TESTING OF COPPER PLATING QUALITY ON REA3 COUPLER BELLOWS AND APPROACH TO IMPROVED PLATING FOR FRIB PRODUCTION*

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Abstract

The SRF community faces difficulties finding sources for repeatable, high quality copper plating for fundamental power coupler (FPC) components. The copper plating of ten small custom bellows of B=0.085 Quarter-Wave Resonator (OWR) variable couplers for the ReAccelerator project has presented technical problems. An improvement plan has been established and includes: better defining plating requirements and specification, creating testing processes via Acceptance Criteria Listing (ACL) to assure plating quality, identify viable plating vendors, develop clean, robust plating fixtures, procedures and quality assurance steps with multiple vendors, and perform ACL testing on plated bellows. A total of 21 prototype and production plated bellows are analyzed through acceptance testing, which include a vacuum leak check, tape test, 1000 psi water rinse, thermal cycle at 77K, borescope inspection and final leak check. Select bellows have been processed and tested with a OWR.

INTRODUCTION

The ReAccelerator (ReA) and FRIB projects at MSU both utilize an 80.5 MHz β =0.085 quarter wave resonator (QWR) design for their LINAC. A coaxial power coupler has been designed and fabricated to provide up to 2 kW of CW RF power reliably. The stainless steel outer conductor bellows of the FPC requires 12-20 µm of copper coating on the RF surface in order to reduce the surface electrical resistance. This reduces the RF power losses, while still maintaining thermal stability during operation.

COUPLER COATING PROBLEMS

Ten ReA3 FPC bellows were plated at vendor 1 and passed a liquid nitrogen thermal shock, leak check and ultrasonic cleaning steps. Select bellows were processed and assembled to a QWR for vertical testing. Some tests resulted in field emission and plating discoloration. The plating quality and processing procedures [1] were further investigated. A 1200 psi, cavity high pressure rinse (HPR) system, with 8 jets of diameter 0.02 inches (0.5 mm), was used to rinse a plated bellows. After a few minutes of rinsing, plating peeled off (Fig. 1), indicating poor adhesion. Tape tests were performed on all bellows using transparent Scotch® tape. Significant flakes were removed

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from three of eight bellows (Fig. 1). A flake removed from bellows 5 was measured to be about 20 μ m thick.



Figure 1: Flakes collected after HPR (left) and removed with scotch tape (center) and (right).

A bellows was cut vertically, using an EDM, to measure plating thickness. The inspection exposed a circumferential crack on the inside, located at the bellows cuff weld. The void traps particles, contamination, plating bath and can cause virtual leaks. Borescope tool inspection (Fig. 4, 5, 6) was instrumental in identifying many of the issues, including detection of plating stains from the residual chemical bath which seeped from the crack (Fig. 2).



Figure 2: Internal crack created from weld.

The bellows design was changed from a weld, to incorporate a full braze joint at each end using Pacusil-25 filler material, therefore eliminating the crack.

SPECIFICATION AND PROCESS QC

Sixteen new brazed bellows were purchased for evaluating improved plating processes. Focus was placed on a copper plating improvement program to ensure high quality plating of the brazed bellows. Ten new brazed bellows were plated at vendor 2, two at vendor 3, two at vendor 4 and two remain un-plated. In parallel, seven of the nine welded bellows were re-plated by vendor 1 due to the copper flaking.

The industry standard, ASTM B734, was used to communicate the plating specification with vendors. The group worked closely with them to optimize fixtures and review procedures for quality and repeatability. A successful plating outcome requires smooth, void free components that can be effectively cleaned, and a well-

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established plating process. Each step of the vendors' process was scrutinized and discussed. A limited number of companies have developed high quality plating procedures for accelerator components. A successful process includes: proper masking and electrode design, thorough pre-cleaning, electro-degreasing, activation, and strike. The plating baths must be well controlled in temperature, voltage and agitation. The time should be closely monitored and plating thickness checked on in-situ coupons during the plating process. Rinsing with hot and cold water in between each bath has shown to improve the release of contaminants and residual bath. The newly plated bellows should be bagged with a desiccant or in a dry nitrogen environment.

The masking fixture design was multifaceted because the small bellows must extend to open convolutions, but also provide compression on ends to create a clean O-ring seal. Fixtures were designed by MSU for re-plating efforts with vendor 1. The fixtures eliminate the use of unreliable manual masking paints commonly used by the plating industry that can cause cross contamination. Peeling at the masking seal edge is a concern and was seen on all three vendors' bellows (Fig. 3). Feedback on masking effectiveness was provided to the vendor, which led to a clean Viton gasket seal being used.



Figure 3: MSU fixture (left) and peeling seen at mini CF flange by vendor 2 (used their own fixtures) (right).

To achieve clean, smooth plating it is essential to apply a steady bath agitation which recirculates fresh solution into the bellows. During a visit to vendor 1, our team suggested to increase agitation in the baths to improve flow into the bellows convolutions. However, the inconsistent manual agitation resulted in gas buildup. Bubble lines formed because the bellows were lifted out of tank, manually agitated and then reset in a slightly different angle or location (Fig. 6). The re-plating passed destructive testing, however, the surface presented imperfections (Fig 4).



Figure 4: Surface flaws on re-plated vendor 1 bellows.

COPPER PLATING ACCEPTANCE TESTS

To confirm the plating integrity a structured ACL was developed. The first test was to apply Scotch® transparent tape to each plated end flange and to a section down into the tube, as discussed in ASTM B571section 11. The tape was rubbed onto the surface, pulled off and placed onto white paper to inspect for flakes.

