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기술논문

Simple Analysis of the Properties of Condenser Lens 1 in SEM

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SEM에서 집속 렌즈 1의 특성에 대한 간단한 분석

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Abstract

It is quite complex to draw the geometry of electron trajectories in electron optics because such trajectories have various aberrations that cannot be easily calculated. However, if we need to know roughly the geometry, the focal length and the principal planes in order to understand the properties of column, a simple numerical solution can be a useful method. We are developing the electron beam machining system based on SEM. In this paper, we show rough geometry, focal length and principal planes by a numerical solution for electron lens 1 in our column. These results will be utilized in developing a simulation program for electron optics.

Key Words : Lens properties(렌즈 특성), Focal length(초점 거리), Principle planes(주요면), Magnification(배율), Condenser lens(집속 렌즈)

1. Introduction

What is most important in developing an electron beam machining system based on a scanning electron micro-scope (SEM) is designing a column of desired resolution. Resolution is determined by the distance between the beam source and the electron lens and the demagnification of each electron lens. The demagnification of an electron lens is the electron beam reduction rate, and determined by the performance of the electron lens. Fig. 1 shows the SEM-based electron beam machining system under development. In the system, the column includes two condenser lenses and one objective lens.

To design the performance of an electron lens or an electron optical column, it is required to consider the solution of the PRE(Paraxial Ray Equation) in terms of

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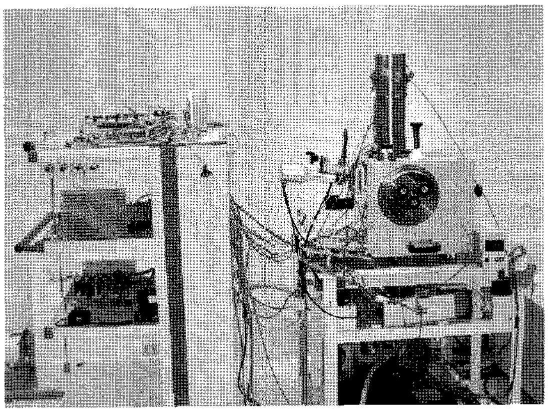

Fig. 1 SEM-based electron beam machine under development

the position of the principal planes and the focal lengths. The purpose of lens design or analysis is to get field distribution, the geometry of the column, and the current in the windings.(1-4) Knowing accurate field distribution and electron beam path is the core of electron lens design. Electron lens design using optical lens is found in references by Klempere, and electron lens design using computer is found in references by Hawkes & Munro, etc.

A real column is designed by sophisticated computer-aided methods because lenses have various aberrations that cannot be easily calculated and consume a lot of time in calculation. If the rough resolution and geometric electron beam path of column are obtainable by a simple numeric equation, it may be useful to understand the performance of electron lenses.

This paper shows whether the properties of electron lens calculated by a numeric equation derived from references agree with the know design specifications of condenser lens 1. Condenser lens 1 is the electron lens close to the electron gun, and adjusts the spot size. The results of this study will be used in developing a simulation program for calculating the demagnification of condenser lens 1 and objective lens and the resolution of column.

2. Behaviour of beam in magnetic lens

The coordinates used are (r, θ, z) in the right-handed cylindrical system, where θ is positive for clockwise rotation looking in the z-direction. The PRE, which is based on the radial force on the particle of mass me to cause its motion, becomes

$$\frac{d^2r}{dz^2}+\frac{1}{2V}\frac{dV}{dz}\frac{dr}{dz}+ \left(\frac{1}{4V}\frac{d^2V}{dz^2}+\frac{e}{8m_eV}B_z^2\right)r=0 \tag{1}$$

This is the equation for an electron path that is very close to the axis and makes a very small angle with the axis, in term of electric potential V and magnetic field B_z on the axis. The PRE in the absence of electron fields, with V constant, is simplified to Equation (2).(5-9)

$$r''=-\frac{eB_z^2}{8m_eV}r \tag{2}$$

Where B_z is a constant

3. Application for electron lens in our system

Equation (2) can be solved as follows:

$$r''+\frac{eB_z^2}{8m_eV}r=0 \tag{3}$$

$$r=c_1\cos\left(z\sqrt{\frac{eB_z}{8m_eV}}\right) \tag{4}$$

where c_1 is the initial value.

$$r=r_0\cos\left(z\sqrt{\frac{eB_z^2}{8m_eV}}\right) \tag{5}$$

with initial conditions of $r=r_0$ and $r'=0$ at $z=0$. The path will be as shown in Fig. 2.

