SECONDARY ELECTRON YIELDS FROM THERMAL SPRAYED METAL SURFACES

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Abstract

We coated the copper or aluminum substrates with copper, aluminum, tungsten and titanium by thermal spraying, and investigated the relations between their properties of secondary electron yield (SEY), roughness and surface compositions. After sufficient conditioning by electron bombardments, most of the values of maximum SEY, δ_{max}, were lower, and the energies of the primary electrons, E_i, that gives δ_{max} were higher than those of flat surfaces. Furthermore, the profiles of SEY against E_i were broader than that of flat surfaces, and sometimes they had two peaks. The SEY of different materials also showed different behaviours against the sprayed conditions, such as the surface roughness and powder sizes. For the same material, the δ_{max} seemed to have weak dependence on the surface roughness parameters.

INTRODUCTION

The electron cloud effect (ECE) has been a serious issue in the high-energy particle accelerators storing positive particles, such as positrons and protons [1-2]. The secondary electron yield (SEY or δ) is a primary parameter for controlling the ECE. One of the applicable solutions would be preparing a material with a low SEY on the inner surface of beam pipes [1, 3]. It is known that a rough surface generally has a lower SEY than a smooth surface. The emitted secondary electrons are likely to be captured on the rough surface, and then the effective SEY should be reduced. From this standpoint, we tried to coat copper and aluminum substrates with copper, aluminum, tungsten and titanium by thermal spraying, in which rough surfaces were formed with these powders. The thermal spraying is an easy method to practice and has been widely used in industries. Here we report the results of SEY measurement from various thermal-sprayed metal surfaces and discuss the dependence on the roughness and the surface topographies.

EXPERIMENTAL

Sample Preparation

Thermal spraying technique is one of popular coating processes in which melted or heated materials are sprayed onto a surface. The thermal spray powders are heated by electrical (plasma or arc) or chemical means (combustion flame) [4]. In our case, copper or aluminum substrates were coated with copper, aluminum, tungsten and titanium powder by plasma. The substrate is a disk with a diameter of approximately 15 mm and a thickness of 3 mm. Fourteen different samples were prepared.

Copper samples The eight copper samples in Table 1 were made by Komiyama Electron Corp. Two different sizes of copper powder were used for thermal spraying. The diameter of the bigger one is 125 - 170 μm (the samples are referred by "R" in the table) and the smaller one is 45 - 50 μm (the samples are referred by "S" in the table).

As for the surface treatment before spraying, except for the normal machined surface (Ra = 1.14 μm), glass beads blast (Ra = 8.14 μm) was used to enhance the coating adhesion [5]. According to the results of roughness measurements and micrograghs of SEM, the surface treatment before spraying did not have a great effect on the roughness and the surface structure of the coating. However, when the coating is applied to a real accelerator beam pipe, glass beads blast could reduce the possibility of coating peeling.

Regarding the thickness of the sprayed layer, all eight coatings are thick enough for the incident electron with a kinetic energy of 2000 eV. But again, if the coating is going to be applied to a real accelerator beam pipe, the thickness of the coating should be reduced to lower the impedance of the surface. That is the reason why we reduced the thickness of the coating after making the first batch of the samples, R1 and S1.

It is anticipated that the emitted secondary electrons will be easily captured if the sprayed particles hold the original spherical shape on the surface. To keep the sprayed particle spherical, H_2 was cut off from the plasma-forming gas to decrease the sprayed temperature of R2, R3, S2 and S3. The coatings of samples S2 and S3, where the smaller powders were used, kept the spherical shape successfully (as shown in Fig. 4 later), but the coatings of samples R2 and R3, where the bigger powders were used, lost the spherical shape and melt on the surface.

Furthermore, as for a special pattern of the coating, the samples R4 and S4 were coated with a "trench" of which depth is 50 μm and the width is 2 mm. The roughness inside the trench was the same as outside. Thus, we could combine the advantages of a grooved surface [6] and a rough surface.

