ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB087

COPPER PLATING QUALIFICATION PROCESS FOR THE FUNDAMENTAL POWER COUPLER WAVEGUIDES FOR CEBAF CRYOMODULES*

L. Zhao#, G. Cheng, K. M. Wilson, G. Ciovati
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Abstract

To provide sufficient energy for CEBAF operation, cryomodules and components are being refurbished yearly as necessary. Copper-plated fundamental power coupler waveguides are important components of the cryomodules. The integrity and quality of copper plating is critical to reduce the heat load from the waveguides into the He bath at 2.07 K. A search of copper plating resources is underway for plating or re-plating CEBAF-style waveguides. This effort ensures a continuous capability of copper plating on cryomodule components, especially on waveguides. To qualify plating vendors, the waveguide copper plating specifications were revisited, and a thorough plating evaluation process is being developed. The evaluation process ranges from coupon testing to sample waveguide qualification. Recent results are summarized and future work is planned.

BACKGROUND

The CEBAF cryomodules use a waveguide (WG) with rectangular cross-section as a fundamental power coupler (FPC) [1, 2] (Figure 1). In C100 cryomodules, the cold waveguide connects to the cavity flange directly [3]. In C20 and C75 style cryomodules, the FPC waveguide connects to the cold section at a flange on the helium vessel. The interiors of these waveguides are copper plated. It has been 30 years since the initial fabrication and installation of some of the C20 style waveguides.

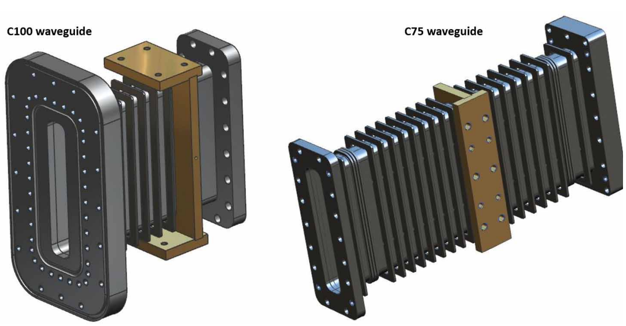

Figure 1: 3D models of C100 and C75 waveguide.

As an effort to maintain the beam energy in the CEBAF accelerator, selected cryomodules are being refurbished each year to recover their performance from degradation [4]. The components in these cryomodules are being reused or replaced. Waveguides can be reused as long as critical features have not been compromised.

During cryomodule refurbishment, it was noticed that the copper plating on some of the waveguide has deteriorated. It is necessary to restore the copper plating on these WGs to ensure satisfactory performance. The original plating vendor is no longer available and new ones need to be found.

WAVEGUIDE COPPER PLATING SPECIFICATION CONSIDERATIONS

The original CEBAF waveguide (C20) plating thickness requirement was 1.5 +0.5/-0.3 µm from inner flange to heat transfer plate, and 3 +/-1 µm from heat transfer plate to outer flange [5]. These values were based on theoretical analysis of static and dynamic heat load on the waveguide [6]. In practice, data from operation experiments and simulation indicates that the copper plating thickness is likely not uniform. An average of 0.2 µm is estimated from the simulation, much less than specified [7]. This can mean there may be areas missing copper plating.

The non-uniformity of plating thickness is difficult to avoid due to the nature of the traditional electro-plating process. During this process, the valleys in the convolutions of bellows are much harder for copper ions to reach, comparing with reaching flat surfaces. Therefore, inside the convolutions of the bellows the plating thickness could be significantly thinner than in other areas. A more realistic goal for plating thickness variation is about 5 µm, based on feedback from industry practice and experience from other projects [8-10]. Taking this variation into consideration, the plating thickness requirement for C75 waveguide was changed to 10 +/- 5 µm. This helps reduce the chance of having unplated areas when the required plating thickness is too thin.

