APPLICATION OF HIGHLY-PURE COPPER LINING TO NORMAL-CONDUCTING RF CAVITIES FOR AN ELECTRON-POSITRON SUPER B FACTORY

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Abstract

We apply a new copper lining with a high purity and a high electric conductivity to normal-conducting RF cavities for an electron-positron super B factory, in which four-times more beam current is required to be stored than in the present KEK B factory (KEKB). The lining is produced first by electroplating in an acid copper sulfate bath without brightener nor other organic additives, where the current is periodically reversed ("PR process"). Then the copper surface is electropolished to make it smoother. There are two differences between our application and the previous one to the accelerator components for J-Parc. The first one is the lining thickness; our target of $120\,\mu$m is much thinner. The second one is that we have no mechanical polishing on the electroplated surface before electropolishing. In this paper, results of the quantitative estimations of the quality factor on the electroplated pillbox test cavity are reported together with microscale investigations of the copper surfaces.

INTRODUCTION

The ARES system [1], which is a normal-conducting RF accelerating cavity system for KEKB, stores high beam currents stably to achieve the high luminosities. The stability is obtained by having the additional energy-storage cavity with a large cylindrical shape (S-cav), which is electromagnetically coupled to the HOM-damped accelerating cavity via the small coupling cavity.

The S-cav has a large unloaded quality factor (Q_0), about 1.7×10^5 (standalone), and can store huge amount of electromagnetic energies in the TE_{013} mode. The size of the cavity is so large that it is made of iron (SS400) to obtain enough mechanical strength. Copper electroplating is applied to the iron cavity with a thickness of about $100\,\mu$m, which is much thicker than the skin depth in copper at the KEKB RF frequency (509MHz) of about $3\,\mu$m. The electroplating on the present cavities was performed in a pyrophosphate bath, where brightener was used to make the surface smoother and to have few defects.

We apply a new copper lining with a high purity and a high electric conductivity to normal-conducting RF cavities for an electron-positron super B factory [2], in which four-times more beam current is required to be stored than in KEKB. The lining is produced first by electroplating in an acid copper sulfate bath without brightener nor other organic additives, where the current is periodically reversed (called "PR process"). The cycle typically has 20 seconds normal and 4 seconds reverse. The electric conductivity of the electroplating is so high, 102%IACS[1] in DC currents, as to be comparable to that of the highest-class oxygen-free copper. However, there could be more defects in the surface. We perform electropolishing (EP) as a post-process to make the surface smoother.

This lining was already applied to the accelerator components for the J-Parc project [3]. There are two differences between our and the J-Parc applications. The first one is the lining thickness; our target of $120\,\mu$m (for *electroplating*) is much thinner than the previous one of about 1 mm (for *electroforming*). The second one is that we have no mechanical polishing on the electroplated surface before EP.

In this paper, results from the basic studies are reported on the Q_0 and microscale surfaces of the copper electroplating before and after EP. The electroplating and EP were performed on the condition in our application.

MEASUREMENT OF Q_0

The test cavity used in the Q_0 measurements has a pillbox shape with a 451.2 mm inner diameter and a 260 mm inner height, consisting of a barrel and two endcap parts. This cavity has no port, just having some small holes for inserting RF cables, therefore, can be considered to be an ideal pillbox. Figure 1 shows the electroplating on the final condition in our application for the Q_0 measurements. Figure 2 shows thickness measurements on the barrel part. The barrel and endcaps were connected with bolts, as seen in Figure 3, where the clamping torque was raised so that the measured Q_0 of the TM_{010} mode[2] was saturated in order to obtain enough RF contact. After a Q_0 measurement, the test cavity was dismantled and then electropolished. Figure 4 shows the electroplating after EP. Finally, we performed a Q_0 measurement again.

We used a network analyzer to measure Q_0, where two RF cables, which had a loop or antenna structure at the end, were connected to the test cavity. One of them is used to

[1] IACS stands for International Annealed Copper Standard.

[2] Surface currents flow across the RF contact in the TM modes, on the other hand, they do not in the TE modes.

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Figure 1: Copper electroplating on the test cavity before EP.