Aluminum, tungsten and titanium samples The six samples in Table 2 were made by Metal Technology Corp (MTC). Each aluminum, tungsten and titanium sample have two types, that is, the S-type with a roughness of Ra = 10 - 15 μm and the R-type with a roughness of 20 - 30

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Table 1: Copper Samples

	Sub-strate	Surface treatment before spraying	Powder size (μm)	Layer thickness (μm)	Plasma-forming gas	Special pat-tern	Sa (μm)	Sz (μm)
R1	Cu	Machined	Big	494	Ar + H_2		21.90	192.09
R2	Cu	Machined	(diameter	26	Ar		4.56	85.78
R3	Cu	Glass Beads Blast	125-170)	20	Ar		11.87	142.39
R4	Cu	Glass Beads Blast		101	Ar + H_2	Trench	16.33	200.23
S1	Cu	Machined	Small	494	Ar + H_2		5.54	60.04
S2	Cu	Machined	(diameter	122	Ar		8.17	91.64
S3	Cu	Glass Beads Blast	45-50)	109	Ar		9.98	106.29
S4	Cu	Glass Beads Blast		80	Ar + H_2	Trench	6.08	63.19

Table 2: Aluminum, Tungsten and Titanium Samples

	Substrate	Surface treatment before spraying	Roughness (Ra) be-fore spraying (μm)	Layer thick-ness (μm)	Sa (μm)	Sz (μm)
AL-S	Al	Beads Blast	14.94	210	12.82	149.50
AL-R	Al	Beads Blast	28.36	220	15.55	146.32
W-S	Cu	Beads Blast	14.94	210	7.45	73.91
W-R	Cu	Beads Blast	28.34	210	21.43	215.17
Ti-S	Cu	Beads Blast	14.00	200	17.26	171.12
Ti-R	Cu	Beads Blast	29.12	150	38.19	384.24

μm. Unlike the copper sample, for which the different sizes of powder were used, the glass beads blast was used to achieve the target roughness firstly, and then a single size metal powder was sprayed onto the surface to change the roughness. The final roughness was almost determined by that of the pre-formed surface of the substrate.

FACILITIES

One-shot 3D Measuring Macroscope, VR-3100, KEYENCE Corp.

The roughness parameters were obtained in several seconds by using this instrument. The roughness parameters include Sa (arithmetical mean height), Sz (maximum height), Sq (root mean square height), Ssk (skewness), Sku (kurtosis), etc.

Scanning Electron Microscope (SEM), VE-8800, KEYENCE Corp.

The topography of the surface of each sample was observed by using SEM. The typical magnifications were 100 and 500.

SEY Measurement

Figure 1 is the schematic layout of the facility for SEY measurement. The electron beam with an energy range from 150 to 2000 eV is generated by an electron gun. The measuring area on the sample is a circle with a diameter of approximately 5 mm. The secondary electrons are collected by a Faraday cup. The currents through the sample and the Faraday cup are recorded to calculate SEY. The total SEY (or δ) is obtained from the following formula;

$$\delta = \frac{I_F}{I_P} = \frac{I_F}{I_F + I_S} \quad , \qquad (1)$$

where I_S is the current measured at the sample, I_F is the current on the Faraday cup and I_P is the primary electron beam current. The sample was at grand potential level and, on the other hand, the Faraday cup was biased at + 50 V to attract the secondary electrons. Each current was measured by a current amplifier (Keithley 486 and Keithley 2400). The electron beam entered the sample at right angle to the surface.

The measurement started after a baking at 160□ for 24 hours. The SEY were measured once before the conditioning (that is, electron-beam bombardment), and then after the conditioning time of 2, 7, 24 and 48 hours. The energy of electron beam during the conditioning was 350 eV and the beam current was ~7 μA. After 48 hours conditioning, the total electron dose reached to ~4×10^{-1} C/mm^2.

