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Simulation of electron beam from two strip electron guns and control of power density by rotation of gun

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Abstract: Electron beam is preferably used for large scale evaporation of refractory materials. Material evaporation from a long and narrow source providing a well collimated wedge shaped atomic beam has applications in isotopic purification of metals relevant to nuclear industry. The electron beam from an electron gun with strip type filament provides a linear heating source. However, the high power density of the electron beam can lead to turbulence of the melt pool and undesirable splashing of molten metal. For obtaining quiet surface evaporation, the linear electron beam is generally scanned along its length. To further reduce the power density to maintain quiet evaporation the width of the vapour source can be controlled by rotating the electron gun on its plane, thereby scanning an inclined beam over the molten pool. The rotation of gun has further advantages. When multiple strip type electron guns are used for scaling up evaporation length, a dark zone appears between two beams due to physical separation of adjacent guns. This dark zone can be reduced by rotating the gun and thereby bringing two adjacent beams closer. The paper presented here provides the simulation results of the electron beam trajectory and incident power density originating from two strip electron guns by using in-house developed code. The effect of electron gun rotation on the electron beam trajectory and power density is studied. The simulation result is experimentally verified with the image of molten pool and heat affected zone taken after experiment. This technique can be gainfully utilized in controlling the time averaged power density of the electron beam and obtaining quiet evaporation from the metal molten pool.

1. Introduction

Electron beam is preferably used for evaporation of refractory material in metallurgical industry owing to its highest achievable power density, crucible free operation and clean environment. Generally pencil type electron gun is used for applications requiring low evaporation rate (few grams/hr) like optical coating industry. In order to increase evaporation area for application requiring higher evaporation rate, either multiple electron guns are used or single high power pencil beam is scanned over a limited region (scanning amplitude proportional to the spot diameter) [1-3]. In specialized applications like isotopic purification required in nuclear industry, a very high evaporation rate (few kgs/hour) along with stringent conditions of quiet evaporation from a linear vapor source generating a wedge shaped atomic beam is essential. The linear vapor source can be conventionally generated by placing multiple pencil electron guns in a row or by scanning a high power density pencil beam over a line. But, the requirement of quiet evaporation puts an upper limit to the power density used to avoid splashing of liquid metal. As an alternate to multiple pencil type beams or scanning pencil type beam,

a true linear electron beam is preferred to obtain high evaporation rate with low incident power density. An indigenously developed strip filament type electron gun [4] is used for this purpose. Such type of electron beam is instrumental in generating high evaporation rate as well as avoiding splashing.

To further scaling up of linear vapor source (increasing length) and to generate a larger molten pool to feed the vapor source, the electron beam is scanned along its length by gainfully utilizing the AC magnetic field generated by the filament heating current [5]. The scanning amplitude is typically of the





order of electron beam length. Still further scaling up of the evaporation length requires use of multiple strip electron guns placed adjacent to each other. When multiple strip electron guns are used, due to finite geometrical spacing between two guns, a dark zone is inevitable on the target surface. To overcome the dark zone, the individual electron gun can be rotated suitably to bring the electron beam from two separate guns closer to each other. A typical configuration of strip electron beam from two strip type filaments traversing through 270° bending before falling on the target surface is shown in Figure-1. The rotation of the gun serves another purpose of controlling the power density of the electron beam. When the gun is rotated, an inclined beam is getting scanned over the length thereby increasing the overall width of the beam and hence reducing time averaged power density.

The concept of how the rotation of the gun leads to reducing average power density and also reducing dark zone is illustrated in Figure-2. The filament length of the electron gun in its normal configuration is parallel to the axial magnetic field. The electron beam is deflected in circular fashion



Fig. 2. Illustration of the effect of rotation of the gun on the overall length and width of two strip beams and hence the average power density of the incident electron beam.

(Figure-1) and fall on the target in a line parallel to axis of magnetic field. When such a beam is scanned along the axial direction the overall beam width is the minimum. On the other hand when the electron gun is rotated by a small angle making an angle with the axial magnetic field, the electron

beam traverses a spiral path and falls on the target at a location closer to the centre. Moreover, the electron beam on target is also inclined with respect to the axial direction. When such a beam is scanned along the axial direction, the overall width of the beam increases. Although the scanning length is reduced, the time averaged power density over one scanning cycle is also reduced due to increase in overall width of the scanned electron beam.

The paper describes the simulation carried out for the power density distribution and change in beam dimension due to rotation of the electron gun.

2. Experimental Setup

The experimental system consists of a large cylindrical vacuum vessel, inside which a copper block (target of 600 mm x 200 mm surface area) is kept inside water cooled copper crucible. The target is heated by electron beam from two electron guns kept below the crucible. Each electron gun consists of a strip type tantalum filament of length 130mm and width 3mm generating thermionic electrons by I^2R heating. The sheet of electron beam accelerated up to 60 keV, focused and extracted by properly shaped grid electrode and anode. The extracted beam is deflected by 270^0 in a circular path of 260 mm radius by an axial magnetic field (~32 Gauss) generated by a pair of Helmholtz coils. The magnetic field is generated in the vicinity of the filament due to filament heating current. Due to tapering of the magnetic field towards end of the filament due to its finite size, electron trajectories are not only permanently shifted but bunch at one end and rarified at other end. On either side of the electron emitting filament, 30 mm of dummy filament is inserted to avoid non-uniform magnetic field due to filament heating current [5].



