Abstract

The present study covers the design and analysis of a thermionic scanning electron microscope (SEM) column. The SEM column contains an electron optical system in which electrons are emitted and moved to form a focused beam, and this generates secondary electrons from the specimen surfaces, eventually making an image. The electron optical system mainly consists of a thermionic electron gun as the beam source, the lens system, the electron control unit, and the vacuum unit. In the design process, the dimension and capacity of the SEM components need to be optimally determined with the aid of finite element analyses. Considering the geometry of the filament, a three-dimensional (3D) finite element analysis is utilized. Through the analysis, the beam emission characteristics and relevant trajectories are predicted from which a systematic design of the electron optical system is enabled. The validity of the proposed 3D analysis is also discussed by comparing the directional beam spot radius. As a result, a prototype of a thermionic SEM is successfully developed with a relatively short time and low investment costs, which proves the adoptability of the proposed 3D analysis. © 2008 Elsevier B.V. All rights reserved.

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1. Introduction

The scanning electron microscope (SEM) is one of the most popular instruments available for the measurement and analysis of the micro/nano structures. The SEM offers a high resolution by using an electron beam source with wavelength of less than 1 nm [1]. The electron beam source is categorized as either a thermionic gun or a field emission gun depending on the way of beam emission. In the thermionic gun, a high acceleration voltage is applied to a filament cathode in order to raise its temperature to a certain range where the electrons become sufficiently energetic to overcome the work function of the cathode material. Field emission is another way to generate electrons and has many advantages in its resolution and stability. In the field emission gun, the cathode is a shape of a rod...
with one very sharp end, which can be regarded as the point source. On the other hand, the thermionic emission gun has a V-shaped cathode, which requires a careful and precise analysis.

In the present study, we developed a thermionic SEM. Though the field emission SEM ensures a better resolution and stability than the thermionic SEM, the latter still has many advantages: a low development cost, relatively low level of vacuum condition, and easy maintenance [2]. For the development of a thermionic SEM, an electron optical system and its components should be carefully designed and analyzed. However, the precise measurement of the electron beam trajectory inside the SEM column is almost impossible, and the dimensions and locations of each component cannot be easily determined.

In order to facilitate the design of the electron optical system, numerical simulations have been widely applied. Munro [3] proposed a first-order finite element method (FEM) to analyze electron lenses. Renau et al. [4] developed an electron gun analysis program based on the boundary element method. Zhu and Munro [5] applied a second order FEM to the analysis of various electron guns. Grella et al. [6] proposed a Monte Carlo simulation to account for electron scattering. Khursheed and Osterberg [7] used a FEM in the design of spectroscopic SEM.

The previous research, however, simplified the analysis domain as a two-dimensional axisymmetric region because most SEM components have rotationally symmetric characteristics. For a field-emission gun, this axisymmetric analysis is quite suitable because the emitter tip can be regarded as being rotational symmetry. In the case of a thermionic gun, however, the V-shaped filament cannot be simplified to be a rotationally symmetric geometry. The present study proposes a full 3D analysis in order to accurately predict the beam trajectory and to determine the various design parameters in the electron optical system of a thermionic SEM.

2. Design of a thermionic SEM column

The thermionic SEM is designed as considering of an electron-optic column, a stage, a chamber, a control unit, and a vacuum unit. The SEM column contains an electron optical system in which electrons are emitted and moved form a focused beam. For this purpose, the column consists of an electron beam source, electromagnetic lenses, apertures, deflection coils, and a detector. Fig. 1 shows a three-dimensional design model of the thermionic SEM column.

The cathode of the electron source for a thermionic emission is a wire filament, bent in a V-shape, with a diameter of 150 μm. The filament is made of tungsten, which has a work function of 4.5 eV. Electron beams are emitted from the bent tip of the filament under a high temperature near 2700 K and accelerated by a high voltage. The Wehnelt cylinder is designed to surround the filament, and biased negatively so as to deflect the emitted beams. Fig. 2 shows the fabricated tungsten beam source.
Magnetic lenses also play a role in refracting electron beams to obtain a focused spot using the magnetic field driven by an electric current from a coil. The present column is compactly designed to contain two condenser lenses and an objective lens as illustrated in Fig. 1. The condenser lenses generate a magnetic field that forces the electron beams to form crossovers at desired locations. The objective lens then focuses the electron beams on the specimen.