X-ray Photoelectron Spectroscopy (XPS)

The surface compositions of the copper samples R3, R4, S3 and S4 were investigated after the SEY measurement by using XPS at Komiyama Electron Corp. The results showed that there was no significant difference in the surface composition in these four copper samples. The main component of the surface was cuprous oxide (Cu_2O), and some amorphous carbon and graphite produced by conditioning were detected. From this, it could be inferred that

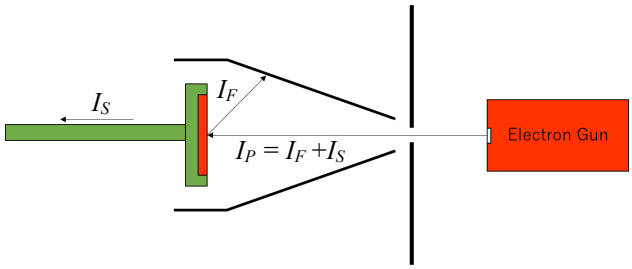
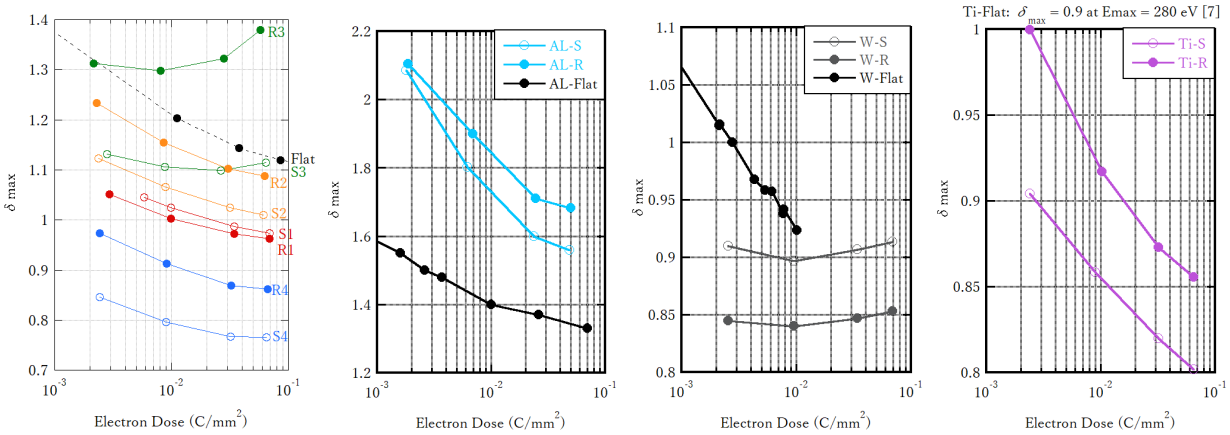


Figure 1: The schematic layout of the facility for SEY measurement.



(a) Cu (b) Al (c) W (d) Ti

Figure 2: The final δ_{max} of (a) Cu, (b) Al, (c) W and (d) Ti samples as a function of electron dose.

the difference in SEY of these copper samples after the conditioning are mainly not caused by the difference in the surface composition, but the surface topography.