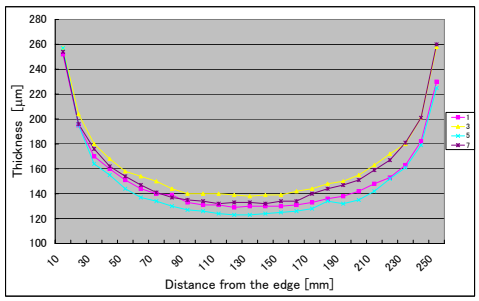

Figure 2: Thickness measurements for the electroplating on the barrel part along its axis at the four different azimuthal positions (1, 3, 5, and 7).

excite an eigenmode, and the other for pickup. We used only monopole modes for the Q_0 measurements to suppress backgrounds from multipole modes. The coupling strengths were set to be small, about 0.1%.

Figure 5 shows measured Q_0 at 20°C divided by the theoretical calculation as a function of the resonance frequency. In the theoretical calculation, the 100%IACS electric conductivity of copper and the completely-even surface with no defect are assumed. The Q_0 before EP is about 5% better than that of the electroplating on the present S-cav, and it can be furthermore improved with EP by about 5%. The Q_0 value after EP is almost at the maximum, predicted from the DC electric conductivity of the oxygen-free copper (102%IACS). It should be noted that no frequency dependence can be observed after EP unlike the case before it, which means that copper surface becomes extremely even with almost no defect by EP. We re-measured Q_0 using the other network analyzer for cross-check, and obtained the same results.

Figure 3: Fabricated pillbox test cavity (after electroplating) used for the Q_0 measurement.

Figure 4: Copper electroplating on the test cavity after EP.

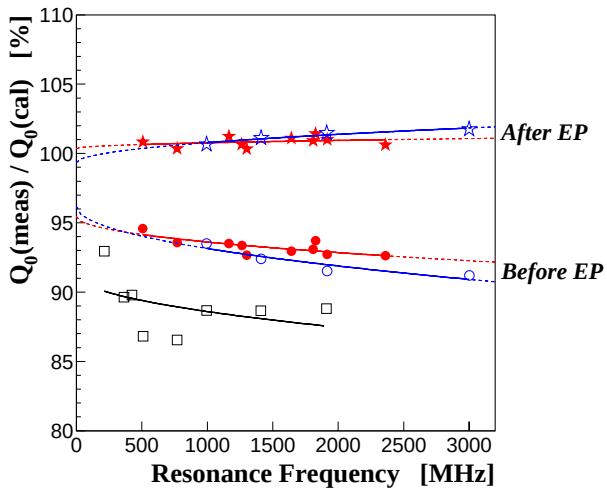

Figure 5: Measured Q_0 ($Q_0(meas)$) at 20°C (circles and stars) divided by the theoretical calculation ($Q_0(cal)$) as a function of the resonance frequency. The circles (stars) are Q_0 for the copper electroplating applied in an acid copper sulfate bath without brightener before (after) EP, and the open (closed) circles and stars are for the TE (TM) modes. The squares are Q_0 measurements for the copper electroplating applied to the present S-cav in a pyrophosphate bath with brightener, where no temperature correction is included. In the temperature correction, the coefficient of the electric resistance of copper: $4.33 \times 10^{-3}\mathrm{K}^{-1}$ is assumed. The lines in the figure are results of the fit with an empirical function: $P_1 + P_2 \times \sqrt{f}$, performed separately for the TE and TM modes.

MICROSCALE INVESTIGATION OF THE COPPER SURFACES

A great interest is in investigation to find how the copper surfaces are, and how the surfaces are different before and after EP in microscale. Below are shown the reports by various microscopies.

Cross-Section Images by SEM

Test pieces were electroplated on the same condition as for the test cavity. They were cut in half, and the tallies were electropolished. Then chemical etching was applied to the cross sections after mechanical polishing. Figure 6 shows cross-section images by a scanning electron microscope (SEM). Grain boundaries in the copper electroplating

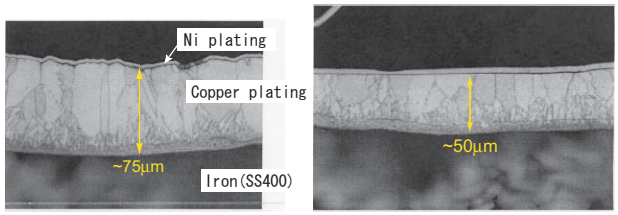

Figure 6: SEM images of the cross sections of the copper electroplating applied in an acid sulfate bath without brightener (PR process) before (left) and after (right) EP. Ni plating with a thickness of about 3 μm was applied to the copper surface for protection.

