STUDY ON THE SECONDARY ELECTRON YIELD OF ALUMINUM SURFACE THERMAL-SPRAYED WITH COPPER POWDER AND ITS FEASIBILITY TO THE SuperKEKB BEAM PIPES

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Abstract

To investigate the effect of the copper thermal spray coating on reducing the secondary electron yield (SEY) and verify its feasibility for accelerators as a countermeasure against the electron cloud effect (ECE), we coated the aluminum substrates (A6063) with copper powder by thermal spraying and measured their SEY, roughness parameters, chemical compositions using XPS, and outgassing rate. In addition, looking ahead to the future application to real accelerators, we tested two different ways of the thermal spraying to the actual aluminum beam pipe of the SuperKEKB. The effect of the spray angles and the thickness on SEY were investigated. In the study of the relation between SEY and roughness parameters, on the other hand, we found that SEY is more correlated with $\mathrm{Sa}\sqrt{\mathrm{Spd}}$, where Sa is arithmetical mean height and Spd is density of peaks, rather than Sdr (developed interfacial area ratio). Because Sa and Spd have lower resolution requirements for the microscope than Sdr, the experimental results obtained so far could be more consistent with the simulation results by using $\mathrm{Sa}\sqrt{\mathrm{Spd}}$.

INTRODUCTION

It has been well known that the electron cloud effect (ECE) in a positron or proton ring seriously deteriorates the beam qualities, such as emittance [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 surface with a low SEY on the inner wall of beam pipes to suppress the multiplication of electrons and then mitigate the ECE.

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. Various roughening methods have been studied so far, including machining, chemical reaction, laser abrasion, and so on. However, the relation between the roughness parameters and the SEY values has not been investigated and clarified so far.

In our last report [3], the rough copper coating on the copper substrate made by thermal spraying had a good result in reducing SEY. The thermal spraying is a well-developed, relatively easy, and suitable for mass production method to form a rough surface on various metals.

The main goal of our study is to find the conditions of thermal spraying that is applicable for the beampipes of SuperKEKB, which must have low SEY, high reproducibility, and low outgassing rate, and also to find the relation between the roughness parameters and the SEY values.

In this report, following the previous studies [3], we applied the copper thermal spray coating to the aluminum (A6063) substrate made of the same material used in the SuperKEKB beam pipe to evaluate its properties, and to measure its outgassing rate. We also tried to apply the thermal spraying to the real beam pipe with a curvature looking ahead to the actual application and investigated the practical fabrication methods, and then measured the SEYs from test samples attached on the beam pipes.

Regarding the research of the relation between the SEY properties and the roughness parameters, we tried a new parameter combination which could reduce the resolution requirement of the microscope for measuring roughness and reviewed the relation for the previous and new experimental data using the new parameter combination.

EXPERIMENTAL

Sample Preparation

At first, in order to confirm the feasibility of the copper thermal spraying on aluminium substrate, three types of test samples were fabricated under different conditions. The substrates of the test samples are made of aluminium-alloy (A6063) and have a diameter and a thickness of 8 mm and 3 mm, respectively. The diameter of copper powder is 45~50 μm. The spray conditions of the three types of samples are listed in Table 1.

The first sample (A1-1) was made under the similar condition of S_STD in the previous report [3] but was sprayed on a glass-beads blasted (GBB) aluminium substrate instead of the machined one. Sample Al-2 corresponded to the previous spray condition of S_GBB_LT [3], where LT refers to the removal of H_2 from the plasma source to lower the plasma temperature, trying to maintain the bead shape of the copper powder. Sample Al-3 reduced the plasma current based on Al-2, so that the surface temperature during spraying was further reduced.

