Comparative study of evaporation using DC and AC filament electron guns

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Abstract. Electron beam assisted physical vapour deposition (EB-PVD) and purification of metal by repeated melting using electron guns is a well-established technique in industrial metallurgy. Strip electron gun is considered a cost effective alternative to multiple pencil guns for handling of large size substrates. In the electron guns, the thermionic emission of the electrons from a filament is achieved by using AC or DC filament heating. A study of their relative merits and demerits was conducted for the both types of electron guns. Due to finite length of the filament, the magnetic field generated around the filament by heating current drops down towards ends. The DC filament heating results in electron beam with a comet shape having high power density hot spot at one end with low power density tails. With AC filament heating, electron beam oscillates with the frequency as that of heating current. The study of vapour flux distribution using DC gun revealed that highly directional vapour evolution takes place from a smaller hot spot whereas with AC gun vapour evolution occurs from an oscillatory 2D-evaporating source. The vapour deposit on substrate indicated that evaporation using DC gun caused splashing and granular deposit due to volumetric melting and evaporation from the ingot. This is contrary to the AC filament heating wherein quiet evaporation was observed due to surface melting and evaporation. The experimental results are critically reviewed to decide the configuration of electron guns for large-scale evaporation.

1. Introduction
Electron beam physical vapour deposition (EB-PVD) is a well-established industrial scale process for material processing \cite{1,2}. In order to handle large surfaces, multiple pencil electron guns and oscillatory electron beams were used. However these techniques have their own limitations. Uniform power density can be achieved only when beam diameter is close to oscillation amplitude \cite{1}. To overcome this disadvantage, the oscillating strip electron gun is considered the best alternative \cite{3}. Filaments of refractory materials such as tantalum and tungsten are used in strip electron guns, based on their low work function, ease of shaping and high operating temperature. The electrons obtained from the thermionic emission caused due to resistive heating of the filament current are accelerated by applying a negative voltage of the order of 50 to 60 kV to the filament and grid cup assembly with
respect to the water cooled anode. The sheet of electron beam is focused using anode-cathode configuration to form a parallel beam focused at $270^\circ$ using magnetic field in field free region with an electromagnet in Helmholtz's configuration.

For generation of thermionic electrons, filaments can be heated using DC or AC. Both these have their merits and demerits. Due to high current passing through the conductor, the magnetic field generated in the vicinity of the filament has a deciding role on various parameters such as residence time, power density distribution and dimension of the beam, etc. [4].

In case of DC filament heated gun, the electron trajectories are permanently shifted at one end and rarefied at the other end depending on the polarity of the DC. This results in highly concentrated hot spot and rarefied tails, similar to that in a comet. Hence, these electron guns provide electron beam with non-uniform power density resulting in trench formation and smaller molten pool on the substrate surface.

In case of AC heated electron gun, the polarity of magnetic field due to current carrying conductor changes with time. This results in oscillation of strip electron beam on the target surface. Hence, the non-uniformity in current/power density gets smeared out to give uniform temperature, larger molten pool but less residence time. Due to the finite length of the filament, the magnetic field tapers off on either side. This end-effect can be overcome by using the dummy filament concept. The dummy filaments are thick filaments of the same material that carry same amount of current but do not contribute to the thermionic emission due to lower temperature. The dummy filament shifts the tapering of the magnetic field so that bunching and rarefaction of electron trajectories are avoided [4].

In this article we present comparative studies of copper evaporation using DC and AC heated electron guns.

![Fig. 1. Schematic diagram of the experimental setup.](image)

**2. Experimental Setup**

The experimental studies with the DC and the AC heated filament electron guns were carried out in a water-cooled double-walled vacuum chamber operating at $5 \times 10^{-6}$ mbar. The details of the 100 kW evaporator, along with its accessories are reported elsewhere [3]. The AC/DC heated strip electron guns are identical in design except the filament heating current. The schematic of the strip electron gun is given in Fig 1. It consists of segmented tantalum filament mounted on the filament holder assembly encapsulated inside the grid cup insulated to − 60 kV potential with respect to ground using alumina insulators. The sheet of electrons emerging out of the anode is focused on the copper ingot by deflecting the electron beam through $270^\circ$ (radius of deflection $R = 260$ mm) in the presence of a magnetic field using electromagnetic coils arranged in Helmholtz configuration. The bending of the beam is necessary to prevent metal vapour from entering into anode–cathode space. In case of DC filament heated electron gun, segmented tantalum had length of 110 mm whereas in case of AC filament heated gun, the filament had a length of 130 mm and the dummy filaments on each side were 30 mm long.
The performance of the AC/DC filament strip electron guns was tested using copper as the target material. The photograph of the evaporating source with DC and AC filament heated electron guns are shown in figure 2. The electron guns were operated with radius of deflection 260 mm. The DC evaporating source was observed to have an average dimension of 110 mm x 10mm with high intensity zone on one end and low intensity comet-like tails on other end. In case of AC filament heating evaporating source the average dimensions were 130 mm x 5 mm with oscillating amplitude of 370 mm.