The second step was a vacuum leak check. The third step was to spray the internal plated surface with a hand held high pressure rinse nozzle using 1000 psi (69 bar) water. The water was collected into filter paper and inspected for flakes. The bellows was submerged in liquid nitrogen for cold shock, then warmed to room temperature. The plating was then inspected for peeling, curling or dimpling. The final inspection was accomplished by use of a borescope camera (Fig. 4, 5, 6).

The last step of the ACL was a vacuum leak check. After the bellows passed ACL steps they were sequenced for processing and FPC assembly. A total of 21 bellows have been tested.



Figure 5: Plated brazed connection (left) and welded connection (right).

The two most common issues found during the ACL procedure were flaking and plating discoloration. Most vendors had issues with the masking near the mini conflat knife edge. However, after some plating had peeled off during the tape test or was removed by hand polishing near the edge, the remaining plating showed good adhesion.

While the visual quality of the plating is not directly linked to all aspects of its performance, it can provide insight into the performance and guide in improving the plating process. The surface appearance, specifically how smooth and shiny it is, affects the thermal radiation properties between the inner and outer conductors. The quality was noticeably different between the three vendors. There were obvious discoloration patterns in the bellows from vendor 1. The bellows from vendor 2 appeared to have a shiny surface almost free from discoloration (Fig. 5, 6). While the plating from vendor 3 had a uniform dull appearance throughout the bellows.



Figure 6: Vendor 1 (left) and vendor 2 (right) plating.

Additional experiments were performed to quantify plating, including electrical resistance, plating thickness and sub-micron surface particle counts.

Bellows Electrical Resistance Measurements

Room temperature resistance measurements were done on plated and un-plated bellows. The calculated resistance for a bellows with 20 μ m of plating is 2.9 m Ω and for an un-plated bellows is 10.6 m Ω .

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The electrical resistance of each bellows was measured (Fig. 7) using a four wire technique. Separate wires, of sufficiently large diameter, as not to affect the measurement, were firmly attached on each end of the bellows going to a current source and a precision voltage meter. An excitation current of 0.25 amps was applied, and the corresponding voltage drop across the bellows was

recorded as soon as the current settled. The Vendor 2 and 3 plated bellows measured 3.5 m Ω average, as expected compared to calculation. The unplated bellows was 13.1 m Ω . The vendor 1 plated bellows were similar to the un-plated, with an average resistance of 13.4 m Ω . Bellows number 3 was plated by vendor 1 and re-plated by vendor 2. The data suggests that vendor 1 bellows has, overall poor quality plating, based on electrical resistance measurements.



Figure 7: Measured resistance at room temperature.

Bellows Plating Thickness Measurements

Vendor 1 plating was measured by x-ray on the conflat face, while micrometers were used by vendor 2 (Fig. 8). The step at the copper plate edge for the vendor 3 bellows, was measured 36-43 µm with a profilometer. It is common to have thicker plating at the ends, where the current density is higher, and is referred to as the dog-bone effect.



One bellows each from vendor 1 and 2 was cut in half to measure the plating thickness in four spots with a microscope. In the bellows plated by vendor 2 plating was seen on the convolution flat and varied in thickness from a few microns up to 25 μ m (Fig. 9). The plating could not be discerned on other locations and was not sufficiently identified on bellows plated be vendor 1. A better technique will be considered for future.



Figure 9: Magnification of vendor 1 plated bellows (left) and vendor 2 plated bellows (right) at convolution flat.

Bellows Particle Experiments

All bellows were cleanroom processed and residual surface contamination quantified by particle diagnostic tools. The bellows were ultrasonic cleaned in a 1% Surface Cleanse-930® solution for 30 minutes at 100°F (38°C). They were then rinsed and ultrasonic cleaned in ultrapure water (UPW) for 40 minutes at 140°F (60°C). The bellows were rinsed with UPW and placed on a Class 100 table to dry.

Liquid particle count (LPC) data was taken to ensure the bellows were rinsed until UPW baseline counts. No trends were identified from LPC data. They were dried and surface particle counts were performed using the OIII surface particle detector tool (Fig. 10). The QIII measures 0.3, 0.5, 1, 5, and 10 µm particles. The goal for certifying a surface are particle counts no higher than 0.33-0.3 µm particles/in² or < 50-0.3 µm particles/ft². The cleanest MILSTD 1246C Level 1 allows for $< 1-1 \text{ } \mu \text{m} \text{ } \text{particle/ft}^2$ and is achieved on SRF cavities and vendor 2 bellows. The MILSTD does not reference particles smaller than 1 µm.



Figure 10: Average surface particle counts.

Vendor 1 bellows had the highest counts and vendor 2 averaged the fewest counts. Vendor 3 exhibited particulate on one bellows. The un-plated bellows also presented some particulate, however they did not have the same cleaning as the plated bellows, which were also degreased at the vendor. The brazed bellows showed a significant improvement in particle count reduction from the welded bellows, supporting the importance of reducing small crevices in the design to minimize trapped contamination.

CONCLUSION

The brazed, vendor 2 plated bellows, on average, were the cleanest, had the best appearance, and resulted in expected electrical resistance, confirming overall plating quality and repeatability. A vendor 2 bellows was used in an FPC assembly on a QWR vertical test and cold tested at ght 4.3K [2]. The test was the final validation of the FPC; there

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was no field emission and the FPC operated at full power for 15 hours.

In the future the resistance measurements, possibly at cryogenic temperatures, will be considered as part of the ACL to provide information on bulk copper properties.

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