Next, in considering the practical application of the thermal spraying to the actual beam pipe, the method to form a uniform coating along a curved inner wall should be established. To find the proper method, we put ten small test samples evenly along the inner walls of two half-cut beam

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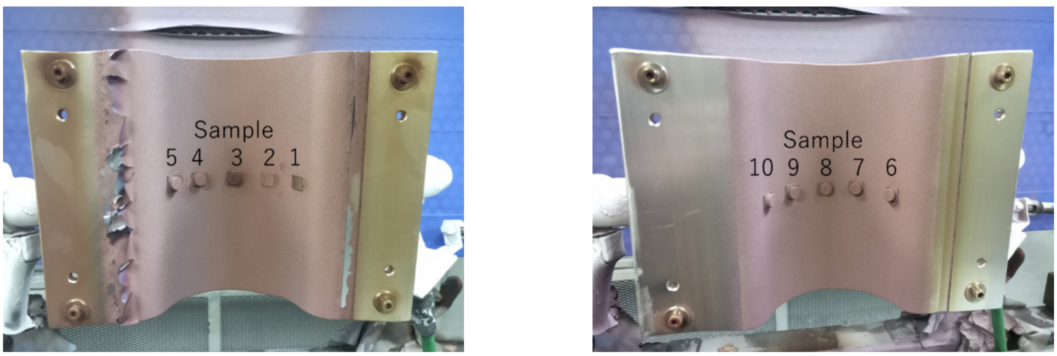
Table 1: Thermal Spray Conditions of S_STD, S_GBB_LT and Al-1~3

Sample	Substrate	Substrate pre-treatment	Plasma-forming gas	Remark
S_STD	Cu	Machined	Ar + H_2	Ref. [3]
S_GBB_LT	Cu	GBB	Ar	Ref. [3]
Al-1	Al	GBB	Ar + H_2	
Al-2	Al	GBB	Ar	
Al-3	Al	GBB	Ar	Reduced plasma current

Table 2: Thermal Spray Conditions of Curve-1~10

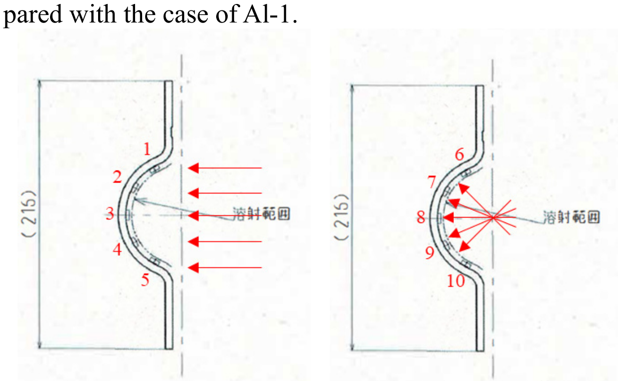
	Method 1					Method 2				
Curve-	1	2	3	4	5	6	7	8	9	10
Rounds of spraying	11	11	20	20	20	10	10	10	10	10
Coating thickness (μm)	47	94	164	171	101	77	92	101	97	77



(a) Curve-1~5 (b) Curve-6~10

Figure 1: Photos of curve series samples attached on the half-cut aluminum pipes.

pipes used in the SuperKEKB and apply the thermal spraying using two promising methods, as shown in Fig. 1. Here the spray condition was the same as that of the previous sample A1-1, since the SEY of it was the lowest as reported later. The materials and sizes are the same as before. Method 1 is spraying with fixed direction during the scanning of spray gun, which is called "horizontal spray"; Method 2 is that the spray direction is always perpendicular to the inner wall, which is called "sectorial spray", as shown in Fig. 2. It should be noted that to prevent the sample from falling off the pipe under the high temperature during spraying, the air cooling was strengthened compared with the case of Al-1.



(a) Method 1. (b) Method 2.

Figure 2: Sketches of the spray direction of Method 1 (horizontal spray) and Method 2 (sectorial spray).

The target coating thickness was ~100 μm which was the same as Al-1 (= 10 rounds of spraying). The coating thickness could be measured after each round of spraying. It is conceivable that Method 2 should ideally have an evenly distributed coating thickness; However, in the case of Method 1, the coating thickness on both sides should be thinner than that of the middle.

