Nb COATINGS ON BELLOWS USED IN SRF ACCELERATORS

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Abstract

Alameda Applied Sciences Corporation (AASC) is developing bellows with the strength and flexibility of stainless steel and the low surface impedance of a superconductor. Such unique bellows would enable alignment of SRF cavity sections with greatly reduced RF losses. To that end, we grow Nb thin films via Coaxial Energetic Deposition (CED) from a cathodic arc plasma. Films of Nb were grown on stainless steel bellows, with and without an intermediate layer of Cu deposited via the same technique, to produce a working bellows with a well adhered superconducting inner layer. The Nb coated bellows have undergone tests conducted by our collaborators to evaluate their RF performance.

MOTIVATION

Any radio-frequency superconducting (SRF) accelerator including multiple cells of cavities must allow for fine adjustment of the joints between beam components, to correct for misalignment and to allow for thermal expansion. Flexible metal bellows are a common choice.

The bellows must be strong and flexible enough to hold vacuum and maintain integrity during tens of thousands of compressions and thermal cycling. Thus, stainless steel is the usual choice. Thin-walled stainless steel bellows also provide the advantage of some measure of thermal isolation between the components it joins.

However, a bellows made of non-superconducting material will increase beam impedance and lead to RF power losses [1]. In some cases, these power losses can eventually damage the bellows and lead to instabilities. Unfortunately, there are no currently known superconductors able to compete with the mechanical advantages of stainless steel.

One possible solution, aside from planning and budgeting for RF power losses to stainless steel bellows, is to add a superconducting shield to the inner surface of the bellows, such as layers of fine mesh or overlapping finger stock, thereby blocking the beam's view of any non-superconducting material. Unfortunately, such a shield necessarily reduces the flexibility of the coupling, while increasing its complexity and reducing available space. Additionally, as such shields are less robust than stainless steel, repeated flexing may result in particulates that can also be harmful to beam performance.

The bellows can also be coated with some other material, such as copper, that, while not a superconductor, has a significantly lower impedance than stainless steel.

AASC is working to develop and benchmark another solution. By coating the inner surface of a stainless steel bellows with multiple skin-depths worth of niobium, we can create a bellows with the mechanical advantages of stainless steel while adding minimal beam impedance and no additional obstacles to proper operation of the accelerator.

COATING TECHNIQUE

To coat the bellows, we grow a thin (microns to tens of microns) film of Nb on their inner surface via energetic condensation. Specifically, we use a proprietary variation on high vacuum (~10^{-7} Torr) cathodic arc plasma that we call CED.

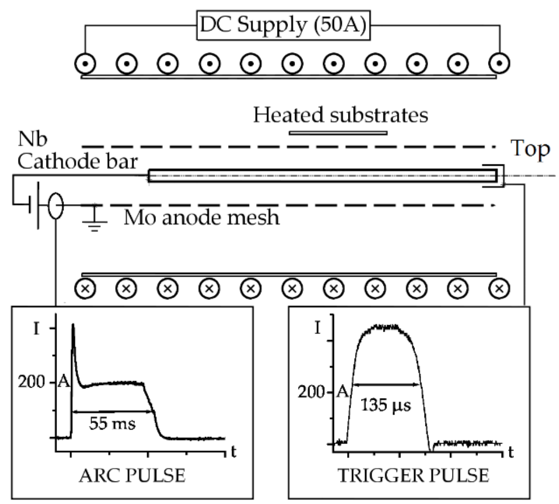

Figure 1: CED process schematic drawing.

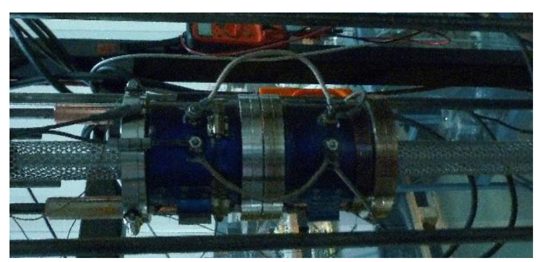

Figure 2: Bellows mounted in CED apparatus.

