Influence of Mechanical Finishing on Secondary Electron Emission of Alumina Ceramics

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Abstract- **Secondary electron emission (SEE) coefficients of alumina ceramics with three different surface finishes have been measured using a scanning electron microscope with a single-pulse electron beam (100 pA, 1 ms). SEE coefficients of those aluminas with annealing process became lower after mechanical grinding operations even though its average roughness was almost same as those of as-sintered ones. SEE coefficients of mirror-finished samples were the smallest among the samples. Changes of SEE coefficient with incident angle of primary electrons for smooth and rough surfaces are also discussed.**

I. Introduction

Alumina ceramic is widely used as electrical insulators for vacuum circuit breaker, high power klystron and various vacuum apparatus, because of its excellent characteristics, such as high mechanical strength, high resistivity at high temperature, small microwave loss and low out-gassing rate [1]. A klystron is used as a microwave source to accelerate charged particles in a high-energy accelerator. Here, alumina ceramics are used as rf windows between the acceleration tubes and the klystrons to pass the microwaves and to seal the vacuum.

Requirement of high-power klystrons currently increases because of growth of acceleration energy demand. Unfortunately, alumina ceramic has a high secondary electron emission (SEE) coefficient, which in high-electric-field applications often induces breakdown of the rf window [1]. When primary electrons in rf field impinge on the window surface, secondary electrons emitted from the surface are accelerated so that they impinge again on the surface due to the alternating rf field. This process causes multiplication of the SEE, which is called multipactor [2]. Thus, studies on the SEE characteristics are necessary to understand this multipactor and the breakdown mechanisms of rf window as well as insulator breakdowns in vacuum.

Many investigations on SEE from insulating materials have been carried out. From these investigations it has been revealed that SEE coefficient is strongly influenced by slight modifications of outer layers of the materials, since SEE is a surface sensitive phenomenon [3]. R. G. Bommakanti and T. S. Sudarshan reported the effects of surface modifications by mechanical grinding and polishing operations on surface flashover characteristics in vacuum [4]. Such processes modify the surface topography which may change the SEE coefficients. However, there is currently lack data concerning the surface modification effects on SEE, especially for commercial alumina ceramics. In this study, incident angle dependence of SEE coefficients of smooth and rough materials has been investigated. Furthermore, measurements of SEE coefficients were also carried out for commercial alumina ceramics with three different surface finishes, i.e. without finishing process (as-sintered), with mechanical grinding operations (as-ground) and with mirror-finished by polishing. In addition, the SEE coefficients of as-received samples are compared with those of in-air annealed samples.

II. Experimental Setup

SEE measurements were performed with a scanning electron microscope (SEM). A schematic diagram of the measurement system is shown in Fig. 1. Detail of this system is explained in ref. [5]. The sample surface was irradiated with single-pulse electron beam with magnitude of 100 pA for 1 ms at a quite low dose (3 $\mu C/m^2$) to prevent serious charging on the surface. The primary electron currents were measured using a Faraday cup with +40 V bias voltage, while the secondary electrons were captured by a biased Faraday cup located above the sample. The latter Faraday cup

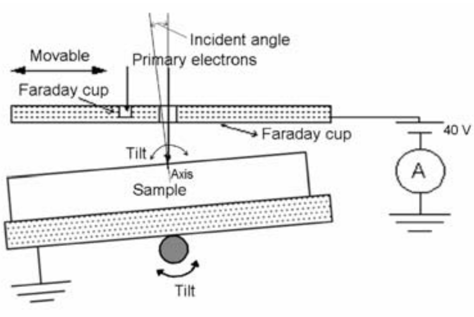


Fig. 1 Schematic diagram of the SEE measurement system

was coated with DLC (diamond-like-carbon) to minimize SEE from its surface. Here, the SEE coefficient was defined as ratio of secondary to primary currents at the beginning of the pulse.

In this work, to ensure the measurement sites of samples "fresh", i.e. without charging, measurements were performed on only one occasion at each measurement site. Then the sample was moved to the next measurement site so that distance between two sites was more than 2 mm.

Examined samples were several kinds of commercial alumina ceramics for electrical insulation applications in a vacuum. The geometry was a disk with diameter of 19 mm and thickness of 2 mm for as-sintered samples and of 1 mm for others. The properties of these samples are listed in Table 1.

