Profiling of back-scattered electrons in opposed magnetic field of a Twin Electron Beam Gun

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Abstract: Electron gun is extensively used in material processing, physical vapour deposition and atomic vapour based laser processes. In these processes where the electron beam is incident on the substrate, a significant fraction of electron beam gets back-scattered from the target surface. The trajectory of this back scattered electron beam depends on the magnetic field in the vicinity. The fraction of back-scattered depends on the atomic number of the target metal and can be as high as ~40% of the incident beam current. These back-scattered electrons can cause undesired hot spots and also affect the overall process. Hence, the study of the trajectory of these back-scattered electrons is important. This paper provides the details of experimentally mapped back-scattered electrons of a 2x20kW Twin Electron Beam Gun (TEBG) in opposed magnetic field i.e. with these guns placed at 180° to each other.

1. Introduction

Electron Beam (EB) evaporation is useful for atomic vapour based laser separation process, where a metallic charge contained in water cooled copper crucible, is evaporated in high vacuum environment [1, 2]. When an electron beam is incident on the charge (metal/alloy), temperature of the substrate under the beam rises causing a molten pool contained in solid skull of metal/alloy. The evaporation rate depends on the surface temperature which is governed by the power density of the electron beam, while the molten pool size depends on the total power of the electron beam and the effective heat transfer coefficient at the surface of water cooled crucible. Two electron beams focused on a single ingot are useful for independently controlling the evaporation rate and the molten pool size. One beam is focused to attain the required power density and the second defocused electron beam supplies the balance power for attaining fully molten condition of the charge. In EB evaporation a part of the incident beam gets back scattered and its trajectory is dictated by the surrounding magnetic field, while the fraction depends upon the atomic number of the charge. It can be as high as 40% for element with atomic number more than ninety [3]. The trajectories of the back-scattered electrons should be contained to ensure (i) no local heating of surfaces and (ii) these electrons do not land in the process zone.

The trajectory of backscattered electrons for 2x20KW twin electron beam gun (TEBG) system, in opposed magnetic field, i.e., with these guns placed at 180° to each other has been experimentally determined. A number of experiments have been conducted to identify the limits of operation of the TEBG, for minimizing its interference with the process. The experimental details and observations have been presented in this paper.
2. Experimental Set-up

TEBG has a water cooled cooper crucible with a cavity of 156cc for holding the charge to be evaporated. The two electron guns are configured opposite to each other, i.e., at 180° orientation as shown in the top view of crucible in Fig 1(a). The magnetic shunt pieces are meant for altering the magnetic field, to increase the extent of sweep of the electron beam in oscillating mode. Each of 270° bend electron gun has independent 12kV, 1.7A power supply for its use up to maximum of 20kW. The copper crucible and the assemblies of both the electron guns have separate water cooling circuit as depicted in the side view of crucible in Fig 1(b). A water cooled copper shroud around the crucible protects the crucible and the assemblies of electron gun from undesirable heating. The entire assembly is placed in a high vacuum water cooled jacketed chamber as shown in Fig 2. This jacketed vacuum chamber (W 550mm, L 550mm, H 750mm) is made of stainless steel. A vacuum of 3x10^{-6} mbar is maintained using 3000lps diffusion pump, backed by a 60m^3/hr rotary pump. The Pirani and Penning gauges were used to measure the vacuum in the chamber.

The orientation of the magnetic fields in the longitudinal direction i.e. along the path of primary electron beam and in direction normal to longitudinal i.e. transverse direction is shown in the Fig 3. The magnetic field of the permanent magnets has been mapped at the surface of crucible in both the directions. The profile of magnetic field for the cases of with shunt and without shunt is given in Fig 4.
3. Experimental Procedure and Results

3.1. Identification of position of primary electron beam

The permanent magnetic field around the electron beam ensures that the primary electron beam always falls within surface of cavity of crucible. However, the magnetic field due to electromagnet is used for fine adjustment of the location of the incident electron beam. The correspondence between the magnetic field and the location of incident beam was initially obtained by the puncturing a metal sheet placed on the surface of ingot at low beam power. The calibration of actual location of beam spot corresponding to the reading on sweep control unit is given on Fig 5. This information is useful in correlating the profile of back-scattered electron with the position of beam.

3.2. Profiling of back-scattered electron

It can be seen in Fig 4 that the magnetic field has a null point at the centre of surface of ingot. In case of profile along longitudinal direction the magnetic field peaks near the electron beam exit port in the crucible and in the transverse direction the magnetic field peaks at the edge of the copper crucible due to the pole pieces of the permanent magnet. It can be expected that the back-scattered electrons from the centre of the ingot may sense minimum or nil magnetic field for its bending and hence may go in vertically upward direction. Whereas, the back scattered beam away from the centre of ingot is expected to bend on both sides along the transverse direction due to significant magnetic field in this direction. Therefore, experiments were carried out in three stages to make an assessment of direction and profile of the back-scattered beam as a function of spot location of primary beam on the ingot. Firstly, the trajectory of back-scattered electron was determined just near the ingot over a cylindrical surface with radius of 75mm. Thereafter, these electrons have been profiled at various distances (0mm, 50mm and 100mm) from the side of the crucible i.e. starting from 75mm from the centre of ingot. And finally, the total current of the backscattered electrons is measured at various heights (150mm, 200mm and 250mm) in vertically upward direction from the surface of ingot. All these results are summarized as follows.