Therefore, in Method 1 there were two-stage targets for thickness: The target of Stage-1 was to make the coating of the central sample (Curve-3) reach 100 μm (11 rounds), and in Stage-2 the object turned into the sample on the side (Curve-5) (20 rounds). We got samples Curve-1~2 in Stage-1 and Curve-3~5 in Stage-2.

In Method 2, because the coating thickness was more uniform, we only sprayed 10 rounds to make the coating thickness of the central sample (Curve-8) reach 100 μm. The detailed information of the Curve series samples is listed in Table 2.

Finally, we made four kinds of samples to measure their outgassing rate, including machined A6063 and Al-1~3. There were 5 pieces of each kind of samples, and the size of each piece was 100×100×3 mm with four φ8 mm holes. The total surface area of the five pieces was about 0.1062 m^2.

Experiment

Roughness parameters measurement The roughness parameters were obtained in several seconds by using one-shot 3D measuring microscope VR-3100 (Keyence Corp.). The magnification we used were 120. The height resolution was ±3 μm and the width resolution was ±1.23 μm at this magnification. The parameters emphasized in this study were Sa (arithmetical mean height), Sdr (developed interfacial area ratio) and Spd (density of peaks) [4].

SEM image measurement The topography of the surface of each sample was observed by using scanning electron microscope (SEM) VE-8800 (Keyence Corp.). The typical magnifications we used were 100. Except for Al-2 and Al-3 where could observe the obvious bead shape, the other samples were difficult to see the difference by SEM.

Surface composition analysis The surface compositions were investigated after the SEY measurement by an X-ray photoelectron spectroscopy (XPS) analysis at Komiyama Electron Corp. In the previous report [3], we have known that the surface composition of copper thermal spray coatings was mainly Cu_2O. In addition, after observing more samples (S_STD, S_LT [3], Al-1~3), we found that their peaks of O(1s) were somewhat different and this would affect the trend of SEY after electron beam exposure (conditioning).

SEY measurement The measurement started after a baking at 160°C for 24 hours and the typical working pressure is at the level of 10^{-7} Pa. The SEY of each sample was measured within 150 - 2000 eV of primary electron energy (E_p) after the conditioning time of 2, 7, 24 and 72 hours. The E_p during the conditioning was 350 eV. After 72 hours conditioning, the total electron dose reached ~ 0.1 C/mm^2. For detailed settings, please refer to our previous report [5].

Outgassing rate measurement The apparatus used to measure the outgassing rate is shown in Fig. 3. The measurement was based on the conductance modulation method (CM method) [6]. This is a well-known formula:

$$P = \frac{Q}{S} \tag{1}$$

where P is pressure [Pa], Q is gas load [Pa·m^3/s], and S is pumping speed [m^3/s]. Because the pumping speed from Chamber 1 to Chamber 2 is restricted by the orifice with conductance C, the pressure P in the Chamber 1 can be obtained by the following equations:

$$\text{(Orifice open) } P_0 = \frac{a+b}{C_0} \tag{2}$$

$$\text{(Orifice closed) } P_1 = \frac{a+b}{C_1} \tag{3}$$

where a [Pa·m^3/s] is the outgassing per second from the inner wall of Chamber 1, b [Pa·m^3/s] is that from sample, C_0 and C_1 are the conductance with the orifice open and closed, respectively. Then, the total outgassing per second in Chamber 1 can be obtained by subtracting Eq. (2) from Eq. (3):

$$P_1 - P_0 = \frac{a+b}{C_1} - \frac{a+b}{C_0} \tag{4}$$

$$a + b = \frac{C_0 C_1 (P_1 - P_0)}{C_0 - C_1} \tag{5}$$

For the apparatus in this study, $\frac{C_0 C_1}{C_0 - C_1}$ is a constant equal to 0.05315 [Pa·m^3/s]. We can obtain a first by measurement without sample, then get b by measurement with sample. It is conventional to divide b by the total area of the samples to get the "outgassing rate" in unit Pa·m^3/s/m^2. In this study, the outgassing rate was measured for about 100 hours after baking at 160°C for 24 hours.