At the exit from the lens, radius r_2 and the slope r_2' will be

$$r_2=r_0\cos\left(z\sqrt{\frac{eB_z^2}{8m_eV}}\right) \tag{6}$$

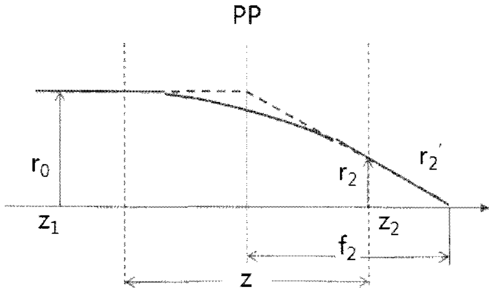

Fig. 2 Relation between lens field, principal plane (PP), and f_2

$$r_2' = (-r_0 \sin(z\sqrt{\frac{eB_z^2}{8m_e V}}))(\sqrt{\frac{eB_z^2}{8m_e V}}) \tag{7}$$
$$= (-r_0 \sin(z\sqrt{\frac{eB_z^2}{8m_e V}}))(\frac{z\sqrt{\frac{eB_z^2}{8m_e V}}}{z})$$
$$= -(\frac{r_0}{z})(z\sqrt{\frac{eB_z^2}{8m_e V}})\sin(z\sqrt{\frac{eB_z^2}{8m_e V}})$$

where, z is the distance of field. Our column consists of two condenser lenses and one objective lens in oreder form the electron gun. In this paper, we analysis the performance of the condenser lens closest to the electron gun.

Electron lenses are general 'thick' lenses, but for many practical considerations, they are treated as ‘thin’ lenses. The focal length of thin lens is long compared with the extent of the lens field. The principal planes are considered to coincide at the center of the lens field. We will also treat our lens as a thin lens here. Then, the focal length is given by

$$\frac{1}{f} = -\frac{r_2'}{r_0} = \frac{(z\sqrt{\frac{eB_z^2}{8m_e V}})\sin(z\sqrt{\frac{eB_z^2}{8m_e V}})}{z} \tag{8}$$

The current through the lens for the range of spot size at each acceleration voltage is measured. Table 1 shows the current. Here, ACC means acceleration voltage.

Table 1 Current range through the lens

ACC [kV]	The current range [A]
1	0.75 - 0.375
3	0.15 - 0.675
5	0.3 - 0.8875
10	0.3 - 1.25
15	0.375 - 1.55
20	0.45 - 1.775
25	0.5 - 2.0
30	0.55 - 2.2

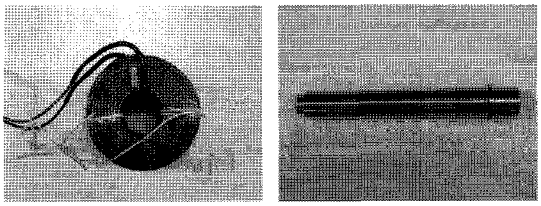

Fig. 3 Lens and pole-piece in our system

The lens used in this experiment has z=2 [mm] and N=920, where N is the number of turns in the lens coil. V is acceleration voltage. The lens and pole-piece used in this experiment are in Fig. 3.

Table 2 shows the focus length and the position of the principal planes for each acceleration voltage. ‘Min’ means the position of the smallest spot size, and ‘Max’ means the position of the largest spot size. ‘Image’ means the position of captured images. Fig. 4 shows the focus range based on these data.

In the Fig. 4, the range of focus length at each acceleration voltage is correspondent to the maximum and the minimum spot size. The short focus length falls within a range between 1 [kV] and 30 [kV] because it is related to the system resolution. The range is from 0.001099 [m] to 0.001117 [m]. The focus length for captured images is within this range. The position of focal length starts from the position of the principal plane.