![Fig. 2. Incident beam on the copper ingot in case of: (a) DC filament heated electron gun (b) AC filament heated electron gun.](image)

The molten pool produced with two DC guns at 45 kW each and two AC guns at 85 kW each are presented in figure 3. It can be seen that the molten pool during DC filament heating was much smaller compared to that formed with AC filament heating. Also there is a trench formation at the ends due to high intensity spots.

![Fig. 3. Images of frozen molten pool in case of: (a) DC filament heated electron guns at 45 kW each (b) DC filament heated electron guns at 70 kW each and (c) AC filament heated electron guns at 85 kW each.](image)

In order to study the evaporation from a source generated using AC/DC filament heated electron gun, the vapour is allowed to deposit on collectors. Cumulative deposits were analyzed. The

![Fig. 4. Deposit collected in case of: (a) DC filament heated electron gun (b) AC filament heated electron gun.](image)
evaporation using a DC electron gun resulted in the formation of granules on the deposit formed on the SS target, placed at a height of 550 mm above the source, as is evident in figure 4(a). The deposit thickness was monitored at regular intervals along the length of the deposit.

In case of AC heated gun generated evaporating source, evaporating source was maintained at 1980 K with Knudsen number 0.06 and evaporation rate 580 g/h. The self-sustaining copper layer was taken for deposit analysis. The eighteen tokens (6.5 cm² each) were cut with known coordinates with respect to evaporating source at a height of 680 mm from the source. The uniform coating on the collector hardly showed any trace of granules, clearly indicating atomic layer deposition (figure 4(b)).

3. Results and Discussion

3.1 Shape of the incident beam
During filament heating for thermoionic emission, a magnetic field is generated around the filament. Due to finite size of the filament, magnetic field tapers off on either side. As a result of this, electron trajectories not only shifts permanently away from filament but also gets concentrates on one end and rarely on other side causing non-uniform current density distribution within the beam [4].

In case of electron guns using DC heated filaments, the direction of the magnetic field is decided by the polarity of the DC. Thus electron trajectories are shifted in one direction with non-uniform current density distribution. As a result, evaporating source generated has non-uniform power density on the target surface with high power density on one side as can be seen in figure 2(a).

On the other hand, AC changes its polarity in each half cycle. The frequency of oscillation is same as that of the supply frequency, i.e., 50 Hz. As a result, the electron beam oscillates on the target surface with amplitude proportional to the magnitude of filament heating current and radius of deflection. Power deposition depends on the residence time of the electron beam at different location within the oscillation amplitude and non-uniformity in the electron beam gets smeared out as can be seen in figure 2(b).

Non-uniform current density distribution in electron beam due to magnetic field end effect caused by the AC/DC filament heating current can be overcome using a dummy filament [4]. As a result of incorporation of dummy filament, the non-uniformity in the magnetic field is done away with and bunching and rarefaction of electron trajectory is minimized. The AC filament electron gun results presented here are with incorporation of dummy filament.

3.2 Molten pool
During evaporation with DC heated gun, electron beam is stationary on the surface. Two DC filament heated guns placed in line and operated at 45 kW each are used to study the molten pool as can be seen in figure 3(a). The frozen profile of the target shows non-uniform power density distribution leading to trench formation, volumetric melting with smaller molten pool size. At higher power (70 kW each), the two trenches merge together to form a molten pool with greater depth but similar width as shown in figure 3(b).