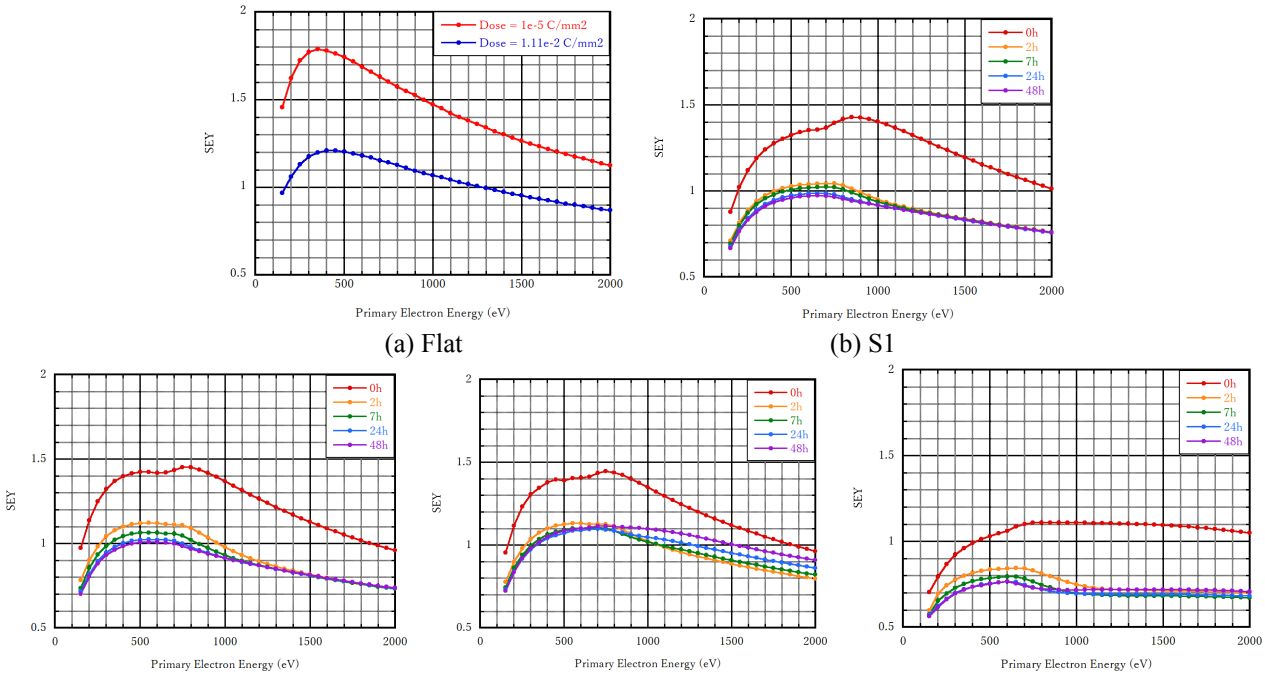
RESULTS AND DISCUSSIONS

Copper Samples

Figure 2(a) shows the δ_{max} of the copper samples as a function of the electron dose together with that of a flat copper sample.

As a whole, the δ_{max} was lower for the "S"-type samples (small powder) than for the "R"-type samples (large powder). Only for the case of samples S1 and R1, the δ_{max} were almost the same. Because the SEY profiles against the energies of primary electrons, E_i, for the "S"-type and "R"-type were similar, only the profiles of the "S"-type are presented in Fig. 3 together with that of a flat surface. It is clearly seen that E_{max} are higher for the thermal-sprayed surfaces. Furthermore, the profiles are broader compared to the case of flat surface, and sometimes have two peaks. This phenomenon seems to come from the combination of SEY from the top (or bottom) and from the slope part of the rough surface, and the further investigation is ongoing.

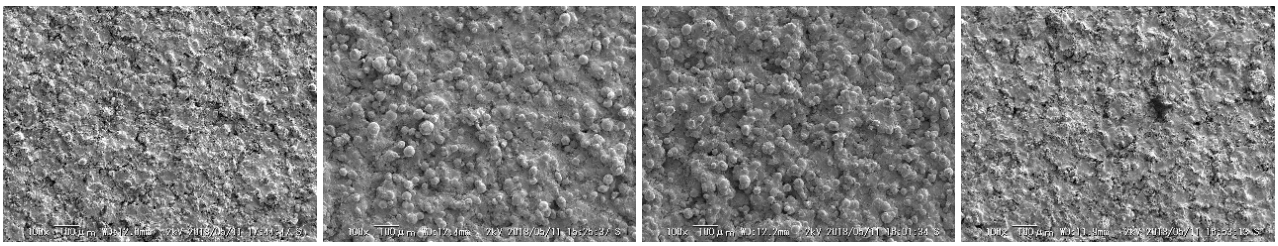
Another interesting phenomenon was observed especially in the samples of R3 and S3. The δ_{max} of these two samples increased with the conditioning time as shown in Fig. 2(a). As shown in Fig. 3(d), the SEY profiles have two



(a) Flat (b) S1

(c) S2 (d) S3 (e) S4

Figure 3: The profiles of SEY against the energy of incident electron, E_i of copper samples (a) flat, (b) S1, (c) S2, (d) S3 and (e) S4 for each conditioning time.



