STUDY ON COPPER THERMAL SPRAY COATING TO MITIGATE ELECTRON CLOUD EFFECT

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Abstract

In our previous studies, we have confirmed that the copper thermal spray coating can reduce secondary electron yield (SEY), but there were still some differences in SEY under different spray conditions. We suspected this was caused by the difference in surface temperature during spraying, so we adjusted the air cooling and the material of the sample backboard to control the surface temperature during spraying, and then measured the SEY, surface composition and roughness of these samples. In addition, we have also produced a straight aluminum beam pipe with copper thermal spray coating that can be installed in SuperKEKB, in order to observe the effect of the coating on reducing the electron cloud in the future. In this report, we discuss some problems and solutions encountered when making the beam pipe, such as the control of the coating edge, the deformation and oxidation during welding, etc.

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 ablation, and so on.

In our series of studies [3-5], we were committed to using thermal spraying to make rough surface. The thermal spraying is a coating process that melts or heats the powdered materials and sprays them onto the surface. It is a well-developed, relatively easy, and suitable for mass production method to form a rough surface on various metals. Our main goal is to find the spray conditions of copper thermal spraying that is applicable for the aluminum (A6063) beampipes of SuperKEKB, which must have low SEY and high reproducibility.

In the initial test, to make the conditions simple, we sprayed the copper powder on the copper substrates, and the sample with the lowest SEY was referred as S_STD [4]. After that, because the material of the beam pipe of SuperKEKB is aluminum, we changed the substrate material to aluminum and roughened the surface with glass beads blasting (GBB) before spraying to improve the coating strength of the different materials. The other conditions were the same as S_STD. This sample was called Al-1 [5]. In the last study [5], we applied the copper thermal spray coating to the samples attached on the half-cut beam pipe with a curvature and analysed them. We also established a large-area spray method, sectoral spray, that is, the spray direction is always perpendicular to the inner wall of the beam pipe, as shown in Fig. 1. These samples were called Curve-6~10.

However, comparing the SEY of the samples above, it could be found that even if the particle size of the copper powder and the plasma source condition were the same, if the material of the substrate and the backboard, and the air-cooling conditions were different (see Fig. 2), the SEYs changed, as shown in Table 1. We suspected that this was due to the different thermal conductivity of different materials, resulting in different surface temperatures during spraying. Therefore, we designed an experiment using four different conditions for spraying and measured the surface temperature during spraying. The variables included air cooling and backboard material. We also analysed the SEY, surface composition, and roughness of these samples.

Finally, after all the spray conditions were established, we produced a straight aluminum beam pipe with copper thermal spray coating that can be installed in SuperKEKB positron ring, in order to observe the effect of the coating on reducing the electron cloud in the future. In this report, we discuss some problems and solutions encountered when making the beam pipe.

EXPERIMENTAL

Sample Preparation

To confirm the surface temperature during spraying, we designed an aluminum substrate that can be connected to the thermocouple, as shown in Fig. 3. The substrates were made of aluminium-alloy (A6063) and had a diameter and a thickness of 15 mm and 3 mm after assembly, respectively. There were eight substrates that can be installed with thermocouples, and six block substrates of the same size. The surface of each substrate was roughened by GBB before spraying. Different from the previous use of double-

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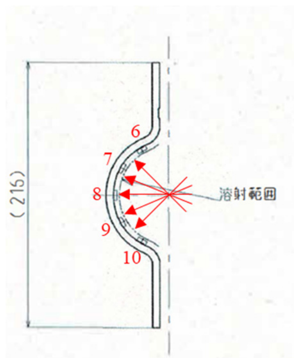


Figure 1: Sketch of the spray direction of sectorial spray [5].

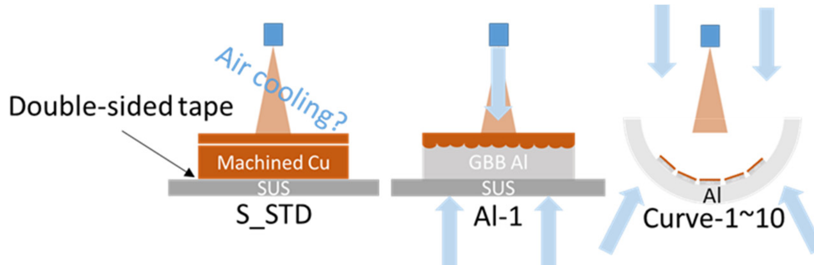


Figure 2: The materials of each part and air-cooling conditions of S_STD, Al-1, and Curve-1~10.