III. Results and Discussion

Change of Surface Topography by Mechanical Finishing

Mechanical finishing process on alumina ceramics affects the surface residual stress and the roughness as well as the topography. Table 1 shows average roughness (Ra) and peak-to-peak roughness (Ry) of examined samples. Surface topographies of as-sintered, as-ground (after grinding process) and mirror-polished HA92 are shown in Fig. 2.

According to Table 1, average roughness of mirror-finished sample was smaller than as-sintered and as-ground samples. Although as-sintered and as-ground samples had almost same average roughness, their localized compositions of the surface topographies shown in Fig. 2 seem different. The localized composition may be edges or ravine-like surfaces. As shown in Fig. 2(a), as-sintered surface consists of a large number of edges or slope surface and a number of ravines. The grinding process of as-ground surface (Fig. 2(b)) causes decrease in the number of edges. However, in contrast, the ravines increase to be dominant. The surface topography of mirror-finished sample is almost flat with a small number of ravines.

Incident Angle Effects on SEE Coefficient

As explained previously, mechanical finishes modify the surface topography. A rough surface typically consists of a larger number of localized slope surfaces than a smooth surface. Since SEE is a localized process, effects of incident angle on the SEE coefficients of smooth and rough surfaces may be dissimilar.

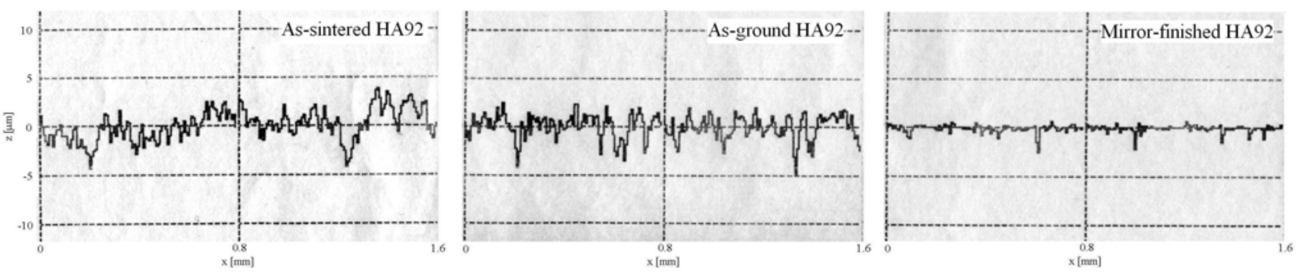
Figures 3 and 4 show relationship of SEE coefficient and incident angle of primary electron beam for HA95 having smooth and rough surfaces, respectively. It is found that for smooth surface SEE coefficients increased with incident angle, while those of rough surface almost did not change with the incident angle. The former can be explained by that for large incident angle θ secondary electrons are created at smaller depth as demonstrated in the range of $x_m \cos\theta$ of Fig. 3(b), where x_m is maximum depth of penetration for perpendicular injection [6]. This condition can increase probability of the number of generated secondary electrons for escaping to the surface. As a consequence, the larger the incident angle becomes, the higher is the SEE coefficients. As represented in Fig. 3, the incident angle effect for primary energy of 1 keV is weak comparing with that of 5 keV. This can be explained by that the penetration depth of the low energy electron beam may be relatively shallow nearly the escape depth, resulting in a small increase of SEE coefficients for high incident angle (Fig. 3(b)).

Rough surface may have localized slope planes with various directions. The randomized slope directions may cancel the incident angle effect due to simultaneous increase and decrease of localized incident angle. As illustrated in Fig. 4(b), when a rough surface is inclined, the localized incident angle of primary electron beam may be larger at A, but smaller at B. This results in almost same SEE coefficient even though the incident angle of the primary electron beam is changed. Since in the breakdown mechanism the injection of primary electrons is not always perpendicular, a rough surface looks better than the smooth one in the insulator

Table 1. Properties and surface roughness of the examined sample

	Purity [%]	Specific gravity [g/cm^3]	Flexural strength [MPa]	Loss tangent (10 GHz)	Average roughness, Ra (μm)			Peak-to-peak roughness, Ry (μm)		
					AS[1)]	AG[2)]	MF[3)]	AS[1)]	AG[2)]	MF[3)]
HA92	92	3.60	350	8E-4	1.15	1.01	0.26	8.9	8.4	4.2
HA95	95	3.65	350	6E-4	1.00	1.01	0.30	7.1	9.6	3.2

[1)]As-sintered [2)]As-ground [3)]Mirror-finished



(a) (b) (c)

Fig. 2 Surface topographies of (a) as-sintered, (b) as-ground and (c) mirror-finished HA92