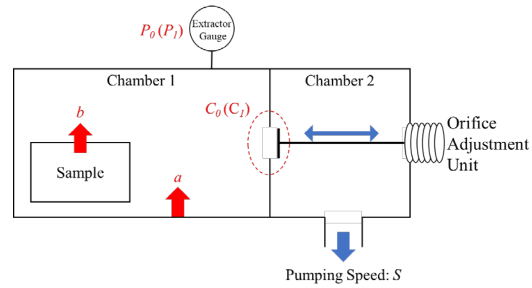


Figure 3: Sketch of the apparatus for outgassing rate measurement.

RESULTS AND DISCUSSIONS

At the beginning, all δ_{max} after conditioning and roughness measurement results are listed in Table 3. E_{max} is the energy of the primary electron corresponding to δ_{max}.

SEY Measurement

Figure 4 shows the δ_{max} of the samples listed in Table 1 as a function of the electron dose. For comparison, we also list the data of the machined flat copper surface [5]. It can be observed from Fig. 4 that Al-2 and Al-3 with bead shape coating could not further reduce the SEY. Al-3 even exposed a part of the aluminum substrate (according to the unshown SEM photos), which means that the thermal spraying at too low temperature could no longer cover the substrate completely. Among them, Al-1 had the lowest δ_{max}, which was slightly lower than that of S_STD with similar spray conditions but based on copper substrate. Therefore, we decided to use the spray condition of Al-1 to test its consistency on the curved inner wall of the beam pipe of the SuperKEKB.

Figure 5 shows the δ_{max} of the Al-1 and Curve-1~10 as a function of the electron dose. It was found that the δ_{max} of Curve-1~10 were all lower than that of Al-1 with almost same thermal spray conditions. This difference in SEY is suspected to be due to the difference in air cooling during spraying. The lowest δ_{max} of Curve series samples reached ~0.7, which is comparable to TiN and grooved surfaces [7].

Besides, the difference of δ_{max} between Curve series samples was about 0.1. From Table 2 and Table 3, it is known that the coating thickness had no significant relationship with δ_{max}, so we suspect again that this difference comes from the unevenness of air cooling during spraying. Regarding the effect of air cooling on the surface temperature during spraying, we will test it in the near future. This difference of 0.1 in SEY is acceptable for us, but the reason for this difference must be clarified to maintain the quality of the thermal spraying.

Coating Thickness and SEY

As mentioned above, the coating thickness had no significant relationship with δ_{max}, but the uniform coating thickness may be easier to control the consistency of the coating. Therefore, future development should be based on Method 2.

Surface Composition and SEY

The XPS results showed that the main component of all measured copper thermal spray coating was cuprous oxide (Cu_2O), which was consistent with our previous results [3].

But this time we found that there were some differences in the peak position of O(1s) between them, and the following rules was found: For those samples where the peak position of O(1s) is at 530 eV, which represented the O in the oxidized metal [8], their δ_{max} increased with electron dose; For those samples where the peak position of O(1s) is at 532 eV, which represented the O in the -OH or -CO_3 [8], their δ_{max} decreased with electron dose. At present, the mechanism of it is still unknown.

