A study of the Electron Beam Irradiator for Core-loss reduction of Grain-oriented silicon Steel

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Abstract – A new compact, low-energy electron beam irradiator has been developed. The core-loss of silicon steels can be reduced by magnetic-domain refinement method. The irradiator was developed for the application of core-loss reduction using the method. The beam energy of the irradiator can be varied from 35 to 80 keV and the maximum current is 3 mA. The irradiation area is designed to be 30 × 30 mm2 now and will be upgraded to 30 × 150 mm2 using a scanning magnet and scanning cone. The electron beam generated from 3 mm diameter LaB6 is extracted to the air for the irradiation of the silicon steels in the air. A special irradiation port was developed for this low-energy irradiator. A havar foil with 4.08 μm thickness were used for the window and a cold air-cooling system keeps the foil structure by removing heat at the window. The irradiator system and its operation characteristics will be discussed.
Keywords : irradiator, core loss, electron window

1. INTRODUCTION

Grain-oriented silicon steels are widely used in transformers as a core material. When AC current is applied around the core materials, energy loss occurs due to the core loss. The core loss is one of the main factors to waste energy and reduction of the core loss is a key issue to increase energy efficiency. Several methods for core loss reduction are developed and the magnetic-domain refinement method [1-3] is used for the grain-oriented silicon steels. The domain refinement method is to reduce width of magnetic-domain wall by scratching surface of the steel using a mechanically sharp tool, laser or electron beam. Both mechanical tool and laser irradiation damage insulating coating on the steel surface and thus the surface must be re-coated. However, electron irradiation refines the magnetic domain without any deformation or damage of the insulating coating because electron beam can penetrate into the steel.

Electron beam processing can be performed in vacuum but this needs high cost and difficulty of continuous works. These defects can be overcome by electron irradiators which irradiate electron beam on the target in the air. In order to extract electron beam into the air, energy of the electron beam should be high enough. Most of the developed electron irradiator has the beam energy of 300 KeV - 1.5 MeV. As the beam energy increases, the irradiation system becomes complex and huge. Furthermore, ozone and x-ray are produced seriously from the high-energy electron beam. High energy beam will be necessary when large penetration depth is needed. However, less than 100 keV electron beam is enough for the core loss reduction because it does not need such a high penetration of the beam.

A new compact, low-energy electron beam irradiator has been developed for application of the core loss reduction of the silicon steel. In this paper, the characteristics of the system and its operation properties will be discussed in detail.

2. ELECTRON BEAM IRRADIATOR

Basic design concept of this system, (1) When withdraw electron beam that is happened in electron gun of vacuum inside to atmosphere, design variable of most suitable that do irradiation window and irradiation device E that can minimize damage of electron beam, electron beam irradiation device development that common use is possible. (2) Make system straightforwardly and irradiation electron beam in stated body effectively.

A. Schematic and design parameters of the irradiator

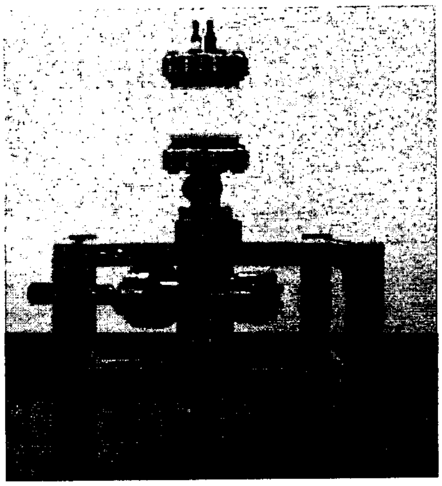

Fig. 1 Photograph of the fabricated electron-beam irradiator

Figure 1 shows photograph of the designed and fabricated irradiator system. The design parameters of the irradiator are shown in Table 1. The beam energy can be changed from 35 KeV to 80 KeV and the maximum beam current is 3 mA. The effective irradiation area is 30 × 30 mm^2

Main component of system is -100kV high voltage device, electron gun, electron beam measurement chamber, Irradiation window and Irradiation device.

Table 1. Basic design parameters of the irradiator

Beam energy	35 - 80 keV
Average current	maximum 3 mA
Beam power	maximum 240 W
Window material	4 μm Havar foil
Irradiation area	30 mm × 30 mm
Cooling method for the window	cold-air cooling
Cathode material for the electron gun	LaB_6 with 3 mm diameter

The schematic drawing of the irradiator is shown in Figure 2. The system consists of an electron gun, a vacuum chamber for measurement of electron beam properties, an irradiation port, a vacuum pump, a high-voltage power supply and a filament power supply. Electron beam generated from the electron gun passes through the measurement chamber and is extracted to the air through an electron beam window. Silicon steel can be located under the window and is irradiated by the electron beam in the air. A 1-dimensional or 2-dimensional linear motion system can move the silicon steel to make linear scratch on the surface of the steel. The irradiator system keeps vacuum below 10^{-6} torr by a turbo molecular pump with the pumping speed of 300 l/s.