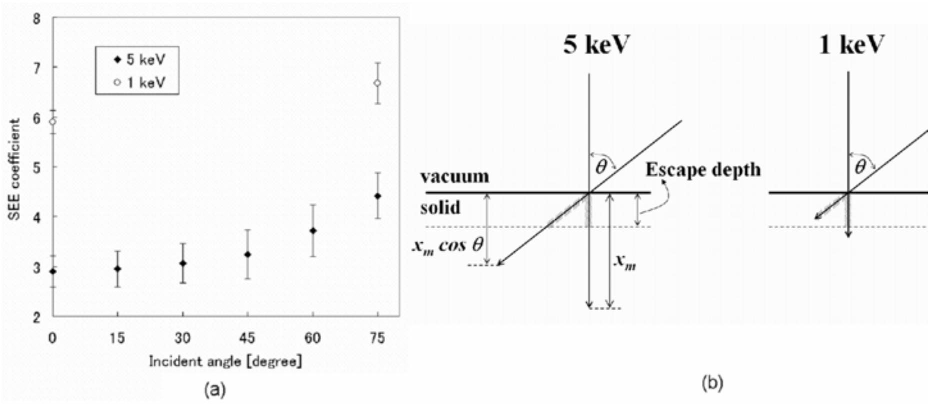


Fig. 3 (a) Relationship between SEE coefficient and incident angle for smooth HA95 having average roughness of 0.3 μm (b) Illustration of incident angle effect for smooth surface

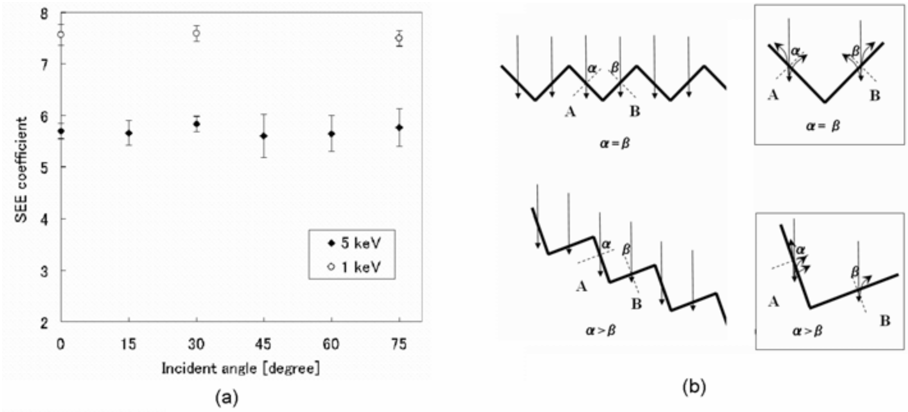


Fig. 4 (a) Relationship between SEE coefficient and incident angle for rough HA95 having average roughness of 1.0 μm (b) Illustration of incident angle effect for rough surface

application because of no incident angle dependence.

Influences of Mechanical Finishing on SEE Coefficient

Figures 5 and 6 show the SEE coefficients of HA92 and HA95 as a parameter of mechanical finishes before and after annealing. Each data point represents an average of 6 measurement results. The incident primary energies were 1 keV. The SEE coefficients of as-sintered and as-ground samples were considerably different even they had almost same average roughness (Ra). This finding demonstrates that the SEE coefficients do not only depend on the average roughness. Therefore, it is not sufficient to discuss SEE mechanism, which is a very localized process, by considering only the average roughness without taking into account the localized composition of its surface topography.

As-received alumina ceramics

Tendency of the SEE coefficients of as-received samples is different for HA92 and HA95. The SEE coefficients of as-sintered HA92 is the lowest, in contrast, those of HA95 is the highest. For as-received samples, effects of the surface finishes become rather complicated because the SEE coefficients are influenced by not only the surface topography, but also by the numerous trap sites in the as-received samples which are capable to catch the created secondary electrons before escaping from the surface [7]. The trap sites are perhaps caused by built-in charging as well as residual stress and defects due to mechanical finishes. Consequently, the SEE coefficients of as-received samples may be different among the same samples with the same finishing method, depending on the specific condition of the sample. Such trap sites can be reduced by an annealing treatment which is explained in the next section.