Figure 1 shows a schematic drawing of the CED process, while Fig. 2 shows two bellows mounted in the CED apparatus before insertion into the vacuum chamber. On the central axis of the apparatus we locate a rod (0.5" O.D.) of the desired coating material, which will act as a cathode. Surrounding the cathode is a coaxial cylindrical mesh anode (1.25" I.D.) made of a refractory metal such as molybdenum or stainless steel. Surrounding the anode, we place the substrate or substrates to be coated. The assembly is then placed inside a vacuum chamber located inside a coaxial DC (~50 Gauss) solenoidal magnet.

By triggering and maintaining a vacuum arc (30-100V, 100-200A) between the cathode and anode we produce an energetic (60-120 eV, in the case of Nb) highly ionized plasma consisting solely of cathode material [2, 3]. By manipulating the average instantaneous location of the

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vacuum arc spots on the cathode, via electronic control and the external magnetic field, we guarantee that the plasma, over many shots, fills the desired angular and longitudinal space set by the substrate to be coated.

The plasma ions reach the substrate with enough energy that the process falls within the regime of ion-substrate interactions known as ‘subplantation’ [4]. In this regime, incident ions have enough energy to penetrate the first few subsurface atomic layers and displace atoms in the lattice. That is, the ions locally ‘melt’ the substrate at their impact. This enables sufficient mobility that the film is able to grow in a low energy state, allowing for epitaxial growth. This mobility is further aided by externally heating the substrate to 150-400 °C.

We can also vary the electrical bias of the substrate. A negative substrate bias will increase the energy of incident ions, potentially leading to better adhered, more crystalline films.

BELLOWS CHARACTERIZATION

To be of practical use, the coating on the bellows must meet two distinct criteria. First, it must be of a sufficiently high quality to reduce the beam impedance of the bellows. Second, it must be sufficiently robust to not compromise the functioning of the bellows and to maintain its level of quality during use.

The quality of the film can only truly be determined by measuring the effect on the impedance of the bellows, but there are relevant figures of merit. First, if the coating is thinner than a couple of skin-depths (down to the limit of nonexistence) the RF power can penetrate to the stainless steel substrate, leading to increased impedance. Second, often the SRF behaviour of a substance is related to its residual resistivity ratio (RRR), defined here as the ratio of resistivity at 300 and 10 K. If we can control the RRR of our coatings, we presumably exercise some control over the SRF quality.

Testing the robustness of the coating requires that it is subjected to the flexion associated with a bellows, repeated thermal cycling, and any necessary cleaning procedures. Then the quality of the coating should be tested once more, to check for degradation.

Coupon Studies

Because the inside of a bellows’ convolutions can be difficult to access with many diagnostics, provisional studies of our Nb coatings were done on coupons and small plates that can be diagnosed more easily. The small size and greater accessibility of these coupons give us greater control over many important parameters of the coating process, such as substrate temperature and inclination to the apparatus axis. Thus, coupon studies serve as a general upper limit on our film quality.

We started by confirming that our Nb films transition to superconductivity and that we can influence the degree to which they do so. A summary of some early results on copper substrates is presented in Table 1.

Table 1: Coupon Test Results

Temp (°C)	Thickness (μm)	RRR	T_c(K)
200	3	23	9.37
200	10	33	9.37
300	3	40	9.41
400	3	60	9.21
400	10	110	9.44

We confirm that our Nb films are superconducting and note a general trend that thicker films deposited at higher temperatures tend to have a higher RRR. Note that coating attempts at more than 400 °C universally showed heavy delamination of the film. Of course, we don’t know in advance which range of RRR is likely to give the best SRF performance.