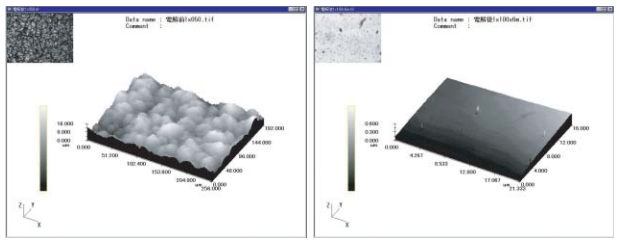

Figure 7: Bird views of the copper surfaces of the electroplating applied in an acid copper sulfate bath without brightener (PR process) taken with a laser scanning microscope before (left) and after (right) EP. The area size is $256 \times 192\,\mu\mathrm{m}^2$ for the left, and $21 \times 16\,\mu\mathrm{m}^2$ for the right one. The height ranges are different; 16 μm in the left, and 0.6 μm in the right.

can be seen as lines in the images.

While there is some roughness on the surface before EP, the surface is extremely even after EP. It should be noticed that the even surface might be influenced by the mechanical polishing and/or chemical etching more or less because this observation is semi-destructive.

Observations by Surface Microscopies

Next, we observed the copper surfaces using two types of surface microscopies. These observations are non-destructive, and can give us quantitative estimations of the surface roughness.

Figure 7 shows bird views taken with a laser scanning microscope (OLYMPUS OLS1100). From the left one, the two-dimensional average surface roughness before EP is estimated to be 0.617 μm in the area of $256 \times 192\,\mu\mathrm{m}^2$. The roughness after EP cannot be estimated even with the maximum magnification and with the best height resolution of about 0.02 μm, as seen in the right view of Figure 7. Some spikes are seen in the right view of Figure 7.

For a further investigation, we used an atomic force microscope (Digital Instruments NanoscapeIII), which has a best height resolution of about 0.01 nm. Figure 8 shows bird views taken with this microscope. From the left view, the two-dimensional average roughness is estimated to be 6.7 nm in the area of $10 \times 10\,\mu\mathrm{m}^2$, and 5.2 nm in the selected area excluding the two largest spikes. From the right view, the two-dimensional average roughness is estimated to be 3.1 nm in the area of $1 \times 1\,\mu m^2$, and 1.8 nm in the selected area excluding the two largest bumps.

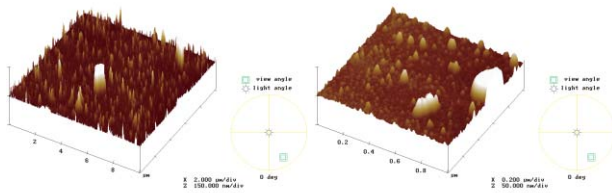

Figure 8: Bird views of the copper surfaces of the electroplating applied in an acid copper sulfate bath without brightener (PR process) taken with an atomic force microscope after EP. The area size is $10 \times 10\,\mu\mathrm{m}^2$ for the left, and $1 \times 1\,\mu\mathrm{m}^2$ for the right. The height ranges are different; 0.150 μm in the left, and 0.050 μm in the right.

At present, we cannot reject a possibility that the relatively-large spikes or bumps observed in the right view of Figure 7 and in Figure 8 might be some dusts attached on the copper surfaces after EP.

CONCLUSIONS AND THE NEXT STEP

Applying the new copper lining, a pillbox test cavity was electroplated with a target thickness of about 120 μm. Then the copper surface was electropolished with no mechanical polishing beforehand. We made Q_0 measurements for the test cavity before and after electropolishing. We have found that the Q_0 before electropolishing is already better by about 5% than that of the electroplating applied to the present S-cav in KEKB. Furthermore, electropolishing has been found to give a significant improvement, and to lead to the excellent and maximum Q_0 at least up to 3 GHz. The microscale investigations of the copper surfaces were also done using various microscopies. It has been found that the roughness after electropolishing is in nano-scale.

The next step is a vacuum test; to fabricate a new test cavity which has a pumping and other ports, to make a copper lining also for the port structure, and to measure the outgassing rate.

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