Table 1: Thermal Spray Conditions of S_STD, Al-1, and Curve-1~10

Sample	Substrate	Backboard	Fixing method	Air cooling	δ_{max}
S_STD [4]	Machined Cu	SUS plate		Unrecorded	0.96
Al-1 [5]	GBB Al	SUS plate	Double-sided tape	Gun + Back	0.88
Curve-1~10 [5]	GBB Al	Al pipe		Front + Back	0.70~0.85

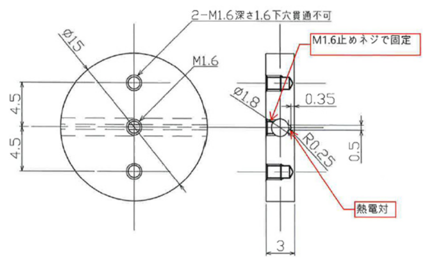


Figure 3: Design drawing of the substrate that can be installed with the thermocouple.

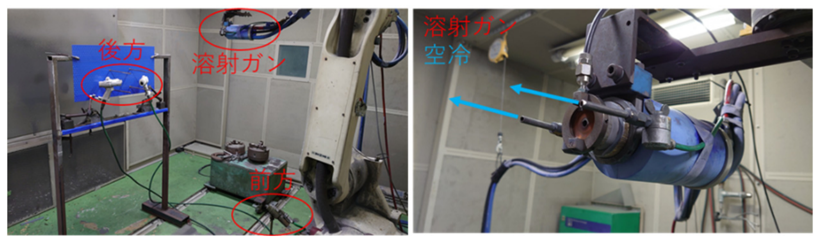


Figure 4: Photos of air cooling from the front, the back, and the spray gun.

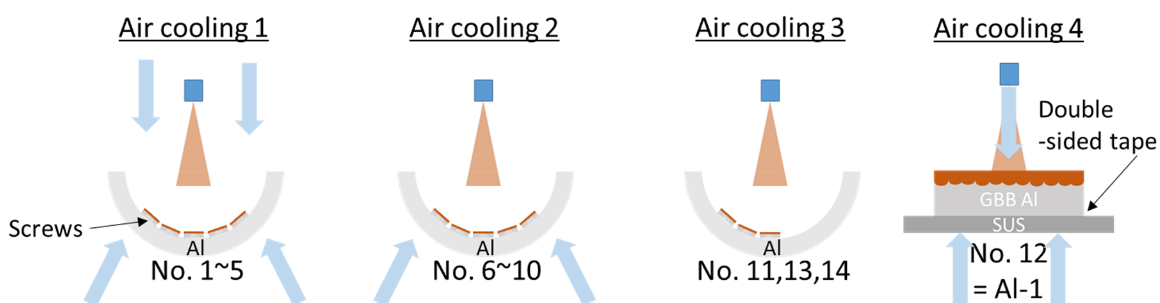


Figure 5: Schematic diagram of air-cooling conditions 1 to 4.

sided tape to fix the substrates [5], we used screws to fix these substrates on the beam pipe.

The fixed spray parameters included the diameter of the copper powder (45~50 μm) and the plasma source mixed with argon and hydrogen. The target film thickness was 100 μm.

To control the surface temperature during spraying, we set four different air-cooling conditions. The first condition was to turn on the front and back air cooling, the second was to turn on only the back, and the third was to turn off all the air cooling. The fourth condition was special. We reproduced the previous sample Al-1. The substrate was fixed on the stainless-steel backboard with double-sided tape, and the air cooling came from the spray gun and the back. The so-called air cooling from the front, back and spray gun were shown in Fig. 4. The above air-cooling conditions and sample installations can be more easily understood by referring to Fig. 5. These fourteen samples were called No.1~14, of which No. 1~3, 6~8, 11 and 12 were installed with thermocouples.

Experiment

Roughness parameters measurement The roughness parameters were obtained by using laser microscope VK-X1100 (Keyence Corp.) in Tohoku University. The magnification we used were 50. The height resolution was

0.5 nm and the width resolution was 0.14 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) [6]. Because according to the previous simulation [4], SEY and surface area (*Sdr*) were positively correlated. Besides, $Sa\sqrt{Spd}$ and *Sdr* have similar meanings, and the use of $Sa\sqrt{Spd}$ was an attempt to reduce the requirements for the resolution of the microscope [5].