We can measure the SRF performance of a film on a coupon by directly inserting the coupon as the wall of an existing SRF cavity. Such a cavity, operating at 11.3 GHz, was used by colleagues at SLAC National Accelerator Laboratory (SLAC) to diagnose our films. Results are presented in Fig. 3.

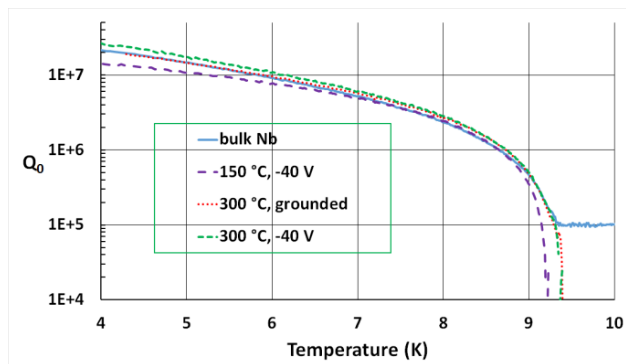

Figure 3: SRF performance of Nb films on coupons.

All samples tested were ~3 μm films of Nb on stainless steel. We varied both the deposition temperature of the films and the electrical bias of the substrate. We see that our films have behaviour comparable to that of a bulk Nb sample, with some indication that higher deposition temperature and a biased substrate lead to better RF performance. Of course, these results are not necessarily applicable to all RF frequencies. While we can scale the BCS resistance of our film, this measurement only places an upper limit on the residual resistance that might present itself at lower frequencies. Additional tests are currently ongoing.

Film Quality on Bellows

There is a very important difference between a coating on a bellows and on a coupon. Unlike a coupon or a simple tube, a bellows cannot be arranged so that all of its interior surfaces have radial normal vectors. If a substrate surface is angled, such as the convolutions of a bellows, the plasma ions will impact at an increased angle of incidence. This may effectively reduce the energy deposited by the ion, or even lead to ions failing to implant entirely, reducing both the film's thickness and, potentially, its quality.

There are two principle varieties of bellows: hydraulically-formed bellows, where the convolutions are formed of a continuous metal tube subjected to hydraulic stress, and welded bellows, where the convolutions are formed of flat annular sheets welded together at their edges. Each presents different challenges for coating. A hydraulic bellows will generally present interior surfaces with a larger angle of incidence for incoming ions, up to and beyond 90° if the bellows is not extended during coating. A welded bellows presents much sharper contours at the weld joints, which are particularly likely sites for mechanical failure of the coating.

We first tested our ability to coat the entirety of a hydraulically formed bellows' convolutions. The bellows was coated such that a straight tube of the same size would have been coated with ~2 µm of Nb. The bellows was cut apart to produce two roughly 1 cm^2 coupons, one from the straight portion at the end of the bellows and one from the convolutions. Both were analysed via energy-dispersive x-ray spectroscopy (EDX) on their coated surfaces. The samples produced effectively identical results: almost entirely Niobium, with traces of Oxygen (presumably from oxide), and no signs of Iron. This confirmed that the interior surface of the bellows was coated in Nb, with no gaps or pinholes.

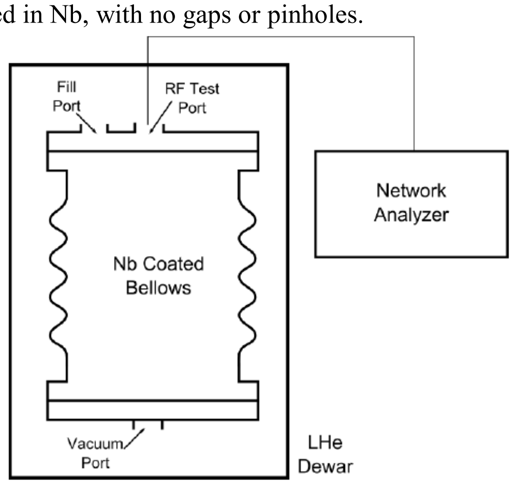

Figure 4: Schematic of coated bellows cavity test.