Fig. 3. The Image of the copper target (600 mm long) after impinged with electron beam from two strip type electron guns. A] When the two guns were co-linear. B] When two guns are rotated by 3^0 towards centre. It can be seen that the overall length of the electron beam is > 600 mm in first case (heat effects are seen on the moly plate kept on the crucible) and less than 600 mm in second case as predicted by simulation.

The dummy filament length, grid electrode and physical separation between two guns add to the spacing between the active filaments. In the present configuration a minimum 150 mm separation between active filaments of two adjacent guns is required. The electron beam is scanned along its length by the AC magnetic field generated by the filament heating current. The scanning of the two

electron beams are in phase so that a constant separation is maintained between two electron beams while scanning. The amplitude of the scanning depends on the filament heating amplitude. In this experiment an AC filament heating current of 90 Amp rms is used to provide oscillation amplitude of 370 mm (±120mm oscillation and 130mm electron beam length).

A molybdenum sheet is kept on the boundary of the crucible to observe if the electron beam is falling beyond the crucible length of 600 mm. As the electron beam falls on it a heat mark is observed (Figure-3). As in-situ measurement of the electron beam length is not feasible in the present experimental system, the heat mark on molybdenum sheet will be an indication of the length of the scanned electron beam.

Two electron guns are initially placed with the filament length co-linear with each other. In this case, the electron beams from both the guns move parallel to each other. The beam impression on the target is observed with the heat mark on molybdenum sheet and molten pool size of copper target. The same experiment is repeated by rotating the guns by 3^0 on its plane in such a fashion that the filament makes an angle with magnetic field axis. The electron beam from both guns in this case traverses towards the centre of the crucible and the gap between the two beams is reduced.

3. Simulation of Electron Beam and results

Simulation of electron beam from the filament up to the target is carried out by solving Lorentz equation numerically in time step of 1×10^{-12} sec. The electrostatic field in the region between anode and cathode, the magnetic field due to filament heating current and the bending magnetic field are incorporated into the Lorentz equation for solving the electron beam trajectory. As filament heating current of 50 Hz frequency is used, the simulation is carried out for 20 msec (one cycle) so that the time averaged beam characteristics can be obtained.

Electron beam is assumed to be emitting uniformly from the surface of active filament (130mm x 3mm). Emission current of 2.5 amp from each gun accelerating to 60 kV is considered. Total power incident on the target is 300 kW (150 kW per gun). The pervience of each gun is $(J/V^{3/2})$, where J is emission current density (0.64 amp/cm²) and V is electron beam energy (60 kV). Thus the pervience of each gun is 0.044 μ Pervience. The space charge repulsion within the electron beam is neglected as



Fig. 4. The simulation result of electron beam trajectory from two strip guns. Trajectory is plotted for 0, +ve peak and –ve peak of filament current. [A] the filaments of two guns are colinear and the scanned beam length is more than the target length of 600 mm. [B] the filaments are at 3° angle and the electron beam is now contained within target length.

the pervience of the electron beam under consideration is much less than the pervience required for onset of charge repulsion within the electron beam.

The simulation is carried out using MatLab program to visualize the trajectory when the gun is rotated by an angle. The simulation is carried out for two cases (Figure-4). One for the filaments from

both guns positioned in one line and in second case filament is making an angle 3^0 with respect to the co-linear position. The filament heating current is 90 amp AC is used for both the cases for oscillating the beam along its length. In first case the scanned electron beam length is higher than the second case. Initially at the beginning of electron beam trajectory, the separation between two beams is 150 mm. In first case as both the electron beams travel parallel to each other, the gap of 150 mm is maintained till the target surface. When the electron beams are made to oscillated in phase, the gap between the two beams remains throughout the oscillation period.

In case of rotated beam the gap between two beams is reduced along the beam trajectory from filament to the target. For 3^0 rotation, it is found that the gap 0f 150 mm has reduced to 20 mm. The reduction in gap has advantageous in avoiding the dark zone in evaporation source.



Fig. 5. The time averaged power density and location of the electron beam on a target from two strip type electron guns. The guns are rotated by various angles $(0^0, 1^0, 2^0 \text{ and } 3^0)$ towards each other. It can be seen that as the angle of rotation is increased, the length of the electron beam reduced from 706 mm to 588 mm where as the average width has increased from 3.5 mm to 8.25 mm. This has resulted in reduction of power density from >15 kW/cm² to <10 kW/cm².

The evaporation rate form the linear vapor source depends on the source temperature which in-turn is dependent on incident power density, material property of target material and cooling. The rotation of the gun has effect on the overall size of the beam and the time averaged power density. The

simulation using in-house developed electron beam trajectory program is carried out for 0^0 , 1^0 , 2^0 and 3^0 rotation. When the gun is rotated the electron beam image on target is also rotated with respect to the scanning direction. When such inclined beam is scanned, the time averaged width of the beam increases with angle of rotation and correspondingly the time averaged power density is decreased. The incident power density is plotted for two 150 kW electron beams as described earlier. As can be seen from Figure 5, as the angle of rotation is increased, the length of the electron beam reduced from 706 mm to 588 mm where as the average width has increased from 3.5 mm to 8.25 mm. This has resulted in reduction of power density from >15 kW/cm² to <10 kW/cm².

4. Conclusions

The results of simulation of electron beam from two strip electron guns shows the overall scanned length, width and time averaged power density of the incident electron beam can be changed by rotating the electron guns. This method can thus be gainfully utilized to suit the process requirement like containing the electron beam within the limit of the crucible length, reducing the dark zone between two strip electron beams and also to reduce the time averaged power density for obtaining quiet evaporation.

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