In case of AC filament heated gun, the electron beam covers larger target surface area during its oscillation and temperature on the target depends on residence time of the electron beam. With present 50 Hz oscillations and 370 mm oscillation amplitude, the residence time is such that it does not allow solidification at any location within the oscillation amplitude maintaining molten pool size of a length more than the oscillation amplitude. We have used two AC filament heated guns placed in line and
operated at 85 kW each to study the molten surface as can be seen in Fig 3(c). The frozen profile of the target shows larger molten pool with uniform depth.

3.2 Vapour flux distribution

In order to study vapour flux distribution, two DC filament heated guns were operated at 70 kW each. The copper vapour generated was allowed to deposit on a SS collector placed at 550 mm above the evaporating source. The vapour deposited was fitted using the generalized vapour flux distribution from a 2D evaporating source defined as

\[ \left( \left( \frac{n_1 + n_2 + 2}{4 \pi} \right) \cos^{n_1} \theta \cos^{n_2} \phi \right) \]

where, ‘\( \theta \)’ is the angle between normal plane passing through strip source and plane containing the collector and ‘\( \phi \)’ is the angle between the line joining an elemental source and a collector area with respect to the normal to the elemental source area in any given ‘\( \theta \)’ plane. The co-ordinate system used for analysis is reported earlier [5] and shown in figure 6. The exponent \( n_1 \) is the beaming coefficient along the width direction of the evaporating source corresponding to ‘\( \theta \)’ and the exponent \( n_2 \), is the beaming coefficient along the length direction of the evaporating source corresponding to ‘\( \phi \),’ respectively.

With this general vapour flux distribution function [5], the vapour flux (atoms/sec) on a horizontal collector of area ‘\( a_c \)’ in SC direction (having length SC) from an elemental source area, ‘\( a_S \)’ is given by

\[ F = \frac{Q}{DL} a_S \left( \frac{n_1 + n_2 + 2}{4 \pi} \right) \cos^{n_1} \theta \cos^{n_2} \phi \frac{a_c \cos \theta \cos \phi}{SC} \]

where \( Q \) is the total evaporation rate (atoms/sec) from the source of dimension \((D \times L)\).

The deposit obtained on the SS collector due to evaporation using the DC gun was analysed by measuring the thickness of deposit along the edge of the shutter, which is parallel to the length of the linear beam. During this fit, the vapour emitting source was assumed to have a high temperature central region of 1 cm x 2.4 cm embedded on a low temperature evaporating source of 1 cm x 30 cm at 1600 K. From earlier measured value of power vs. temperature [6], the central hot spot was assigned a temperature of 2000K. The beaming coefficient, length of the hot spot and the temperature difference between high & low evaporating area were kept as variable parameters while fitting the experimental data. The measured thickness could be fitted with error <14% with beaming coefficient as high as 15 with high evaporating source of 1cm x 2.4 cm with temperature 2000 K embedded on 1 cm x 30 cm evaporating source of 1600 K.

The vapour flux distribution using AC filament heated strip electron gun was carried out using single gun operated at 116 kW with copper as a target. The evaporating source was maintained at 1980 K (Knudsen number=0.06). The collection run was conducted by opening the shutter for 5160 sec. The
vapour deposited on SS substrate placed at 680 mm above the evaporating source was analyzed by weight difference technique. The data was fitted using above mentioned generalized vapour flux distribution function for 2D source using Eqn. 2. The beaming coefficients were found to be: \( n_1=2 \), \( n_2=3.5 \). The error of fitting was found to be 13%.

The deposition using DC/AC filament heated strip electron gun is presented in Fig 7. The difference in the deposition thickness is due to difference in collection time. The drastic fall of thickness of deposit along the length and the high beaming coefficient during DC filament heated strip electron gun evaporation clearly indicate highly collimated atomic beam from a hotspot embedded in a low temperature evaporating source generated from a comet-shaped electron beam having high power density spot with low intensity tail. Thus evaporation from a DC strip electron gun can be considered as volumetric with splashing. The uniform deposits along the length with moderate beaming coefficient during evaporation with AC heated electron gun clearly indicate quiet and uniform evaporation from the surface of the molten pool of the target.

4. Conclusion
It can be concluded that the high evaporation rates can be achieved using DC filament heated strip electron gun from a smaller molten pool. One has to be careful about power density distribution in the electron beam, as it is likely to result in hotspot formation, splashing and volumetric evaporation. It is possible to achieve uniform deposition over large substrate length from quiet surface evaporation using AC filament heated gun.

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