductivity such as polymers. Particularly when the substrate is biased, care must be taken in electrically isolating the measurement circuit, shielding it from arc-induced electrical noise, and deliv-

ering the signal to electrical instrumentation which is at ground potential. Infrared radiation detectors have the advantages of measuring the front substrate surface temperature, which is the desired quantity, and can be arranged to view moving substrates. However, an infrared viewing port must be provided and shielded from the coating. Surface radiation is dependent on the emissivity of the surface, which in general may be wavelength dependent and can be time varying, changing from that of the substrate to that of the coating during the process and even alternating from coating material to coating material if multilayer coatings are deposited. It should be noted that some infrared temperature monitors use multiple wavelengths, and thus an assumption of a common emissivity could be a cause of error.

Temperature control can be divided into three phases: (1) preheating to a desired temperature before deposition, (2) maintaining temperature during deposition, and (3) cooling the substrate to room temperature after deposition. If preheating is desired, it can be effected prior to deposition by biasing the substrate and subjecting it to ion or electron bombardment or by resistively or radiatively heating the substrate.[186–191] In laboratory apparatus, radiative heating can be conveniently provided by placing a commercially available halogen lamp[188–191] within the substrate holder. Maintaining a steady-state temperature during deposition may require additional heating or cooling depending on the deposition heat flux and the desired temperature. In laboratory apparatus, additional heating can be supplied by a resistive or radiative heater built into the substrate holder. If bias is supplied during deposition, electrical insulation or isolation of the heaters must be considered and can be a challenge. In industrial apparatus, external infrared heaters are sometimes used. Alternatively, the deposition parameters (arc current, and hence the deposition rate, or the bias voltage, and hence the impacting ion energy) are sometimes adjusted to maintain a particular substrate temperature. After deposition, the cooling time can be decreased by water cooling the substrate holder in laboratory apparatus or by providing the system with apparatus for circulating and cooling nitrogen gas.

It is often desired to bias the substrates, often at varying potentials, to provide sputter cleaning of the substrate surface before deposition and to control the film properties during deposition. The bias may be dc, rf, or pulsed, and an appropriate power supply must be provided, as discussed in Sec. VIII B. Generally the substrate holder must be electrically insulated from the chamber, and thus usually an insulated vacuum feedthrough with a voltage-withstand rating commensurate with the bias (typically 1 kV) under vacuum conditions must be provided. The substrate holder and its feedthrough should be designed so that the insulator is shielded from the plasma and depositing material to prevent degradation of its insulating characteristics.

In laboratory systems, where the research objective is to study film properties, uniformity only over a small area is usually sufficient, and the complications of having a rotary holder can often be forgone. The substrates are usually flat and can be attached to the substrate holder with tape, spring clips, or screws. It should be noted that the thermal conductance between the substrate and the holder can be an issue and often depends on the mounting force. In most industrial arc deposition equipment, large batches of complex workpiece substrates must be accommodated, and speed of mounting and dismounting is a significant economic issue. To provide sufficiently uniform coatings, a rotary fixture providing multiple degrees of rotation is usually used. Round-shaft cutting tools are usually held by their shafts in sockets which shield them from deposition. Insert tools having a central mounting hole are usually mounted on skewerlike holders, with spacers between adjacent tools, in a shish-kabob-like arrangement. Cemented carbide insert tools without a mounting hole are held on the substrate holder by high-temperature permanent magnets, which can effectively hold the tool because of the Co used in their liquid sintering. In typical industrial applications, particularly where different substrates must be coated, fixturing is a significant component (10%–25%) of the system cost. In contrast to the usual batch systems, in a few advanced in-line systems, the substrates are transported linearly past a broad vacuum arc plasma source.[60,61,192]

VII. PLUMBING

While the "scientific" aspects of the coating process are most influenced by the features described in the previous sections, a significant fraction of deposition system costs is contributed by more mundane "engineering" components of the system to be described in the following sections. Furthermore, these components often affect the operational convenience, reliability, and scientific throughput of the system.