Figure 3 shows parts that are composing design manufactured electron gun.

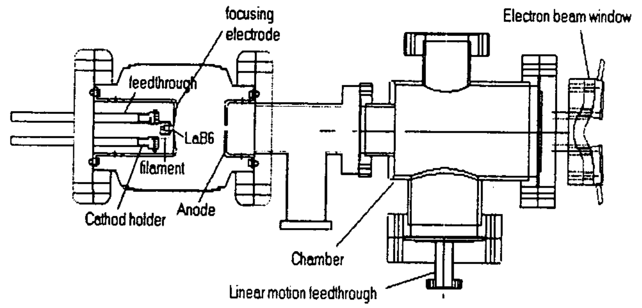

Fig. 2 Schematic drawing of the irradiator

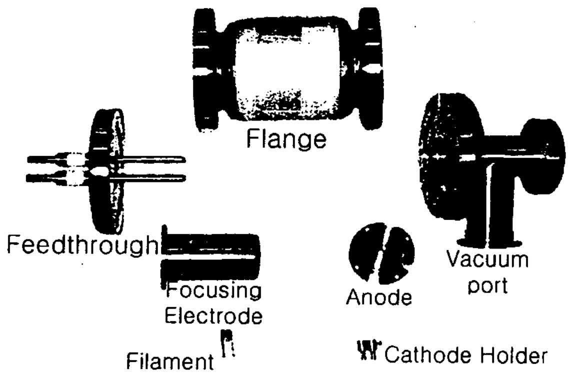

Fig. 3 Photograph of the electron gun components

B. The electron gun and the measurement chamber

The electron gun is a thermion type, which extracts electron beam from a heated cathode. The cathode material is LaB_6 with 3 mm diameter. A button type cathode is used to increase beam quality. A tungsten filament is wound around the cathode and the cathode is heated up to 1500^0C by applying AC current through the filament. A focusing electrode is installed near the cathode to keep the beam size properly. The electron gun was designed and optimized by EGUN code [4]. The beam size can be controlled by applying DC voltage between the focusing electrode and the cathode.

Beam passing through the anode of the gun reach the measurement chamber. A phosphorous screen and a Faraday cup are installed inside the chamber. The phosphorous screen reflects visible light when electron beam hits it. The light image is measured by a CCD camera. The electron beam size, position, and spatial profile are analyzed through the CCD camera and a frame grabber. The beam current is measured by a Faraday cup which is made of copper. Beam current is important in the irradiators because it determines the irradiation dose and finally it will affect the quality of the core loss reduction. Since the secondary electron generated from the Faraday cup affects the beam current measurement, DC voltage is applied to the Faraday cup to measure the beam current more precisely. The applied voltage can be changed from +300V to +1,000V.

C. Irradiation port

The irradiation port is composed of an electron beam window, window frame, window cooling system. The electron beam window is the main part of the irradiator through which electron beam generated in the vacuum is extracted to the air. One side of the window is vacuum less than 10^{-6} torr and the other side is the air. The window should sustain its mechanical structure at the pressure difference (vacuum pressure) between the air and the vacuum. A foil is generally used for the window. A thicker foil is better to keep its mechanical geometry against the vacuum pressure. When electron beam passes through the window, part of the beam is lost in the window. Since beam loss increases with the foil thickness, a thinner foil is better to reduce the beam loss. Furthermore, the beam passing through the window loses its kinetic energy and it heats the window. The window will be broken if it is not properly cooled. Thus, the window should be designed to solve a contradictory problem of beam loss and mechanical structure. This problem is much more serious for the designed irradiator because it has comparatively low beam energy. The beam loss increases when the beam energy decreases.

The beam loss can be estimated by range of electron beam [5, 6]. For the window material, Aluminium (Al) or titanium (Ti) is widely used. However, we used a havar foil for the window material. Havar foil has never been used for the electron window and this is the first trial for the window.

Table 2 shows physical special quality for Havar foil and Figure 4 shows the calculation result of the electron range

(0~100keV) for aluminium, titanium, beryllium (Be), and havar foil.