Surface composition analysis The surface compositions were investigated by X-ray photoelectron spectroscopy (XPS) analysis in the Industrial Technology Innovation Center of Ibaraki Prefecture. In the previous report [4], we have known that the surface composition of all copper thermal spray coatings was mainly Cu_2O after conditioning. This time we intended to measure the composition change of the coating before and after conditioning. It should be noted that the XPS measurement in this study was a qualitative measurement. The requirements for quantitative measurement with XPS are strict, and the rough surface will affect the position and width of the XPS peak, which may be difficult to accurately quantify each component [7].

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 [3].

Production of the Real Beam Pipe

The structure of the beam pipe of SuperKEKB is shown in Fig. 6. The cross-section is a circle with a diameter of 90 mm plus the antechambers. This time we made a straight beam pipe. We used sectorial spraying and air-cooling condition 1 during spraying, and the target coating thickness was 100 μm. First, we divided the longer pipe into upper and lower parts, and then sprayed on the half-cut pipes. Second, we cut off the excess parts and welded the two half-cut pipes with the cooling water channels. Finally, we cut out the hole for the electron monitor, installed the screens to isolate the NEG, and welded the port for the electron monitor and other flanges. The total length of the beam pipe after assembly was 1200 mm. We will cut out some samples from the excess parts, and then confirm whether their SEY, roughness, and surface composition are consistent with the test samples.

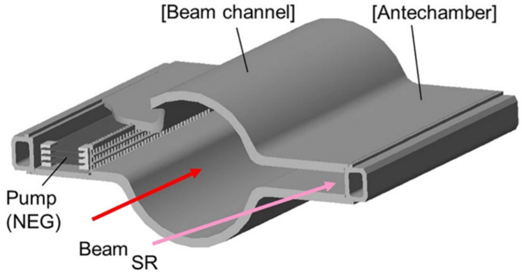


Figure 6: Sketch of the beam pipe of SuperKEKB.

RESULTS AND DISCUSSIONS

SEY and Surface Temperature

All δ_{max} after conditioning, highest surface temperature during spraying, roughness measurement results and XPS measurement progress are listed in Table 2. Figure 7 shows the δ_{max} of sample No. 3, 8, 11, 12 as a function of the surface temperature during spraying. It should be noted that the SEY measurement of sample No. 12 has not been carried out, but because its spray conditions were the same as the previous sample Al-1, we used the δ_{max} of Al-1 to plot here. It can be found that the surface temperature during spraying was positively correlated with SEY. This may be caused by temperature affecting the surface roughness or surface composition.

As can be seen in Table 2, we have not performed the roughness measurement of samples No. 1~14. But based on previous experiences, the roughness parameters of different thermal spray samples were very similar, so we predict that the roughness parameters of these new samples will not be significantly different.

Regarding the measurement of surface composition, the measurement of sample No. 1, 3, 6, 8, 11 before conditioning has been completed. Because the apparatus for measuring SEY is currently being adjusted, the measurement of surface composition after conditioning will be performed after the SEY measurement in the near future. Combining the results of the previous [4, 5] and new measurements, the following conclusions could be drawn: Before conditioning, the main components of copper thermal spray coating were CuO, Cu_2O, adventitious carbon, and $CuCO_3/Cu(OH)_2$; After conditioning, the main components became Cu_2O, graphite, and $CuCO_3/Cu(OH)_2$ disappeared. Although the measurement has not been completed, we predict that the surface composition after conditioning under different air-cooling conditions should not be significantly different.

With the current data and presumptions, we can only speculate that the differences in SEY may be caused by subtle surface structure differences (caused by different temperatures) that cannot be distinguished by the microscope.

At last, the air-cooling condition 1 was used in the subsequent beam pipe production.