To improve the performance of the magnetic lenses, the amount of resulting magnetic fields and their peak locations should be analyzed. We performed a finite element analysis to predict the magnetic field distributions using OPERA-3d/TOSCA® [8]. Table 1 summarizes the basic specifications of the coils and corresponding current densities for the three magnetic lenses. Fig. 3 represents the distributions of the magnetic flux around the first condenser lens and the objective lens. It is noted that the magnetic flux is concentrated in the polepiece region for each lens, which helps the beams to refract around these locations.

Table 1
Basic specifications of the coils for the three magnetic lenses.

| Lens Type          | No. of turns | Outer diameter (mm) | Inner diameter (mm) | Height (mm) | Current density (A/mm²) |
|--------------------|--------------|---------------------|---------------------|-------------|-------------------------|
| Condenser lens (1) | 920          | 78                  | 26                  | 65          | 1.09                    |
| Condenser lens (2) | 920          | 78                  | 26                  | 65          | 1.73                    |
| Objective lens     | 600          | 84                  | 46                  | 55          | 1.52                    |

3. Finite element analysis of the SEM column

3.1. Beam emission analysis for the thermionic source

The characteristics of the emitted beams are described by adopting the thermal saturation limit model for the thermionic electron gun. The current density of an emission is expressed as a function of cathode temperature [1]:

\[ J_0 = AT^2 e^{\frac{\phi_e}{kT}} \]  

where \( J_0 \) is the current density on the tip surface, \( A \) is the emission constant for the surface, \( \phi_e \) is the work function of the cathode material, \( T \) is the temperature on the tip, \( q \) is the electronic charge, and \( k \) is the Boltzmann constant. The current density of electrons at a particular velocity \( (v) \) is expressed by assuming Maxwell’s distribution:
\[ J = \frac{2m}{\pi kT} \left( \frac{m_0}{e^{m_0/kT}} \right) J_0 \] (2)

Under an electromagnetic field in the electron optical system, the emitted electrons are deflected by the Lorentz force, and the resulting momentum equation is expressed in Equation (3) which considers the increase of electron mass during their acceleration [9]:

\[ \frac{\partial \mathbf{p}}{\partial t} = -q \left( \mathbf{E} + \frac{\mathbf{P} \times \mathbf{B}}{m_0(1 + E/E_0)} \right) \] (3)

where \( m_0 \) is the electron mass. Then, the resulting equation of motion for electron particles is obtained by solving the momentum equation.

Considering the geometry of the filament, we conducted a 3D finite element analysis in order to predict the beam emission characteristics. We used OPERA-3d/SCALA® [9] to analyze the beam trajectory considering space-charge effects. Fig. 4 shows the analysis domain and the resulting beam trajectory. The analysis domain includes a tungsten filament, a Wehnelt cylinder, a detector plate, and the surrounding air. A finite element model of the filament is generated by measuring the profile of the real model illustrated in Fig. 2. Diameter of the filament is 150 \( \mu \text{m} \), and an acceleration voltage of 15 kV is applied to the tungsten filament. Due to the bias voltage applied to the Wehnelt cylinder, 15.5 kV, the emitted beams are condensed and form a crossover as marked in Fig. 4. The variations of the maximum spot radius with an increase of the axial distance are plotted in Fig. 5. The minimum spot radius at the crossover position, approximately 0.8 mm from the filament, was predicted to be 141.2 \( \mu \text{m} \).

3.2. Analysis of the beam trajectory considering the effect of a magnetic lens

In order to account for the effect of a magnetic lens, the first condenser lens is added to the analysis model. The axial length of the analysis domain is set as 120 mm in order to investigate the effect of the condenser lens. A 3D finite element mesh is constructed for a quarter section of the model considering the geometric symmetry and consists of 1,877,567 nodes and 3,730,122 tetrahedron elements. Fig. 6a is the resulting beam trajectory with the electric field distribution, showing that the electric field is concentrated between the filament and the anode. Fig. 6b represents the beam trajectory associated with the magnetic field. This figure shows that the emitted electron beams are deflected due to the magnetic field and converge on a specific region with an amount of spot radius.

Fig. 7 is the result of the beam trajectory analysis inside the SEM column. The electron beams are emitted from the tip of the filament and proceed through the anode and the sleeve section. The beams that passed into the sleeve hole are refracted due to the magnetic field originating from the condenser lens and focus into a point. Then, the beams diverge after the first crossover and converged again due to the magnetic field generated by the second lens.
For further discussion, the variation of the spot radius along the axial direction is plotted in Fig. 8. As the axial distance increases, the spot radius also increases until it reaches a distance of 60 mm, and then it decreases due to the beam refraction. The minimum spot radius is estimated to be 55.44 μm at the focal point that is located at the axial distance of 88.69 mm. After the focal point, the spot radius increases again as the beams diverge. This spot radius should be reduced in order to improve the resolution of the electron optical system, and this requires investigation into the lens design parameters through finite element simulations. From this result, we could determine the aperture positions by being located at the axial distances of 78.85 mm and 98.40 mm, in order to maintain their distances from the focal point as equal as possible.
3.3. Discussion: the validity of the 3D analysis

Though most parts in the analysis domain have rotationally symmetric characteristics, the filament cannot be regarded as being rotationally symmetric. This is the main reason for conducting 3D analyses instead of the traditional axisymmetric analysis. In this section, the validity of the proposed 3D analyses is discussed.