We use the relation between an object and image location to get the demagnification range of ‘Image’ position. The crossover position is regarded as the origin. Then, the total distance from the crossover to the pole piece is 0.102 [mm] in our column. We suppose that the

Table 2 Focus range for each acceleration voltage

ACC [kV]	Spot size	Focus [m]
1	Min	0.012473
	Image	0.005741
	Max	0.001099
3	Min	0.008707
	Image	0.006171
	Max	0.001104
5	Min	0.008880
	Image	0.002805
	Max	0.001111
10	Min	0.007943
	Image	0.005203
	Max	0.001109
15	Min	0.007628
	Image	0.002203
	Max	0.001115
20	Min	0.007079
	Image	0.005812
	Max	0.001111
25	Min	0.007178
	Image	0.007178
	Max	0.001115
30	Min	0.007128
	Image	0.005203
	Max	0.001117

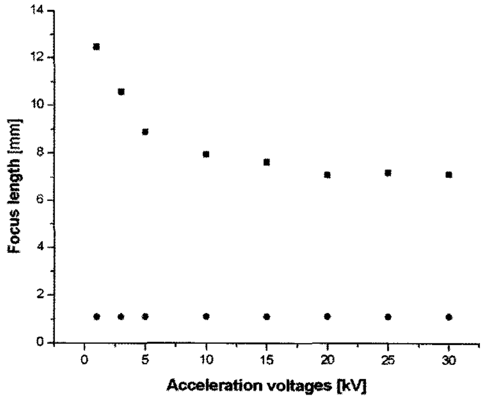

Fig. 4 The distribution of focus length

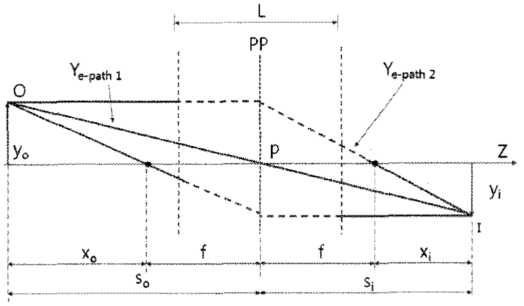

Fig. 5 Electron paths for calculating demagnification

Table 3 each parameters of electron path's diagram

Symbol	Meaning	Unit [m]
O	Object position	
I	Image position	
L	Pole piece' length	0.002
xo	From object to PP	0.096797
xi	From focal length to image	0.001277
f	focal length from PP	0.005203
p	Principal plane position	0.103
so	From origin to principal plane	0.103
si	From principal plane to image	0.10848
yo	Height of height	0.00002
yi	Height of image	-0.00000106

redius of electron beam at the crossover position is 0.00002 [m] because the source size of tungsten is 30-100 [㎛].[9] So, the object position is (0, 0.00002), the focal length is 0.005203 [m], and the pole piece length is 0.002 [m]. The principal plane is at the center of pole piece because we treat the pole piece as a 'thin' lens. The electron path is in Fig. 5. To calculate the demagnification, we use two linear equations $y_{e\text{-path }1}$ and $y_{e\text{-path }2}$. The data for Fig. 5 are in Table 3.

Demagnification is calculated by Equation (9). The minus sign means that the image formed by this lens is inverted. The result of Equation (9) agrees with 1/20, the demagnification of condenser lens 1 as in its design specifications.

$$M=\frac{y_i}{y_o}=\frac{-0.000001064}{0.00002}=-0.0532 \qquad (9)$$

4. Results

The result of equation (9) shows that the demagnification of condenser lens 1 calculated by a simple equation derived from references agrees with the known design specification. This result cannot be used in designing accurate electron beam paths and columns because it neglects aberrations of electron lenses, but is helpful to understand the properties of lenses. The result of this study will be utilized in analyzing the properties of condenser lens 2 and objective lens. Furthermore, it will be used in developing a resolution simulation program that can test the overall resolution of column simply.

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