(a) S1 (b) S2 (c) S3 (d) S4

Figure 4: SEM micrograghs (×100) of samples (a) S1, (b) S2, (c) S3 and (d) S4.

peaks at lower (the first peak) and higher E_i (the second peak). The SEY for E_i lower than the first peak decreased with the conditioning time as a usual case. On the other hand, the SEY for E_i higher than the second peak increased with the conditioning time after 2 hours' conditioning. Although the phenomena were not so clear as in these cases, this tendency was observed for other samples as seen in the samples R4 and S4 (Fig. 3(e)) for example. The reason of the increase in SEY at high E_i region has not been understood yet. Further investigation is required.

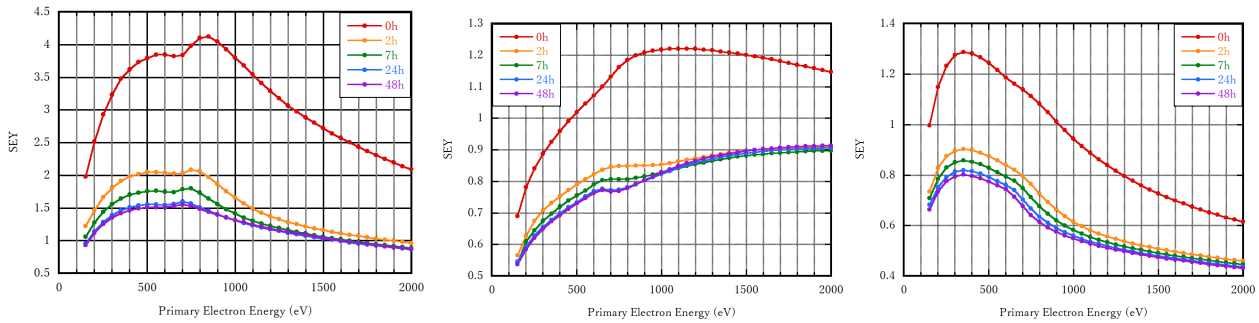
As described before, the coatings of samples S2 and S3 kept the spherical shape successfully. But the δ_{max} of S2 and S3 are only slightly lower than R2 and R3. This may be related to the incompleteness of the distribution of the particles that retain the spherical shape. As indicated in Fig. 4(b) and (c), although there were actually some particles with spherical shape, other particles in the deeper part of the surface were melted. If it is possible to keep the spherical shape even in the deeper part of the surface like titanium samples (as shown in Fig. 6(c) later), the SEY may be further reduced.

Among all samples, R4 and S4 have the lowest δ_{max} 0.8612 and 0.7661 by only adding a single trench. Compared samples R4 and S4 with samples R1 and S1, the surface appearances by SEM are almost the same as shown in Fig. 4, and also the roughness parameters are similar as indicated in Table 1. Therefore, it is inferred that a key to the decrease of SEY can be the trench. We are now making new samples with meshed and striped trenches to confirm the effect of trench. And we will check if they have much lower SEYs or not.

Aluminum, Tungsten and Titanium Samples

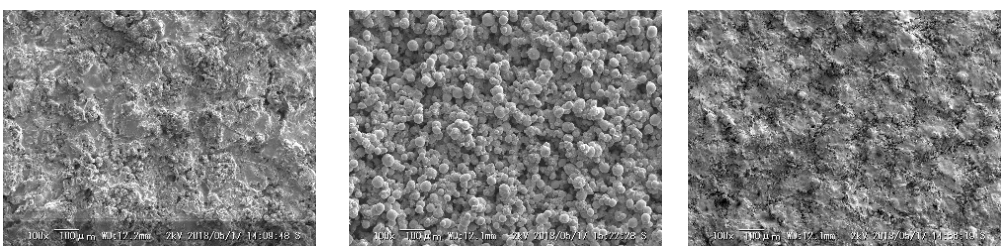
Figures 2(b), (c) and (d) show the final δ_{max} of the aluminum, tungsten and titanium samples as a function of electron dose, respectively. Note that the δ_{max} of pure titanium is in the reference [7]. It was found that the δ_{max} of rough samples are smaller than the flat one, except for the aluminum samples AL-S and AL-R. The SEY profiles of these samples are presented in Fig. 5.