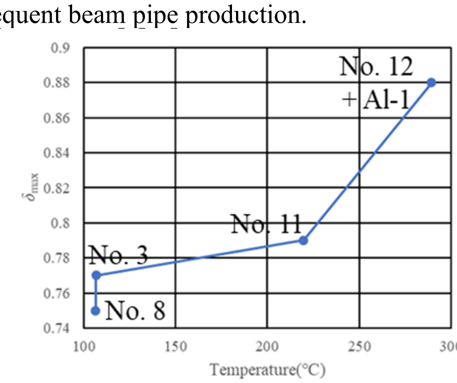
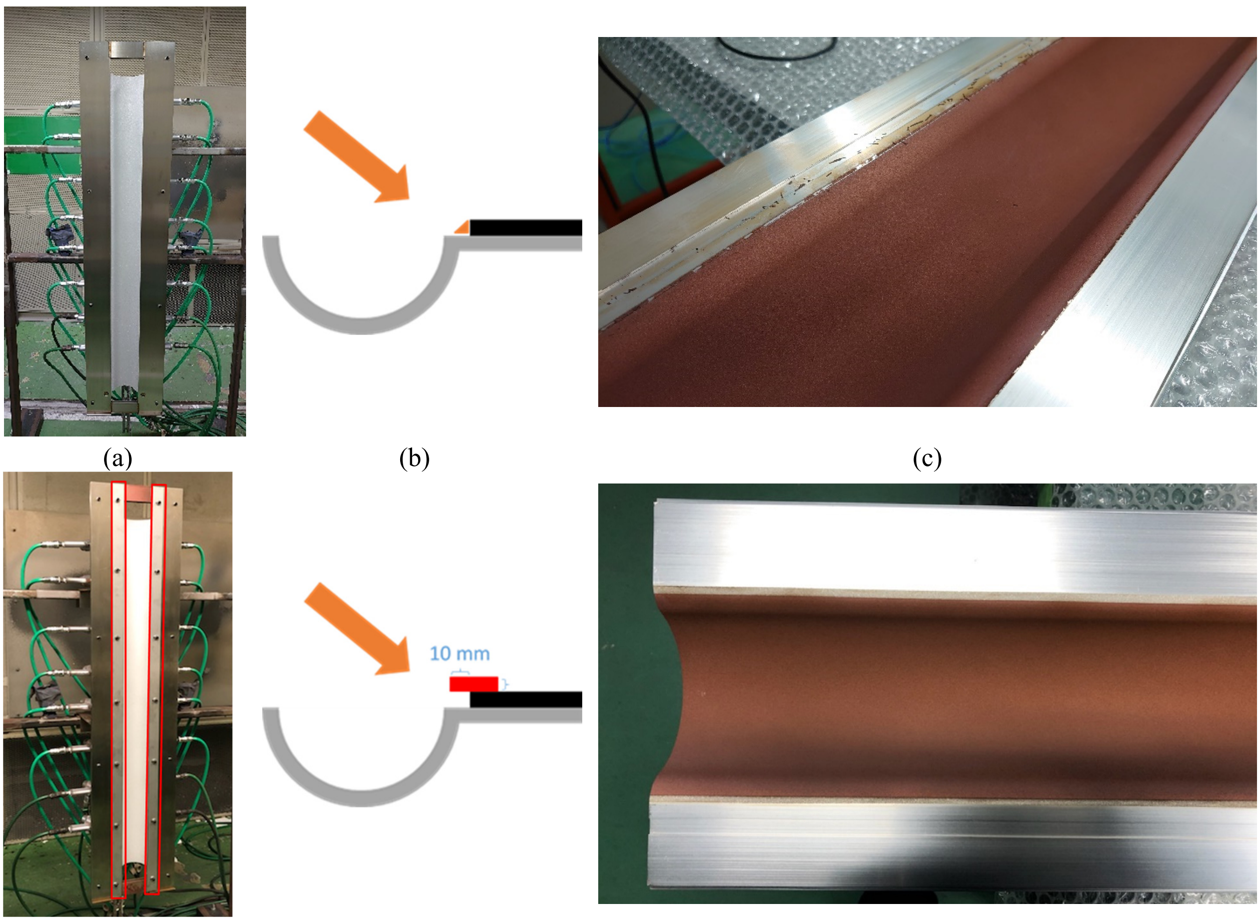


Figure 7: The δ_{max} of sample No. 3, 8, 11, and No.12 + Al-1 as a function of the surface temperature during spraying.