Table 3: Comprehensive Results of SEY and Roughness Measurements

Sample	δ_{max}	E_{max} (eV)	Sa (μm)	Sdr	Spd (mm^{-2})	$Sa\sqrt{Spd}$
S_STD [3]	0.96	650	5.44	0.11	526.00	157.63
S_GBB_LT [3]	1.06	600	10.55	0.20	413.21	214.46
Al-1	0.88	750	5.16	0.11	593.25	125.58
Al-2	0.98	550	8.36	0.15	451.56	177.65
Al-3	1.20	550	13.28	0.19	448.91	281.37
Curve-1	0.71	1750	8.71	0.13	329.93	158.15
Curve-2	0.81	1950	6.01	0.12	587.35	145.63
Curve-3	0.72	2000	5.17	0.08	487.42	114.18
Curve-4	0.70	1900	9.01	0.10	596.41	220.14
Curve-5	0.72	1650	10.04	0.14	444.98	211.77
Curve-6	0.73	1100	5.38	0.11	373.15	103.87
Curve-7	0.71	2000	6.38	0.10	485.52	140.47
Curve-8	0.73	1250	6.38	0.08	383.06	124.77
Curve-9	0.77	1550	5.34	0.12	488.89	118.01
Curve-10	0.83	1000	6.77	0.12	604.21	166.34

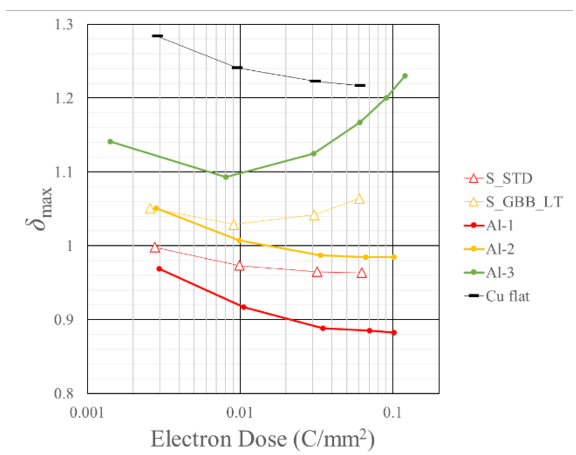


Figure 4: The δ_{max} of flat copper surface, S_STD, S_GBB_LT and Al-1~3 as a function of electron dose.

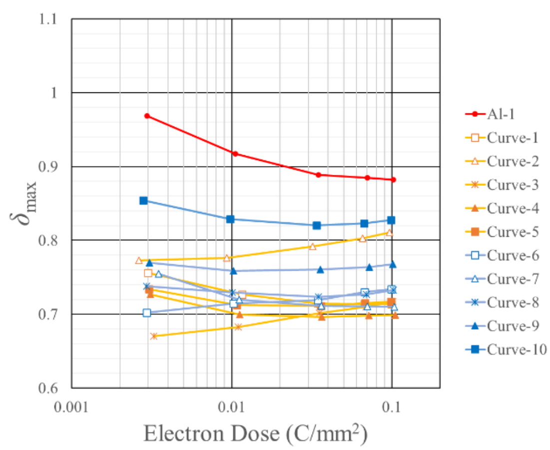
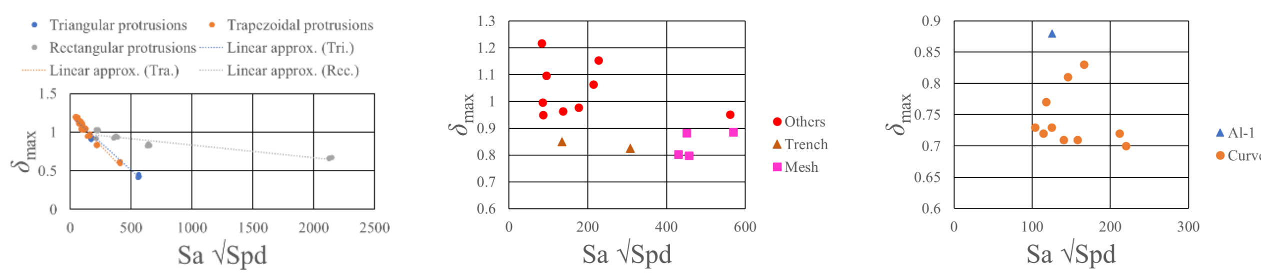


Figure 5: The δ_{max} of the Al-1 and Curve-1~10 as a function of the electron dose.



(a) Simulation results [3]. (b) Previous experimental results [3]. (c) New experimental results.

