ENERGETIC CONDENSATION GROWTH OF Nb ON Cu SRF CAVITIES*

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Abstract

Alameda Applied Sciences Corporation (AASC) grows Nb thin films via Coaxial Energetic Deposition (CED) from a cathodic arc plasma. The plasma from the cathode consists exclusively of 60-120eV Nb ions (Nb^+ and Nb^{2+}) that penetrate a few monolayers into the substrate and enable sufficient surface mobility to ensure that the lowest energy state (crystalline structure with minimal defects) is accessible to the film. AASC is coating 1.3 GHz SRF cavities using a graded anode to ensure uniform film thickness in the beam tube and elliptical regions. Copper cavities are centrifugal barrel polished and electropolished (done for us by the Fermilab Technical Division, Superconducting RF Development Department and by Thomas Jefferson National Accelerator Facility (JLAB)) before coating, to ensure good adhesion and improved film quality. The Nb coated copper cavities will undergo RF tests at JLAB and at Fermilab to measure Q_o vs. E.

INTRODUCTION

The goal of replacing bulk niobium with niobium films for SRF accelerator cavities and resonators has been pursued since the 1980's [1] and remains an attractive though elusive goal. LEP-II used 256 niobium coated copper cavities that operated with gradients up to 7 MV/m [2]. However, present research employs accelerating gradients of 20 MV/m. To replace bulk Nb in future SRF applications, thin film Nb cavities must achieve the same operating parameters of $Q_o > 10^{10}$ out to 20 MV/m. AASC is developing and implementing a technique called Coaxial Energetic Deposition (CED) to grow a film using a cathodic arc plasma. Demonstration of superconducting properties of a Nb film comparable to the properties of bulk Nb will allow for a cost reduction in SRF accelerator fabrication. This paper covers advancements made in the CED coating process with regard to copper elliptical cavities. Fermilab and JLAB are providing AASC with welded copper 1.3 GHz SRF cavities that have been centrifugal barrel polished (CBP) and electropolished (EP). Our partners will test the niobium coated copper cavities.

ENERGETIC CONDENSATION

The CED process uses a 30–100 V arc discharge to generate a highly ionized plasma made exclusively from the cathode material. A Nb cathode produces 60–120 eV ions (Nb+ and Nb2+) bombarding the substrate and undergoing subplantation [3]. The ions deposit their energy a few monolayers beneath the surface, bringing the local area to the melting point. This promotes film growth with excellent adhesion and crystallinity. Heating the substrate promotes defect free crystal growth.

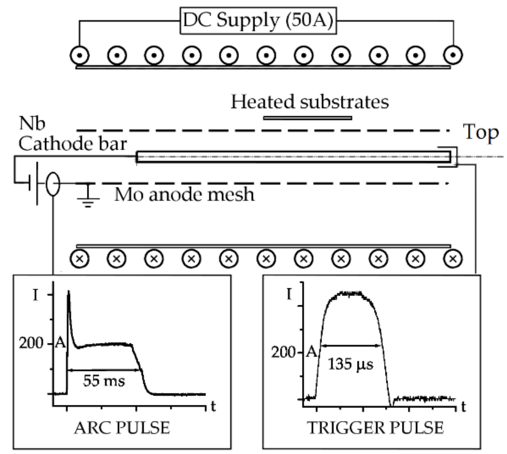

Figure 1: Schematic drawing of CED showing coaxial geometry and typical current pulses to run the vacuum arc.

A schematic drawing of the CED process in shown in Fig. 1. A cathode rod is surrounded by an anode mesh made of stainless steel or a refractory metal. A vacuum arc is triggered and sustained using a 100 V, 200 A power supply. In the presence of a magnetic field, the cathode spots traverse a stochastic helical path along the length of the cathode. The CED chamber is oriented vertically such that the arc is triggered at the top and travels down the length of the cathode. Each arc pulse deposits a monolayer of Nb and a multi-micron film is built up over thousands of pulses.