A. Deposition chambers

The vacuum arc plasma sources and the substrate holders must be mounted in a vacuum deposition chamber. For most applications currently studied, vacuum systems conforming to "high-vacuum" standards are sufficient, and the cost and inconvenience of adhering to "ultrahigh-vacuum" standards are not warranted. Thus deposition chambers with elastomer o-ring-sealed flanges are usually used. Care must be taken that the temperature rating of the elastomer is not exceeded, however.

Most industrial systems[193] handle large batches of substrates, and the chamber is opened to the atmosphere to change the substrates. Laboratory systems are sometimes equipped with a load lock, e.g., a gate valve and loading chamber, so that only the loading chamber is exposed to air when exchanging substrates, thus reducing the cycling time.[55,92,175,182–184]

The chamber may be constructed from any material which is hermetically sealable and sufficiently strong to withstand atmospheric pressure from the outside. Austenitic stainless steel is the most common material, while sometimes mild steel is selected for lower cost, aluminum for better thermal conductivity and lower weight, or glass for laboratory convenience.

Thermal control is a significant issue, as the inner surface of the deposition chamber may be exposed to considerable heat flux from the plasma or radiation heaters. The most

elegant industrial chambers are provided with water jackets. Cooling water is flowed through the system during deposition, and flowing hot water is provided when the vacuum system is open to minimize moisture condensation and thus minimize pump-down time.

B. Vacuum pumps and gauges

Vacuum arc deposition chambers are generally evacuated with two stage pumping systems: a mechanical roughing pump and a suitable high-vacuum pump. In the authors' laboratory, oil diffusion pumps (without cold traps) are used exclusively due to their low cost, convenience, and robustness. In other laboratory and industrial systems, high-vacuum pumping may also be provided by turbo-molecular or cryogenic pumps. Generally only moderate vacuum levels are needed in comparison to other PVD technologies because of the high deposition rate and hence the higher tolerance for background gas for a given purity level.

Any suitable combination of vacuum gauges, e.g., a thermocouple gage for low vacuum and an ionization gauge for high vacuum, can be used to monitor the pump-down procedure. However, for control of reactive deposition processes, the use a of gauge which is independent of gas type is recommended, such as a capacitance manometer.

C. Gas flow control

Gas flow control is critical in reactive deposition processes. In the authors' laboratory, a constant pressure is maintained using feedback from a capacitive manometer to control a solenoid needle valve or a flow controller, using a proportional-integral-derivative (PID) control scheme embedded in a personal computer. Other setups are based on constant gas flow (rather than constant pressure) and implemented using commercially available gas flow controllers.

The gas flow geometry can also be a significant issue. Gas can be introduced near the substrate to minimize "poisoning" of the cathode.[194] Alternatively, the gas can be introduced near the cathode[195,196] or even through the cathode[197–199] in order to maximize the excitation and ionization of the gas and thus aid the activation of the reactive deposition processes. Alternatively, the gas can be introduced through an external discharge apparatus to a point near the substrate to provide independent control of the gas excitation.[69,152,200,201]

VIII. POWER SUPPLIES

A. Arc current

One of the advantages of arc deposition over sputtering is that relatively low-cost low-voltage power supplies can be utilized for exciting the arc discharge. Generally, commercially available dc welding power supplies are cost effective and convenient. Units which provide an open circuit voltage of at least 70 V (Refs. 60 and 99) are preferred. Third generation welders using 10–20 kHz switching and current control are commonly used today.

B. Substrate bias

Most systems use dc of up to −1 kV to bias the substrate for predeposition ion bombardment and lower values during deposition.[172] Placing a negative bias on the substrate in a plasma environment subjects the substrate to the risk of electrical breakdown leading to the substrate serving as an arc cathode, leading to cathode spot erosion damage of the substrate. This can be minimized or eliminated by using a power supply which detects arcing (i.e., by the rise of the bias current) and automatically shuts down until the substrate arc is extinguished. Such power supplies are commonly used in sputter coating systems and are commercially available. A few studies have used rf bias or pulsed bias.[202–210] Here also commercial units, which include rf impedance matching networks, are available from sputter equipment suppliers and are normally used in rf and pulsed sputtering, respectively. However, some studies with pulsed bias and, in particular, those involving pulsed plasma immersion implantation[211,212] use higher voltage peaks than those used in pulsed sputter equipment and may require custom-built power supplies.