To evaluate the impact of changing plating thickness requirement on the total heat load, a 2D numerical analysis of C75 WG total heat load was done for plating thickness ranging from 0.2 µm to 15 µm. This range covers possible plating thickness scenarios using both the original requirement and the new requirement. This calculation adopted the same method as mentioned in reference [7], using a 2.78-inch wide thermal intercept plate to evaluate heat loads from 8 kW forward power. The results (Table 1) show that the 10 +/- 5 µm specification yields lower 2 K heat load as compared with the 0.2 µm case, indicating that the new coating thickness specification is acceptable.

* Work supported by Jefferson Science Associates, LLC, under U.S. DOE contract DE-AC05-06OR23177.
# lzhao@jlab.org

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB087

Table 1: Heat Load Calculation for C75 Waveguide with Different Copper Coating Thickness

Coating Thickness (µm)	2 K Q_tot (W)	50 K Q_tot (W)	300 K Q_tot (W)	2 K Q_inc (W)
0.2	2.76	24.71	15.79	0.00
1.5 & 3	1.55	7.71	1.29	-1.21
5	1.84	7.67	0.97	-0.93
10	2.24	7.95	0.17	-0.53
15	2.62	8.27	-0.63	-0.14

In terms of critical area requirement, the 1/4 inch wide plating band going over to flange surface is changed from required to optional.

For plating purity requirement, the residual resistance ratio (RRR) is used as a guideline to evaluate the purity of plating. A RRR of 15 or higher is required for the plating, based on common practice for beamline components in other recent projects [11, 12]. RRR measurement is done using the system built at JLab [13], with later improvements in data collection and data processing.

PLATING VENDOR QUALIFICATION PROCESS

Qualifying a plating vendor involves several steps. At the beginning, to verify if the plated copper meets the requirements, plating coupons from the vendor are measured for RRR and cross section. Then a practice part representing the waveguide geometry with bellows is plated. Plating thickness is verified at a few locations on the practice part. After demonstrating the ability to plate on the practice part, the vendors receive a sample waveguide for plating. The existing plating needs to be removed before re-plating. A series of inspection and testing on the sample waveguides are performed after plating. After the sample waveguide passes all necessary testing, a vendor will be considered as a candidate for plating future CEBAF waveguides.

Coupon Measurement

Coupons from 3 plating vendors were evaluated. Figure 2 shows RRR coupons and their cross sections. The dimension of the coupons for RRR measurement is 0.25 inch by 2.75 inch. The RRR-value measured on these coupons is shown in Table 2. Scanning electron microscope was used to exam the cross sections of coupons as verification of plating thickness. Ten data points were taken on one coupon from each vendor. And the measured thicknesses are: vendor #1, 12.1 +/- 0.5 µm; vendor #2, 15.1 +/- 1.9 µm; vendor #3, 20.4 +/- 2.4 µm.

Table 2: Summary RRR Measurement from 3 Plating Vendors

Vendor	#1			#2		#3
RRR	50	18	15	18	38	121
Without SS Substrate	x					
With SS Substrate		x	x	x	x	x
After Baking			x		x	x

Figure 2: Coupons from three plating vendors: 1) RRR coupons, 2) cross section by SEM.

Practice Piece

The practice piece has similar shape and bellows as C100 waveguides. The existing copper plating was removed by plating vendor #1 and re-plated. The targeted thickness was 1.5-3 µm. Figure 3 shows the practice piece re-plated by vendor #1 before and after baking, with selected areas for cross section analysis labeled. Figure 4 shows SEM images of selected locations and thickness analysis results. Large variation in plating thickness is observed on the practice piece. As expected, the bellows and rectangular geometry of the waveguide is challenging for traditional electroplating process to plate uniformly.