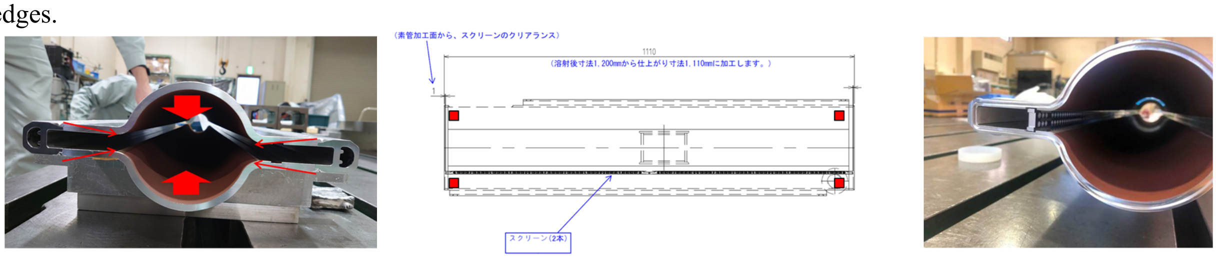
Table 2: Comprehensive Results of Al-1, Curve-8, and No. 3, 8, 11, 12 (× Means Undone)

Sample	Surface temp. (°C)	δ_{max}	Sdr	$Sa\sqrt{Spd}$	XPS before cond.	XPS after cond.
Al-1 [5] (Same spray condition as No. 12)		0.88	1.12	2.06		○
Curve-8 [5]		0.73	1.24	2.06		×
No. 3 (Air cooling 1)	106.80	0.77	×	×	○	×
No. 8 (Air cooling 2)	106.65	0.75	×	×	○	×
No. 11 (Air cooling 3)	219.8	0.79	×	×	○	×
No. 12 (Air cooling 4) (Same spray condition as Al-1)	289.35	×	×	×	×	×



(a) (b) (c) (d) (e) (f)

Figure 8: (a) Setting of the first thermal spraying on the long half-cut beam pipe. (b) Schematic diagram of the accumulated coating between the fixture and the pipe. (c) The accumulated coating peeled off and formed dust. (d) The setting after installing two stainless-steel baffles. (e) Schematic diagram of the baffles (f) Coating with well controlled edges.



(a) (b) (c)

Figure 9: (a) The stress generated by the welding material squeezed the beam pipe. (b) Positions of the four aluminum spacers. (c) The installed screens after improvement.

Production of the Real Beam Pipe

At present, the beam pipe has been completed and installed in the test section of SuperKEKB, waiting for the operation in October to observe the effect of the reduction of the ECE. During the production process, we encountered the following four on-site problems:

1. Coating edge control
2. Deformation control during welding
3. Oxidation of the coating during welding
4. The sequence of cutting and spraying

Coating edge control The first attempt to spray directly on the half-cut beam pipe is shown in Fig. 8(a). The coating accumulated between the fixture and the pipe was easy to peel off, as shown in Fig. 8(b) and 8(c). We would rather narrow the coating range and leave some clean GBB surface, and do not produce a coating that is easy to peel off and cause dust problems. Therefore, we added two stainless-steel baffles at the junctions of the fixture and the pipe, which made it easier to control the spray range, as shown in Fig. 8(d) and 8(e). After this improvement, we got a nice coating with clean edges as shown in Fig. 8(f).

Deformation control during welding The shape of the pipe was squeezed due to the stress generated by the welding material, as shown in Fig. 9(a), causing the NEG screens to be inserted only halfway. To solve this problem, we placed four aluminum spacers (red squares in the Fig. 9(b)) on both ends of the pipe to prevent the pipe from deforming. After that, this problem was successfully corrected, as shown in Fig. 9(c).

Oxidation of the coating during welding We found that the high temperature caused by welding discolored the surrounding thermal spray coating, as shown in Fig. 10. We should evaluate the effect of discolored parts in the future.

Figure 10: The high temperature caused by welding discolored the surrounding coating.

The sequence of cutting and spraying This time, the pipe was sprayed first, and then been cut and welded. If the spray step can be adjusted after some cutting and welding, it may be possible to reduce the peeling caused by cutting and the discoloration during welding.

CONCLUSIONS

The copper thermal spray coating had a low SEY, can be implemented in a large area, and is found to be a potential method for reducing ECE. This study confirmed that the surface temperature during spraying did affect the SEY, and the surface temperature is positively correlated with SEY. But the mechanism of this effect has not been confirmed yet.

After establishing the optimized spray conditions and solving several on-site problems, we successfully fabricated an aluminum beam pipe with copper thermal spray coating and installed it in the test section of SuperKEKB. In addition to the measured outgassing rate [5], we will also measure its impedance, dust, and coating strength. We are looking forward to the operation in October to observe the effect of the reduction of the ECE.

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