The SEY profiles of samples W-S and W-R as a function of E_i show a special shape, as shown in Fig. 5(b). The SEY increased with E_i and the E_{max} was 2000 eV, that is the



(a) AL-S (b) W-S (c) Ti-S

Figure 5: The profiles of SEY against the energy of incident electron, E_i of (a) AL-S, (b) W-S and (c) Ti-S samples for each conditioning time.



(a) AL-S (b) W-S (c) Ti-S

Figure 6: SEM micrograghs (×100) of samples (a) AL-S, (b) W-S and (c) Ti-S.

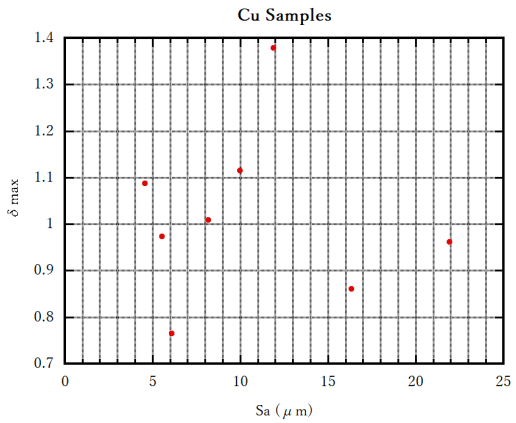


Figure 7: The final δ_{max} of copper samples as a function of Sa.

maximum energy of the electron gun. This is similar to the results of laser-treated (blackened) copper surface in the reference [8].

Roughness Parameters and SEY

Copper samples Figure 7 shows the relationship between the final δ_{max} and the roughness parameter of Sa for each copper sample. No obvious dependence of δ_{max} on the Sa was found. This tendency was also the same for other roughness parameters such as Sz, Ssk, Sku, Sal, Str, Sdr, Spc and Spd. One potential cause is that unlike the laser-treated surface, the topographies of our coatings are not highly ordered in microscale (μm), so the average surface parameters could not represent the real surface situation. The nanoscale structure should be considered [8]. However, it is also a fact that the profiles of SEY are different by the samples as shown in Fig. 3. Since many roughness parameters may affect the SEY, it is possible that we cannot find the relationship between SEY and a single parameter. More detailed consideration should be done for the dependence of SEY on the roughness parameters.

Aluminum, tungsten and titanium samples It seems that the roughness has different effects on different materials. In the case of tungsten, the δ_{max} decreases as the roughness increases. But for aluminum and titanium, it is completely opposite. Furthermore, the δ_{max} of AL-S and AL-R were higher than the flat one. It is inferred that the oxide layer for thermal-sprayed sample is thicker than the flat sample. More samples with different roughness should be tested to clarify these issues.

CONCLUSION

Thermal spraying is a potential technique to reduce the SEY. After conditioning, the values of δ_{max} were within the range of 0.7661 to 1.683, most of them were lower than the flat surfaces. We could also change the pattern of coating, such as sample R4 and S4, which have a trench structure. The copper samples with meshed and striped trench are expected to reach a much lower value of SEY. The profiles of SEY against E_i of thermal-sprayed surface were different from that of flat surfaces, that is, the E_{max} was higher and the peak was broader than those of flat surfaces. These should come from the property of rough surfaces but has not been well understood yet. Further investigation including a model calculation is in progress.

There are still many issues that we cannot explain that need to be clarified, such as the SEY of R3 and S3 increased when the conditioning time exceeded 2 hours, the weak dependence of SEY on roughness and the different effects of roughness on different materials. Besides, there are also many parameters of thermal spraying that can be adjusted, such as sprayed temperature, environment, surface pre-treatment, etc. Further surface analysis should be done to clarify these issues and improve the performance of the thermal sprayed surface.

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