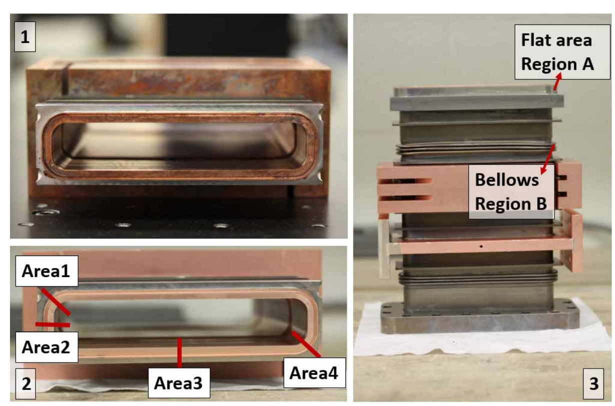

Figure 3: Practice piece as re-plated (1) and after baking (2)-(3). Image (2) and (3) show selected locations for thickness analysis.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB087

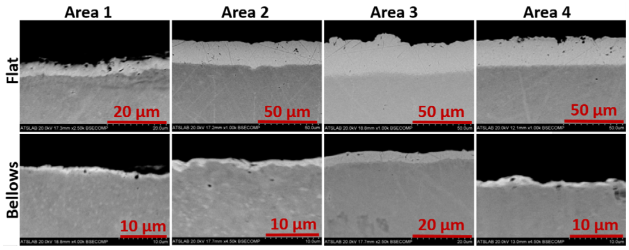

Figure 4: SEM images of cross sections at selected locations as shown in Figure 3 and thickness analysis result. Location #1A, 4.4+/-0.4 um; Location #1B, 1.4+/-0.1 um; Location #2A, 20.2+/-0.7 um; Location #2B, 1.5+/-0.2 um; Location #3A, 28.5+/-3.0 um; Location #3B, 3.5+/-0.4 um; Location #4A, 24.0+/-1.0 um; Location #4B, 1.3+/-0.3 um.

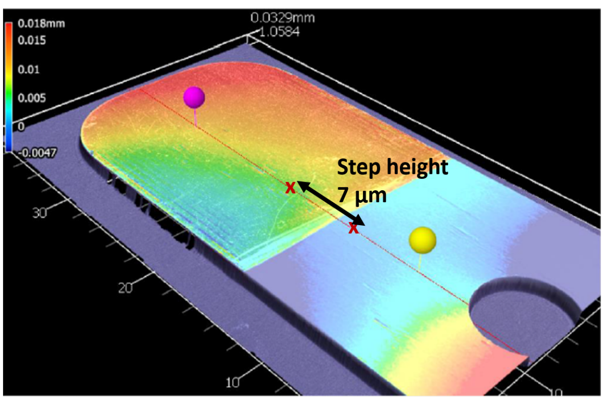

Figure 5: Copper plating thickness verification on the witness piece from the sample C100 waveguide.

Sample C100 Waveguide

A C100 waveguide was re-plated by plating vendor #1. Figure 5 shows thickness measurement on the witness piece from C100 waveguide plating. 3D surface profile was measured using 3D optical profilometer (Keyence VR-6000 Series). The plating thickness on the witness sample meets the requirement. A blister test was performed in a vacuum furnace. The furnace temperature was held at 400 °C for 2 hours. No degradation of the plating was found after furnace run. Figure 6 shows the picture of the original plating, after re-plating, as-received and after cleaning and blister test.

This waveguide was put on an RF test stand to check for plating defects. The same set-up was used during the original production C100 waveguides receiving inspection for sample checking. An infrared (IR) camera monitors the temperature of one wide side of the waveguide, and 9 thermocouples are attached to the exterior of the waveguide at selected locations. After running 1.497 GHz 12 kW RF power through the waveguide for 30 minutes, no significant temperature rise or "hot spot" was observed. Figure 7 shows the IR image at 30 minutes into the RF run.