While the RF penetration is on the order of 50 nanometers, previous work has found that a thicker film may have better crystalline properties, which may lead to better RF performance [4]. However, internal stresses can cause a thick film to buckle and delaminate. To adequately coat an SRF cavity with the desired thickness, we need to characterize our coating process by accounting for the average arc spot behaviour and niobium deposition rate.

Global Axial Arc Veloctiy

To ensure we fully coat the entire length of a cavity, we measured the apparent axial velocity of the cathodic arc. This is a measure of the time it takes the initial plasma breakdown to travel from the trigger location, down the length of the cathode, and run past the bottom of the substrate that is to be coated.

To characterize the average axial velocity of the cathodic arc as a function of ambient magnetic field, multiple loops of copper wire were placed concentric with the cathode and anode at various axial locations. Figure 2 shows the experimental arrangement.

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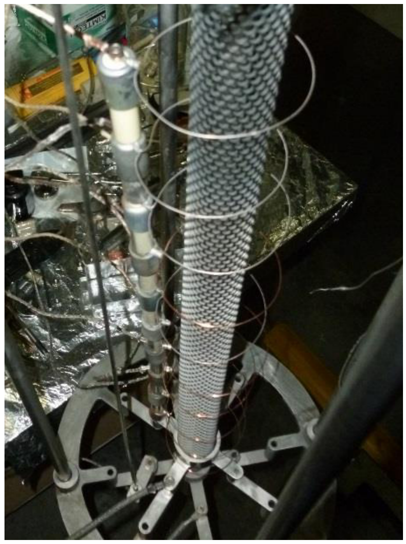

Figure 2: CED electrodes with copper wire loops arranged along the axis to measure spoke axial speed via time-of-flight.

A negative bias of -22 V was applied to the loops to collect the ion saturation current; the peak of each signal was used to calculate the axial velocity from the time-of-flight and loop-loop distance. The data from each loop presented in Fig. 3 are averages of 64 pulses for a magnetic field of 5.6 mT. The time-of-flight data give an average velocity of 4.0 m/s for an applied magnetic field of 5.6 mT.

The axial velocity has been measured at various magnetic field strengths. The speed is constant along the cathode for a given magnetic field and decreases with increasing field. Figure 4 shows the dependence of arc velocity on the applied axial magnetic field. Typical operation uses a magnetic field of 3.8 mT which gives an axial velocity of 4.5 m/s.

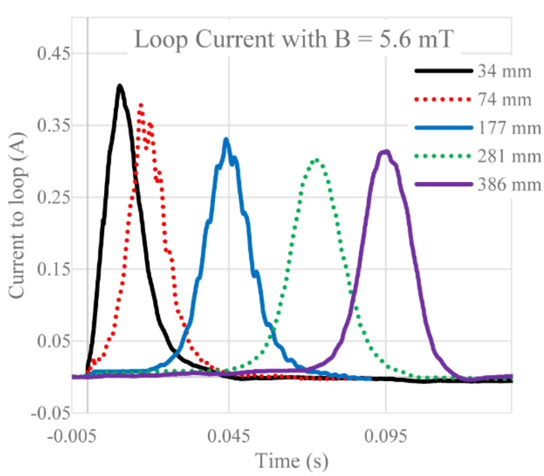

Figure 3: Scan showing ion current to all loops for B = 5.6 mT. Legend indicates the axial location of each loop with respect to the trigger.

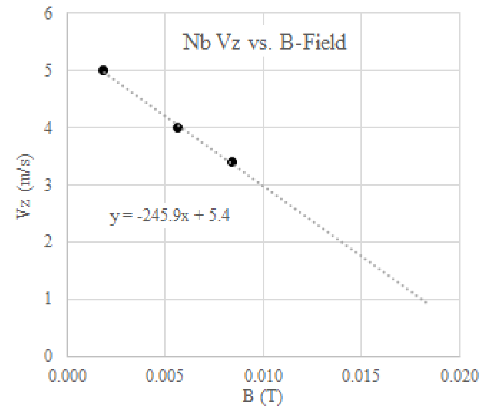

Figure 4: V_z as a function of magnetic field for the niobium cathode. Blue circles are data points and red squares are an extrapolation.