Table. 2 Physical properties of materials for window

	Be	Al	Ti	Havar
Atomic number (Z, Z_{ef})	4	13	22	28
Atomic weight (A, A_{ef})	9.01218	26.98154	47.88	60.676
Density(gcm^{-3})	1.848	2.70	4.5	8.3
Melting point(℃)	1,278	660.4	1,660	-
Temperature coefficient @ 0-100℃ (K^{-1})	0.0090	0.0045	0.0038	9.5 -11*10^{-6}
Specific heat @ 25℃($JK^{-1}kg^{-1}$)	1825	900	523	-
Tension intensity (MPa)	310 - 550	50-195	230 - 460	1,860
Excitation potential (eV)	-	160	246	302

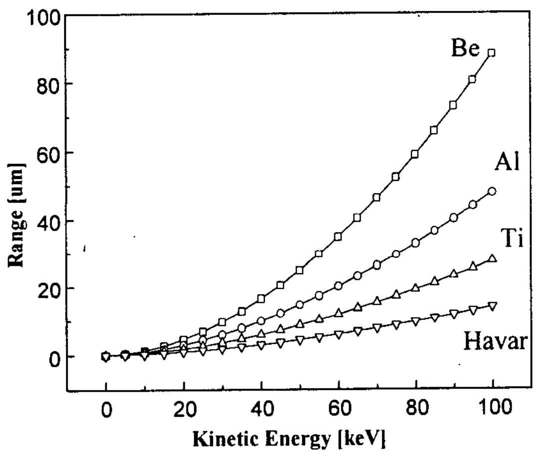

Fig. 4 Range of several materials with beam energy

Beryllium is one of the best materials for the window. We do not use it for the window because its oxide material is very toxic to human. As shown in Figure 4, havar has 2 - 3 times shorter range than Al or Ti at the same electron energy. However, it has 8 - 9 times higher tensile strength (1860 MPa) than Al (50 - 195 MPa) or Ti (230 - 460 MPa) and much thinner foil can sustain vacuum pressure. Thus, havar is better for the window material considering both beam loss and mechanical structure. In this study, a havar foil with 4.8 μm thickness is used. The window should separate the vacuum part from the air. The window is vacuum-tightly connected to the window support by a indium wire with 1 mm diameter. In order to reduce stresses in the foil, the window support was designed to have a cylindrical shape. The beam energy dissipated in the foil heats the window and can damage it. The window is cooled by cold air to prevent the damage. A Vortex tube converts compressed air (3 kg/cm^2 ~ 10 kg/cm^2) down to -65 ^0C cold air and it feeds the cold air to the window.

Stopping power is average energy damage by unit distance that particles moving. Stopping power says that is energy damage, speciality energy damage, or differential energy damage. Stopping power about electron can save by next time way.

$$\frac{dE}{dx}(MeV/m) = 4\pi r_o^2 \frac{mc^2}{\beta^2} NZ \times \left\{ \ln\left(\frac{\beta\gamma\sqrt{\gamma-1}\,mc^2}{I}\right) + \frac{1}{2\gamma^2}\left[\frac{(\gamma-1)^2}{8} + 1. - (2\gamma^2 + 2\gamma - 1)\right]\right\}$$

Component is as following

$\gamma_o = e^2/mc^2 = 2.818\times10^{-15}m$ (Classical electron radius)

$mc^2 = 0.511MeV$ (Rest mass energy of the electron)

$\gamma = T + Mc^2/Mc^2 = 1/\sqrt{1-\beta^2}$

$T = (\gamma-1)Mc^2$ (Kinetic energy)

$\beta = v/c$

$c = 3\times10^8\, m/s$

N = Atomicity per capacity of material that particle passes

Z = atomic number of material

I = Average excitation potential of material.

Below Figure 5 is graph that display electrons stopping power for material.

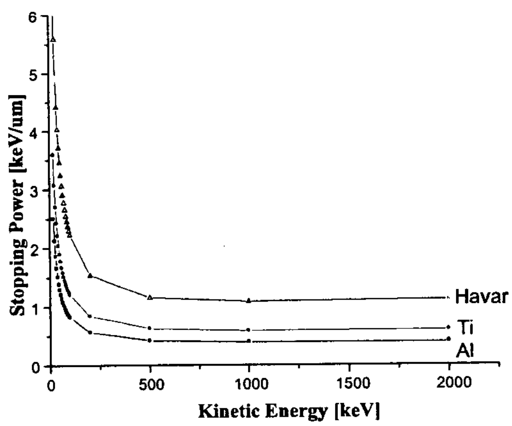

Fig. 5 Stopping Power in each material versus Kinetic Energy

Figure 6 is the photograph of the fabricated irradiation port. The window size is designed to be 30 × 30 mm^2.

3. EXPERIMENTAL RESULTS

The size, position, spatial profile of the beam is measured by the phosphorous screen and the CCD camera. The beam size is about 15 mm in diameter without applying a voltage to focusing electrode. In a certain case, the beam is not on axis due to misalignment of the cathode. A correction magnet, shown in Figure 2, is installed after the anode to steer the beam to center of the window.