Annealed alumina ceramics

Since for industrial applications brazing process of alumina ceramics is carried out at ~1000°C, SEE coefficient of annealed alumina is preferred to be

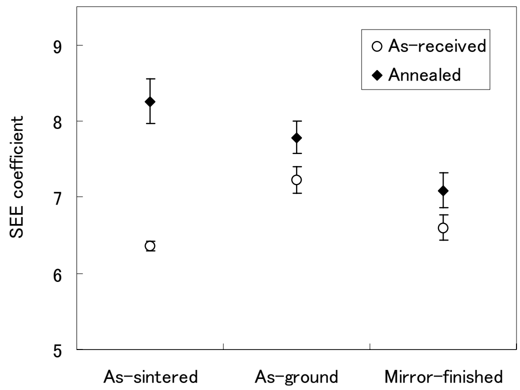


Fig. 5 SEE coefficients of HA92 with primary energy of 1 keV as a parameter of mechanical finishes before and after annealing

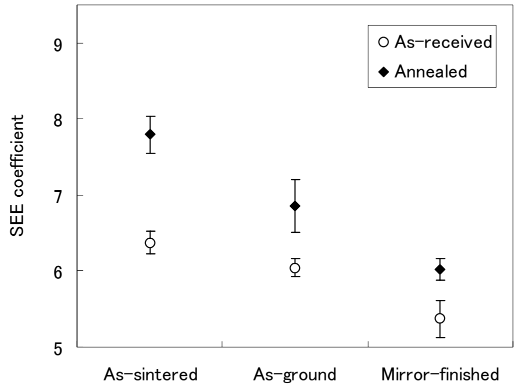


Fig. 6 SEE coefficients of HA95 with primary energy of 1 keV as a parameter of mechanical finishes before and after annealing

discussed. As shown in Figs. 5 and 6, the annealed samples attained an obvious dependency of SEE coefficients on the surface topography. The SEE coefficients became lower after mechanical grinding operations, and lower again after mirror-finished. The decrease can be qualitatively analyzed from a viewpoint of dissimilarities of the local compositions of the surface topography that may consist of ravine-like surfaces or of edges. From this viewpoint, the SEE coefficient is affected by existences of the ravines and of the edges. The former reduces the SEE coefficient due to reentrance effect of secondary electrons, while the latter enlarges the SEE coefficient due to the high incident angle.

As explained previously, localized surface composition of as-sintered alumina was dominated by the edges and rather low number of ravines. The edges of its surface probably cause a large number of SEE, while reentrance effect in the ravines is inferior for reducing the SEE. The number of edges of as-ground sample is reduced by the grinding process, but contrarily the ravines increase so that the reentrance effect becomes superior. As a consequence, the edge reduction and the ravine increase result in decrease in the SEE coefficient of as-ground samples. The smallest SEE coefficients of mirror-finished samples are probably caused by its flat surface with almost no edge.

Results of present investigation show that materials having few of localized slope surfaces or edges but high number of ravine-like surfaces may look suitable for the application of insulator in vacuum apparatus, because such surfaces reduce the SEE coefficient. However, the SEE coefficients of such materials may be still much larger than unity. One way to suppress the SEE coefficient is to coat the insulator with a very thin conductive material, such as TiN [8].

Annealing Effects on SEE Coefficient

Relation between the annealing process and the SEE coefficients becomes interesting, since the secondary electrons generated by injected primary electrons may be trapped or scattered at such defects as vacancies before they escape to a vacuum.

After annealing process in air at 1400°C for 1 hour, the SEE coefficients of all samples considerably increased as shown in Figs. 5 and 6. The increase is considered that the annealing is capable to reduce the trap sites with the following mechanisms. First, the annealing causes charge transfers then relaxes the surface charging or neutralizes the localized potential at point defects of F^+-centers, as well as at other defects, such as dislocations. The second mechanism concerns relaxation of the surface residual stress and recovery of oxygen vacancies since sufficient oxygen presents in the in-air annealing environment.

Furthermore, it is revealed that the annealing affects the grain boundaries of the alumina surface to be appeared clearly, caused by evaporations of sintering additives which in general have low SEE coefficients [6]. These evaporations resulted in higher SEE coefficients of annealed samples.

IV. Conclusion

1. SEE coefficient of smooth surface increases with incident angle while that of rough surface does not depend on the incident angle.
2. SEE coefficient depends on localized topography of the surface, rather than on its average roughness. This dependency has been qualitatively analyzed from a viewpoint of composition of the localized surface topography, which may consist of edges or ravine-like surfaces. The former enlarges the SEE coefficient, while the latter reduces it due to reentrance effect of the created secondary electrons.
3. SEE coefficients of alumina were considerably increased by in-air annealing process due to defect recoveries as well as neutralizations of localized charging.

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