Film Thickness Estimation

The CED arc is maintained for the length of time necessary to traverse the axial extent of the copper cavity. To control the thickness of the coating, we vary the number of arc pulses. An estimate of the thickness is made as outlined in Table 1. The mass eroded from the Nb cathode on each pulse is calculated using the pulse width, apparent arc velocity, arc current, and erosion rate. The eroded mass per shot is assumed to coat the entire cylindrical surface uniformly at the radius of the substrate, subject to attenuation by the screen transparency of the anode mesh. The erosion rate is calculated using coupons with a known film thickness, measured by profilometry. The erosion rate for all test coupons of 36 µg/C ± 5 µg/C agrees with published rates [5].

Table 1: Thickness of Nb Film

Measure	Value	Unit
Coating pulse width	.118	s
Arc velocity	4.5	m/s
Coated length	53	cm
Arc current	145	A
Charge per pulse	17	C
Erosion rate	36	µg/C
Eroded mass per pulse	6.2e-4	g
Substrate radius	3.9	cm
Anode transparency	33%	
Fluence at substrate	1.6e-7	g/cm^2
Nb density	8.57	g/cc
Thickness per pulse	1.8e-8	cm/pulse
# of pulses	17000	
Film thickness	3.1	µm

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Variable Anode for Thickness Uniformity

To create a film with uniform thickness on a copper elliptical cavity with varying diameter, we use a graded mesh anode with two regions of different transparency, as the thickness is a function of the substrate radius. Figure 5 shows the variable transmission anode used in the cavity coating described in the next section. The hollow anode has 33% transmission in the beam tube and >90% in the elliptical region. This geometry was used to provide the greatest transmission and maintain uniformity of the film thickness at the equator, iris, and beam tube.

Figure 5: Anode mesh with >90% open area in elliptical region and 33% transmission in the beam tubes.

COPPER CAVITY COATING

The copper cavities prepared for AASC will be centrifugal barrel polished in the same manner as are the conventional bulk niobium cavities. The cavity described in this section was polished to a mirror finish using colloidal silica followed by electropolishing to remove any embedded media. The final step is a high pressure water rinse to fully clean the cavity. The surface preparation is done by our partners at Fermilab and JLAB. At AASC, the cavity is removed from its box in a Class 1000 cleanroom and immediately installed in the CED chamber. The cavity is shown mounted with heaters in Fig. 6.

Figure 6: Fermilab cavity mounted with heaters.

The cavity was baked to 350 °C and the coating run started when the chamber vacuum was 2.5e-6 Torr. The cavity was coated with a total of 17,000 shots for a thickness of approximately 3 µm in the beam tubes and at the equator.

Figure 7: Cu cavity before (left) and after (right) coating.

Figure 7 shows the interior of the cavity before and after the coating. The Nb film showed no signs of delamination or buckling. The cavity was rinsed using a high pressure water rinse with a 40 degree fan nozzle at 1000 PSI. Unfortunately, there were 4 sites of localized delamination. The ~2 mm diameter spots appeared in both iris regions and are shown in Fig. 8.

The jet from the water rinse is much larger than the spot size indicating the film was well adhered at the edge of the defect.

The highly localized delamination appears to be damage caused from the formation of footpoints or anode spots [6] In the elliptical region, the cavity itself acts as the anode. The current at the anode is generally distributed over the size of the plasma spot contacting the anode. However, in transitioning from the stainless steel mesh anode to the cavity as anode, it appears that a local region of higher current density formed, enhancing conduction to the cavity, which resulted in highly localized damage. It is possible that there was some defect in the copper surface that promoted the anode spot formation, which may explain why there were few spots. Because of the damage to the Nb film, the RF test was not performed.