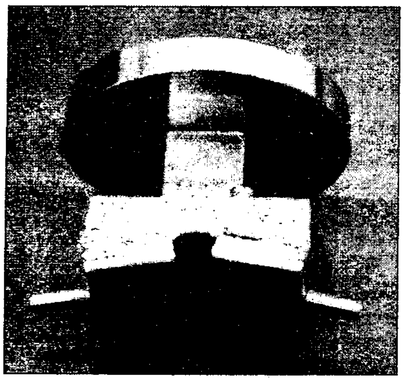

Fig. 6 Photograph of the irradiation port

In order to check the possibility which the havar foil can be used as a window, beam transport experiment was executed in the vacuum. A havar foil with the same thickness of the window and a phosphorous screen were installed in the measurement chamber. The foil was fixed on the edge of a linear motion feed through and the position of the havar is controlled by the feed through. Figure 7 shows the image of the electron beam when half of the beam passes through the havar foil and the other does not pass the foil.

As can be expected, the image made by the beam which does not pass the foil is much brighter than the other part. It is found that the foil in the vacuum was melt down at the beam current above 200 μA.

Fig. 7 Image of the electron beam passed through the havar foil

The beam was extracted to the air while the window is cooled by cold air. The transport efficiency of the window was measured at different beam energy. The transport efficiency is defined by the ratio of the beam current after passing the window to that before passing the window. A Faraday cup was installed in the measurement chamber and it measures the beam current before the beam passes through the foil. Another Faraday cup was installed 10 mm apart from the window. It measures the beam current after the beam passes through the foil. The Faraday cup cannot be installed just after the window because the window support has a cylindrical shape. The measurement result of the transport efficiency for the havar window is shown in Figure 8 with the theoretically calculated value.

Simple formulas that do electron beam permeate that is incidence foil is given with that depend to Rao [5].

$$\eta = \frac{[1+\exp(-gh)]}{\left\{1+\exp[(g\frac{t}{r}-h)]\right\}}$$

Here, η expresses the transmission amount of real electron beam that permeate to material that have thickness t, and constant g and h are given as following by atomic number Z of the material and atomic weight A.

$$g = 9.2Z^{-0.2} + 16Z^{-2.2}$$

$$h = 0.63Z/A + 0.27$$

In case foil for Windows is mixture or inorganic compounds, effect atomic number and affect atomic weight are used instead of atomic number Z and atomic weight A.

As shown in Figure 8, the measured transport efficiency is 43 % at 80 KeV, which is much lower than the theoretical value of 73 %. We suppose that some of the beam current passing after the window is lost in the air before it reaches the Faraday cup. We have found that the irradiator works until 1 mA beam current without any problem of the window when it is properly cooled with the cold air. The beam current density at the window should be reduced to meet the design value of extraction current of 3 mA. A scanning system will be necessary in future to increase the irradiation area and the extraction current.

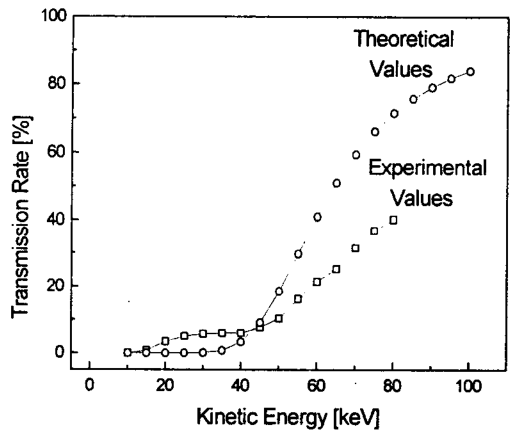

Fig. 8 Experimental result and theoretical calculation of the transport efficiency for the havar foil

4. CONCLUSION

A new compact, low-energy electron beam irradiator has been developed for core-loss reduction of silicon steel. The maximum energy of the irradiator is 80 keV and the current is 3 mA. The beam is generated from a button-type LaB_6 cathode, which has good beam quality compared to a filament type. For this low-energy irradiator, the irradiation port should be specially designed to maintain its mechanical geometry while electron beam is extracted to the air without large loss. This is the main reason why low-energy irradiators are not well-developed. In this study, a havar foil with only 4.08 μm thickness was used for the window material. It is the first trial to use a havar foil for the window of the electron irradiator. The window support and cooling system for the window were specially designed to sustain the vacuum pressure and to reduce the beam loss. With the support and the cooling system, such a thin metal foil can be used as a window for 80 KeV, 1 mA beam. The present system has the irradiation are of 15 × 15 mm^2. If a linear motion system is used below the window, the irradiator can be used for a long sample. The irradiator is now used for the study of core-loss reduction and the results will be published [7]. However, silicon cores commercially used for transformers have the width more than 30 mm. Thus, the irradiator will be upgraded to have the irradiation area of 30 × 150 mm^2 by using a two-dimensional scanning magnet and the irradiation port for it.

5. REFERENCES

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