From here, we moved to measure a superconducting transition in another bellows with an expected 3 µm coating. This bellows was mounted in an ad hoc RF cavity at the Thomas Jefferson National Accelerator Facility (JLab), presented schematically in Fig. 4. The loaded quality factor (Q_L) of the TE_{011} mode was measured as the temperature of the bellows was lowered. The results are shown in Fig. 5. We note that the cavity goes through a superconducting transition. Unfortunately, Q_L was limited by the quality of the external probes used (note that Q_L does not vary with temperature below the transition). Thus, this test gave only a lower limit on the potential SRF performance of the bellows.

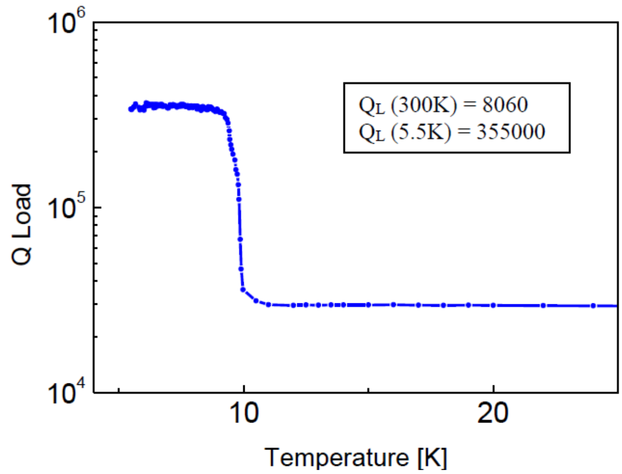

Figure 5: Q_L of bellows cavity vs. temperature.

Coating Robustness on Bellows

For testing the robustness of our coating, two welded bellows were coated with ~6.5 µm of Nb. One of the two was first coated with 10 µm of Cu, in the expectation that this might improve film adhesion. These bellows are shown in Fig. 6. Note that the rougher texture of the bellows on the right is a result of the interstitial Cu layer.

Figure 6: Nb-coated (left) and Nb-on-Cu (right) welded bellows.

These bellows were shipped to colleagues at Brookhaven National Laboratory (BNL) committed to testing the robustness of the film and testing the SRF performance of the bellows after this heavy use.

For wear testing, the bellows were mounted, as depicted in Fig. 7, such that it could be cycled 24,000 times through a full stroke of 0.89", at a rate of 0.33 Hz. Some particulate dust was produced, but no significant degradation of the film was apparent. Note that, for real SRF use, this dust will need to be eliminated through either variation in the coating technique, cleaning, or pre-cycling of the bellows.

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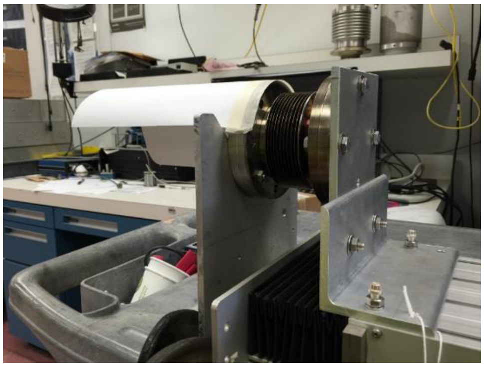

Figure 7: Bellows cycling device.

The bellows were also cycled between room temperature and 77 K by immersion in liquid nitrogen three times, remaining immersed overnight on the third cycle. No degradation of the film was apparent.

The RF testing of these bellows is currently ongoing.

CONCLUSION

We have coated the inner surfaces of stainless steel bellows with a layer of superconducting Nb. These coatings have survived repeated mechanical and thermal cycling. After completing ongoing tests, we will proceed to improve the SRF performance of these bellows, if necessary, to meet the needs of current and future SRF devices.

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