Figure 6: The δ_{max} of simulation and experimental results after conditioning as a function of $Sa\sqrt{Spd}$.

Roughness Parameters and SEY

From the results of previous simulations [3], it was found that the Sdr was negatively correlated with δ_{max}, although the correlation coefficients of surfaces with different "patterns" (triangular, rectangular, trapezoidal protrusions) were different. However, we did not find this trend in the previous experimental results. The possible reasons are as follows:

1. Insufficient resolution of the instrument for measuring roughness.
2. Pattern differences between samples.
3. Different surface composition between samples.

Regarding the second point, under the precise control of surface topography in the simulation, different patterns had different slopes of δ_{max} versus Sdr. However, the pattern of the real thermal spray surfaces was messy, so the thermal spray samples with the same Sdr might not necessarily correspond to the same δ_{max}.

About the third point, although the main component of the thermal spray samples was Cu_2O, the different chemical forms of some minor components such as oxygen might affect SEY.

The improvement made in this study for roughness analysis was only related to the first point. By analysing the previous simulation results [3], we accidentally found that δ_{max} had similar trend to $Sa\sqrt{Spd}$ and Sdr, as shown in Fig. 6(a). And the resolution required for Sa and Spd should not be as high as that of Sdr, so we used $Sa\sqrt{Spd}$ to analyse all experimental data so far to see if it can reduce the requirement for resolution.

Figure 6(b) shows that after we changed Sdr to $Sa\sqrt{Spd}$ in the analysis of the previous experimental results [3], a weak downward trend was found. Figure 6(c) shows the result of the new experimental data of the samples with similar spray conditions (Al-1 and Curve-1~10) in the same way. There was still a weak downward trend for the new experimental results, but it was not on the same line as the previous samples. It is inferred that the surface patterns of the new samples and the previous samples may be different. The possible reasons for the low correlation coefficient are the same as the three points at the beginning of this section.

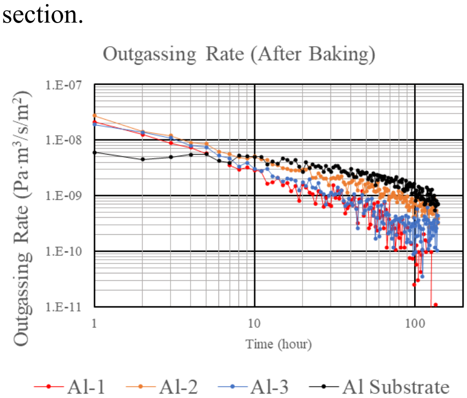


Figure 7: Outgassing rate of Al substrate and Al-1~3 for 100 hours after baking at 160 °C for 24 hours.

Outgassing Rate

Figure 7 shows the outgassing rate of Al substrate and Al-1~3 for 100 hours after baking at 160 °C for 24 hours. Al-1 has the lowest outgassing rate, which was lower than 1×10^{-10} at 100 hours. Compared with oxygen-free copper (OFC) with the outgassing rate 2.90×10^{-11} [$Pa\cdot m^3/s/m^2$] at 200 hours after baking at 100 °C for 24 hours [9], the outgassing rate of Al-1 was higher than that of OFC within an order of magnitude. Therefore, the outgassing rate of Al-1 can be considered as applicable in accelerators.

CONCLUSIONS

The copper thermal spray coating had a low SEY, a low outgassing rate, and a possibility to be implemented in a large area, and is found to be a potential method for reducing ECE. However, better control of the thermal spray conditions like air cooling is needed to further ensure the consistency of the properties of the thermal spray coating on a large area.

About the relation between roughness parameters and SEY, the surfaces roughened by thermal spraying had a lower SEY than that of a flat surface as expected from the simulation. A negative correlation between SEY and $Sa\sqrt{Spd}$ was found for the experimental data, although it was weaker than expected from the simulation. Further investigations from various viewpoints are required on this weak dependence, such as topography, formation temperature, and compositions of the surface.

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