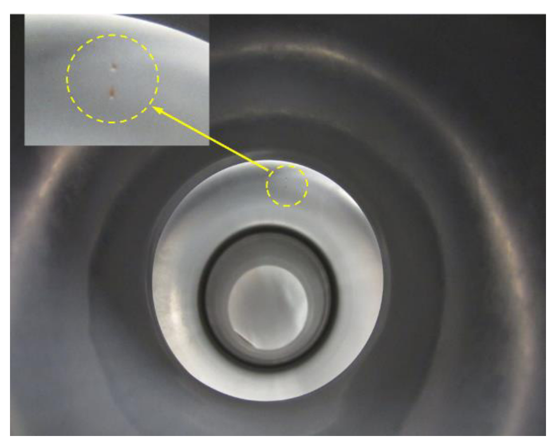

Figure 8: Spots delaminated from high pressure rinse.

In future coatings, the hollow anode will be replaced with a variable anode mesh that has 23% transmission in the beam tubes and 64% transmission in the elliptical region. This will allow for thickness uniformity and remove potential problems created by switching anodes

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during the coating run. The niobium film was removed through CBP at Fermilab and awaits the EP step before the coating will be repeated with the new anode.

CERN QUADRUPOLE RESONATOR

In collaboration with CERN, we coated a copper Quadrupole Resonator with a niobium film. The resonator was electropolished in a similar manner as was the Cu cavity. Figure 9 shows the resonator as mounted for coating (upper) and after an approximately 2 µm Nb deposition (lower). The Nb coating was done with the Cu substrate heated to 350 °C at a baseline vacuum of 3e-7 Torr. The planar substrate will have a thickness variation across the 70 mm diameter so while the film is 2 µm at the center, it will be only 1.6 µm at the outer edge. The thickness of the Nb coating on the resonator measured after a previous run, shown in Fig. 10, gave the expected thickness variation. The coated Resonator has been leak checked and is scheduled to undergo a cryogenic RF test at 1.2 GHz.

Figure 9: Upper: Resonator mounted for coating. Lower: Coated Resonator.

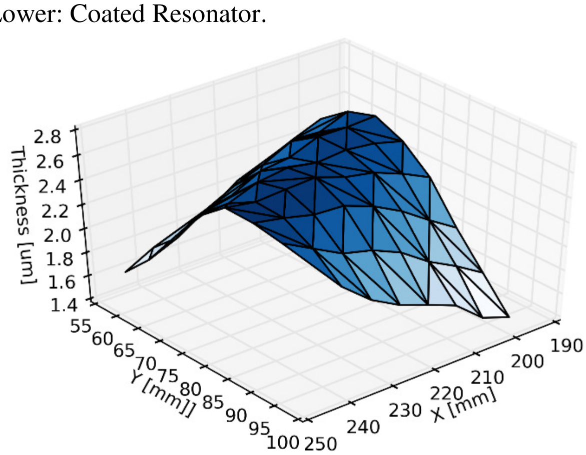

Figure 10: Thickness variation of Nb film on CERN Quadrupole Resonator.

CONCLUSION

Past efforts in cavity coating have indicated that cavity surface preparation is extremely important in the success of a niobium deposition. The same procedures used in preparing an SRF bulk Nb cavity have been applied to a copper cavity supplied to AASC by Fermilab. The cavity has been coated using a variable transmission anode to allow for a uniform thickness. However, the cavity acting as anode resulted in the formation of anode spots in the elliptical region, which caused localized delamination of the Nb. Subsequent coatings will use a new variable transmission anode that has two region of stainless steel mesh that will prevent anode spots from forming on the cavity itself. Additional cavities will be coated in partnership with Fermilab and JLAB.

The CERN Quadrupole Resonator has been coated with Nb and will undergo an RF test at 1.2 GHz, which allows for direct comparison to the performance of 1.3 GHz elliptical cavities that will be tested in the future.

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