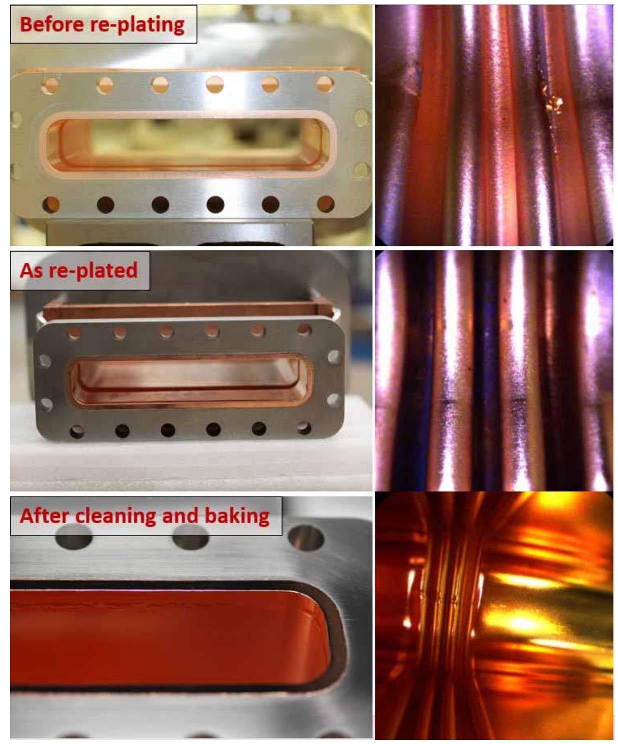

Figure 6: Sample C100 waveguide before re-plating, as re-plated, after cleaning and baking.

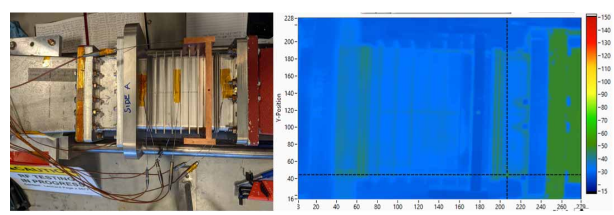

Figure 7: IR image of the re-plated sample C100 waveguide after 1.497 GHz 12 kW RF test for 30 minutes.

Sample C75 Waveguide

A sample C75 waveguide was selected for re-plating at vendor #1. This waveguide had weld repair work done near one flange. About 2 cm wide band of plating near the flange was removed by mechanical grinding when smoothening out the weld repair. Figure 8 shows the waveguide before re-plating, after re-plating, and after post-cleaning baking. It is waiting for further testing to be qualified for use.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB087

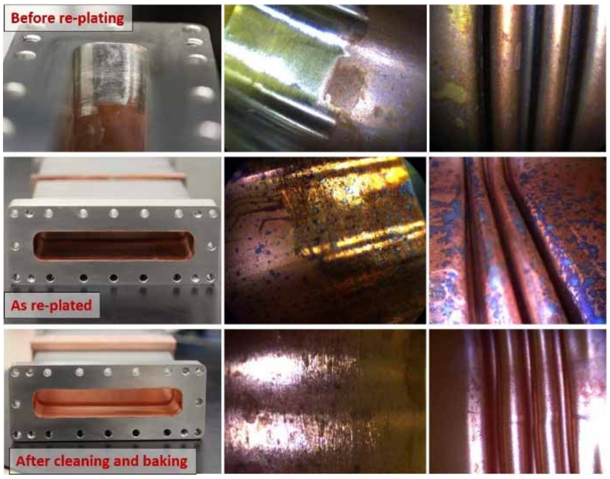

Figure 8: Sample C75 waveguide before re-plating, as re-plated, after cleaning and baking.

SUMMARY AND FUTURE WORK

Working with plating vendor #1 through the qualification process showed promising results so far, although heavy oxidation on the plated surface was noticed upon receiving. After cleaning and baking, oxidation was removed, and the resulted surface is acceptable. As a common issue found on copper plating, oxidation is manageable, but it is preferred to have a plating vendor capable of providing oxidation free plating using necessary cleaning and drying steps, especially for large quantity production.