3.2.1. Profiling in cylindrical coordinates with fixed radius

The semi-cylindrical structure with 15 numbers of 12 x 270 mm² stainless steel strips as electron collector at a radius of 75mm is shown in Fig 6. Each of these collectors is electrically insulated from the frame and is shorted to ground through a resistance. The voltage drop across the resistance provides the information of current collected by respective collector.
One of the electron guns was located with and without magnetic shunts and the current collected by each collector is measured. The electron beam power was 600W (12kV, 50mA). The Fig 7(a) and Fig 7(b) provide the plots of electron current of these strip electron collectors, for various locations of the primary incident beam along longitudinal direction, with and without the magnetic shunt pieces respectively. The Fig 7(c) is a plot of electron current collected by collectors for changing location of primary incident beam along transverse detection and without magnetic shunt pieces. These results clearly show that the electron current in vertical direction is in general more in case of use of magnetic shunt pieces in comparison to without use of magnetic shunts and this current drastically reduces if the position of electron beam is kept towards the operating gun side. The movement of primary beam along transverse direction only shifts the location of peak of back-scattered electrons but does not change its magnitude.

3.2.2. Profiling at various distance from the sides of crucible

The set-up for profiling the back-scattered electron at various distances on the side of crucible consist of a number of electron collectors with a diameter of 25mm and with a pitch of 33mm mounted with electrical insulation on a 300mm wide plate. Fig 8(a) shows this plate placed on the edge of the side of crucible. The back-scattered current on the disc collectors in each row and each column have been recorded for electron beam power of 1200W (12kV, 100mA) and for the distance of 0mm, 50mm and 100mm from the side of crucible.

Table-1 & 2 show the consolidated results of cumulative current collected by each row and each column of these disc collectors for all the cases of distances and for with and without magnetic shunt pieces. These results clearly indicate that the back-scattered electrons from the centre travel longer radius. A major fraction of these electrons is contained in bottom three rows, i.e., up to height of ~120mm and within middle three columns i.e. 70 to 80mm measured in the transverse direction.

Fig 7: Profile of current collected on 15 numbers of 12 x 270mm² strip shape electron collectors on cylindrical surface with diameter of 75mm radius
3.2.3. Profiling at various heights from the surface of crucible

The same structure with an array of $\varphi 25$ disc collectors was used for measuring the electron current in vertically upward direction from the surface of the crucible. However, in this case only the total current of all of these collectors have been recorded for the location of primary beam near centre on the ingot. This structure, holding the disc collectors, is mounted on a linear motion feed through from the top of chamber as shown in Fig 8 (b). This mechanism helps in changing the height of structure and hence for recording the current of back-scattered electron at various heights. Fig 9 (a) shows the current of back scattered electrons collected for 50-600mA primary beam at 150, 200 & 250mm height from the crucible surface, when only one of the electron gun is operated. It clearly shows (i) there is a significant back-scattered current in the vertical upward direction above the crucible, (ii) current of back-scattered electron collected at various heights is, as expected, proportional to the primary beam current, and (iii) there is no change in the current collected by array of disc collectors on 170x300 mm$^2$ plate as the bending of back-scattered electron, due to magnetic field is only below this height. Fig 9 (b) shows the current of back scattered electrons collected for the cases when only one gun is operated and also when both the guns are operated with 50-600mA current of primary beam. The beam positions, as indicated on the control panel (-5, 0) for beam A and (0, 0) for beam B, are at nearly same location and is around the centre of the ingot. The results clearly show that behavior of back-scattered electron, for both the guns, is the same and linear with respect to the current of primary beam.

![Typical orientation used at the side of crucible](image1)
![Typical orientation used at position vertically above the crucible](image2)

**Fig 8: Experimental set-up with an array of electrically insulated disc for profiling back-scattered electron with a diameter of 25mm and pitch of 33mm**
Conclusions

The trajectories of TEBG suggest that the distribution of the backscattered electrons is concentrated at certain locations according to the resultant magnetic fields in the vicinity of electron beams. These electrons can also interfere with the process zone if the EB incidents on the ingot towards opposite side gun. To confine the back-scattered electrons, the primary electron beam should not cross the mid plane along longitudinal direction, as it leads to enhanced back-scattering in vertically upward direction. Moreover, magnetic shunt pieces are not useful in TEBG with 180° orientation as shunt pieces are meant for increasing the extents of oscillating beam in order to cover a larger area over the crucible surface.

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