In order to check whether the analysis results show rotationally symmetric characteristics or not, the spot radius was subdivided into an X-directional radius and a Y-directional radius. The larger the difference between the directional radii, the more the rotationally symmetric assumption becomes inadequate. The variation of each spot radius along the different axial direction is compared in Fig. 9. It is noted that the two directional radii show similar values at the emission location and focal point, while a considerable deviation is evident in the intermediate range. The maximum deviation is 0.5 mm at the axial distance of 70 mm, which corresponds to 36.2% of the effective radius of 1.38 mm. Thus it can be concluded that the proposed 3D analysis ensures a more reliable result than an axisymmetric analysis, even though it requires a considerable increase in computation time.

![Fig. 9. Comparison of the axial variations of the directional spot radii.](image1)

4. Development of a thermionic SEM

Through the finite element analysis, we determined various design parameters for the SEM column, such as the dimensions and locations of the lenses, the Wehnelt location and bias voltage, and the aperture locations. As a result, the thermionic column was developed in a compact length of 320 mm. To reduce the vibration originating from the vacuum pump and ground noise, an anti-vibration pad was installed beneath the column. Additionally, the upper body, encompassing the electron gun, lenses, specimen chamber, and detector, and the lower body, consisting of the vacuum line and vacuum pump, were completely isolated by a trapped air panel in order to diminish the vibration. Fig. 10 shows a photo of the developed SEM and its specifications are summarized in Table 2.

![Fig. 10. Photograph of the developed SEM prototype.](image2)

Because the developed SEM works under a high acceleration voltage up to 30 kV, the stability of the power unit is very significant in obtaining a high quality image. In the present study, the power supply was developed to maintain a low level of ripples, less than $10^{-3}$ percent. The controller was developed in a digital manner, which helps to control all the components easily. Along with the help of these digitized values, we developed a GUI-based control program from which all the control signals could be adjusted conveniently.

The performance of the developed SEM has been verified by observing images of a test sample of 100 µm nickel mesh coated with ceramic powders. The observed images are shown in Fig. 11, with a magnification of 3,000 times (Fig. 11a) and 10,000 times (Fig. 11b). It is noted that the image of the powders, which have diameters of approximately 1 µm, can be clearly identified.
Table 2. Specifications of the developed SEM

| Contents            | Specifications                          |
|---------------------|-----------------------------------------|
| Magnification       | 15 ~ 300,000 x                         |
| Acceleration Voltage| 0.3 ~ 30 kV                             |
| Electron Gun type   | Tungsten hairpin filament               |
| Gun Alignment       | 4-pole electromagnetic                  |
| Stigmator           | 8-pole electromagnetic                  |
| Scanning Coil       | 2 stage electromagnetic                |
| Condenser lens      | 2 stage electromagnetic                |
| Objective lens      | New super conical type                 |
| Specimen stage      | 80 x 40 x 35 (mm)                      |
| Stage control       | Stepping motor, Encoder attached        |
| Image display unit  | 17 inch CRT                            |
| Operation system    | MS Windows XP                          |
| Column vacuum capacity | $10^{-6}$~$10^{-7}$ (torr)             |
| Pump system         | Rotary and turbo-machinery pumps       |

5. Conclusion

In the present study, we developed a thermionic SEM with an electron optical system. For the optimal design of the thermionic SEM column, a finite element analysis was performed to predict the electromagnetic field and the resulting beam trajectory. Particularly, a 3D finite element analysis was utilized to account for the geometry of the filament. Through the finite element analysis, we could determine various design parameters of the thermionic SEM column, and successfully develop a prototype SEM with relatively low time and investment cost.

After the thermionic SEM was fabricated by following the design criterion suggested from the finite element analysis, we strictly calibrated each component in order to obtain a high resolution. Then we could obtain a stable image with a resolution of up to 6 nm, which implies that the beam focusing components are satisfactorily fabricated and located appropriately inside the column and the chamber. In order to improve this limitation of the resolution, a field emission SEM can be the next solution, which remains as further research.

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