It has proven to be challenging to achieve uniform coating thickness on rectangular waveguide with bellows. There are still questions to be answered:

- Is this challenge vendor specific?
- Can other coating techniques work better?
- Does this plating allow waveguides to meet performance goals?

Continuing work will address the questions above:

- More vendors will be qualified using the same process if needed;
- Alternative coating techniques other than traditional electro-plating, such as pulse and pulse reverse electrodeposition, and high power impulse magnetron sputtering (HiPIMS), are also being considered;
- More plating evaluation tools are being considered; for example, measuring plating resistance directly on the WG instead of coupons, and measuring the WG heat load under conditions resembling that of cryomodules.

ACKNOWLEDGMENT

Authored by Jefferson Science Associates, LLC, supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177. Thanks to David Beverstock for helping with RRR measurements; James Henry for providing 3D modeling support; Leonard Page for RF testing support; Gregory Gross and Scott Williams for furnace support; support from chemistry group and cryomodule assembly group; Anne McEwen and Thomas Huratiak for logistic support; and Michael P. Kelly for sharing related experience.

REFERENCES

[1] L. R. Doolittle, "Strategies for Waveguide Coupling for SRF Cavities", in *Proc. LINAC'98,* Chicage, IL, USA, Aug. 1998, paper MO4080, pp. 246-248.

[2] F. Marhauser and G. Ciovati, "Evidence of increased radio-frequency losses in cavities from the fundamental power coupler cold window", *Phys. Rev. Accel. Beams*, vol. 24, p. 092001, 2021. doi:10.1103/PhysRevAccelBeams.24.092001

[3] I. E. Campisi *et al.*, "CEBAF Upgrade Cryomodule Component Testing in the Horizontal Test Bed (HTB)", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper MPPH152, pp. 1137-1139. doi:10.1007/978-1-4613-0639-9_80

[4] A. Freyberger, "Commissioning and Operation of 12GeV CEBAF", in *Proc. IPAC'15*, Richmond, VA, USA, pp. 1-5. doi:10.18429/JACoW-IPAC2015-MOXGB2

[5] D. Machie, "Waveguide – Copper Plating Specification", JLab Specification No.11141S0040C.

[6] J. P. Kelley and J. Takacs, "Thermal Design and Evaluation of the CEBAF Superconducting RF Cavity's Prototype Waveguide", *Adv. Cryog. Eng.*, vol. 35, pp. 675-682. doi:10.1007/978-1-4613-0639-9_80

[7] F. Fors *et al.*, "C75 Fundamental Waveguide 1D Thermal Analysis", JLab TN-18-013.

[8] L. Popielarski *et al.*, "Testing of Copper Plating Quality on REA3 Coupler Bellows and Approach to Improved Plating for FRIB Production", in *Proc. SRF'13*, paper THP067, pp. 1077-1080.

[9] E. Kako *et al.*, "Quality Control of Copper Plating in STF-2 Input Power Couplers", in *Proc. SRF'17*, paper MOPB061, pp. 186-190.

[10] D. Trompetter, "Remarks on the Industrial Production of FPC", TTC at CERN, Feb. 2020.

[11] M. Fouaidy and N. Hammoudi, "RRR of Copper Coating and Low Temperature Electrical, Resistivity of Material for TTF Couplers", in *Proc. SRF'05*, Ithaca, NY, USA, Jul. 2005, paper TUP65, pp. 392-398.

[12] K. M. Wilson *et al.*, "Production of Copper-Plated Beamline Bellows and Spools for LCLS-II", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1167-1169. doi:10.18429/JACoW-IPAC2017-MOPVA132

[13] J. K. Spradlin *et al.*, "A Multi-sample Residual Resistivity Ratio System for High Quality Superconductor Measurements", in *Proc. SRF'15*, Whistler, BC, Canada, Oct. 2015, paper TUPB063, pp. 726-730