IX. SYSTEM INTEGRATION AND HYBRID SYSTEMS

The choice of the specific components as well as the size of the deposition chamber, the speed of the pumps, and current rating of the various power supplies, etc., depend on the anticipated work load and are generally proportional to them. Thus system planning begins with defining the anticipated work program. This is of course absolutely essential in industrial installations but should be fully considered in research installations as well. The choices influence how many different samples can be produced in a given time and their cost and thus influence how many choices of parameters can be tested and how many samples for statistical verification can be produced and thus directly affect the potential quality of the research.

It should be noted that most of the components and most of the system cost are common for a variety of vacuum deposition technologies. Thus it is often feasible to fabricate a hybrid system which incorporates more than one technology at a relatively small marginal cost. Generally a VAD system can be used for sputtering if an appropriate background gas is employed, and an appropriate power supply to excite a glow discharge is connected. Alternatively, more efficient operation is possible by mounting additional sputter cathodes having optimized magnetic fields. Hybrid systems which include both vacuum arc and unbalanced magnetron sputtering deposition are available commercially. Likewise, with appropriate initial planning, evaporative sources can be incorporated in the deposition chamber, or the chamber can be used for chemical-vapor deposition or plasma-assisted chemical vapor deposition; such systems have been used to fabricate superhard nanocomposite coatings.[213–218]

Likewise, vacuum arc deposition can be combined with ion implantation. The implanted ions may be metallic, produced by the vacuum arc, or from a gaseous source. In plasma immersion ion implantation (PIII), ions may be implanted by applying a high-voltage pulse to a substrate in a

plasma, including a vacuum arc plasma, and thus a hybrid VAD-PIII system requires additionally beyond the requirements of a VAD system only that the substrate holder be able to withstand the requisite voltages and an appropriate power supply to produce the voltage pulses.[152–154,211,212,219–221] Hybrid systems containing a separate ion source[177–179,222–226] or an ion/electron source,[227] along with a vacuum arc metal plasma source, allow considerable operational flexibility, including processing different substrates by different technologies according to the desired coating properties, depositing multilayer coatings, where the different layers are deposited by different technologies, ion implantation before, during, or after deposition, or even formulating hybrid processes, depending on the hybrid chosen.

While laboratory apparatus can be operated totally manually, it is often desired, especially but not only in industrial production, to have automated control of the deposition system and to log process parameters and fault conditions during the procedure. In laboratory equipment, it is often convenient to implement the control and data collection procedures using a personal computer equipped with suitable analog and digital input/output cards. If the computer-based equipment is used to monitor instruments which may come in contact with the plasma or other instruments which might be exposed to high voltage, high-voltage clamping circuits should be added to the inputs and outputs. In industrial systems, programmable controllers, which are more robust and reliable, are often preferred for automated control, with a personal computer operator interface.

X. DISCUSSION

The design of vacuum arc deposition systems is influenced strongly by the particular physical properties of the vacuum arc and the plasma which it produces. In particular, in the most common cathodic arc systems, a combination of shields and magnetic fields is used to control the location and motion of cathode spots. In some applications, macroparticles must be removed, and this is accomplished by magnetically guiding the plasma beam around an obstacle which blocks the macroparticles. The deposited film properties depend strongly on (1) the substrate temperature, which must be controlled through a combination of a temperature sensor and heating and/or cooling means, and (2) the energy of the depositing ions, which may be controlled by negatively biasing the substrate. These physics-dependent elements are integrated with engineering elements including a vacuum chamber, vacuum pumps and gauges, gas flow controllers, cooling, and power supplies to produce laboratory or industrial vacuum deposition systems.

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