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SPLIT 6 GHz SRF THIN FILM CAVITIES

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Abstract

Superconducting Radio Frequency (SRF) cavities are widely used in particle accelerators and provide much higher Q than normal conducting cavities. Most commonly the cavities are manufactured from two half cells, which are electron beam welded together. During operation of such cavities, the peak surface current goes across the weld and may limit their performance due to higher roughness and material morphology at the weld. An alternative solution is to produce a cavity also from two halves but split along the induced current. In such a cavity the weld should not affect the performance as no current is crossing it. These cavities are easier to manufacture and coat with a superconducting thin film (TF). Thus, different coating techniques may be used leading to new materials and multilayer coating options which may allow SRF cavities to operate at higher Q than current state of the art cavities. TF SRF cavities have been developed for use in particle accelerators, as they have many advantages over normal conducting (NC) and bulk niobium (Nb) cavities. One such advantage is that SRF TF cavities have a lower surface resistance, below the critical temperature, than NC cavities and a higher thermal conductivity than bulk Nb cavities leading to a more uniform temperature of the superconductor.

This work discusses development and testing of longitudinally split seamless TF SRF cavities at Daresbury Laboratory (DL).

INTRODUCTION

Superconducting Radio Frequency (SRF) cavities have a surface resistance of 10^4 to 10^6 lower than bulk copper cavities [1]. Thus, the power dissipation in the cavity walls is lower, therefore, the cavities can be run in continuous operation at higher accelerating gradients [1–3]. In continuous operation at high gradients the losses in a copper cavity can lead to deformation of the cavity causing it to no longer resonate at the required frequency.

Superconducting cavities made of bulk niobium (Nb) have a lower thermal conductivity than that of copper cavities, which can cause localised heating. This heating can cause a small area of the superconductor to become normal conducting causing the rest of the material to quickly follow and become normal conducting, this is called a quench and is the main issue with bulk superconducting cavities [2, 3]. For many decades the idea of coating the inside of a copper cavity with a superconducting thin film has been in development [2, 3]. The combination of a copper cavity with a superconducting TF can provide better thermal conductivity than Nb dispersing any localised heating on the superconductor to the rest of the cavity and more efficient cooling while the current in the cavity is carried by the superconducting TF [2, 3]. Materials with better superconducting properties than Nb that are too brittle to be made into a cavity can be coated as a TF onto a copper cavity providing RF performance that may exceed that of pure Nb cavities. Other materials include Nb_3Sn [4], MgB_2 [5], V_3Si [6], etc. Particle accelerators that have used cavities with superconducting thin films include PIAVE-ALPI at INFN [7] HIE-ISOLDE [8, 9], LEP [8, 10] and the LHC [8, 11].

RF cavities are commonly manufactured by creating two half cells, then joining them together by means of electron beam welding at the equator of the half cells. The weld in this method of manufacture is around the area of the highest magnetic field and surface current in the cavity and may result in a higher surface resistance of the cavity. When a cavity manufactured in this way is coated with a superconducting thin film, problems may occur such as micro cracks around the weld causing a large decrease in quality factor as accelerating gradient increases, this occurred in the HIE-ISOLDE cavities [12]. To resolve this issue, new cavities were then designed with the same geometry but manufactured without a seam, and then coated, this lead to a reduced Q-slope [12]. At CERN, longitudinally split SRF cavities are also currently under development. These cavities are the baseline solution for the Future Circular Collider (FCC) and are called Slotted Waveguide ELLiptical (SWELL) cavities. The welds of these cavities will be in the Higher Order Mode (HOM) dampeners and so, will be away from the electric field of the TM11 mode [13]. These cavities, however, have not been reported as tested yet.

This work describes design, manufacture, polishing, coating and testing of seamless split Nb coated copper cavities at Daresbury Laboratory (DL). The cavities were designed to be split and so not welded so that they could be coated in an open geometry. This also allowed easier access for an inspection of the coated cavity surface. Details of the measurement facility and calculations of surface resistance were previously presented in [14].

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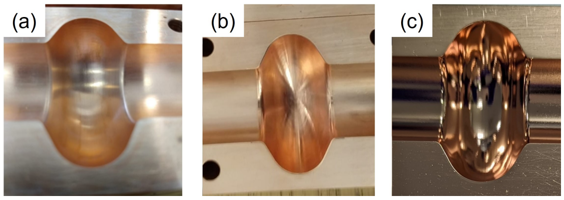

Figure 1: Cavities machined with (a) the initial machining tool, (b) the fast machining tool and (c) after EP.

CAVITY PRODUCTION

Copper Cavity Manufacture

Three Oxygen Free High Conductivity (OFHC) copper cavities were designed and manufactured at DL, these are the same cavities that are described in Ref. [14]. The milling tool for the initial machining had a 10 mm bore nose at a speed of 6000 RPM (the fastest speed it could be used). To improve the smoother surface finish, the cavities were machined again using a new high speed head with a 5 mm bore nose at a speed of 45000 RPM.

Cavity 'A' was left as a reference while Cavities 'B' and 'C' were sent to LNL/INFN for ElectroPolishing (EP). The EP was performed in a solution containing phosphoric acid 85% and n-butanol 99.9% in a volume ratio of 3:2 with a fixed voltage between 2.5 and 3.5 V. The process was maintained at ambient temperature without any agitation for 30 minutes.

Images of the cavity after each stage of machining and EP can be found in Fig. 1.

Thin Film Coating

After the second machining and without any further polishing, Cavity 'A' was cleaned then coated in two parts simultaneously using pulsed DC sputtering from a pure Nb target. The sputtering was performed with a 300 W pulse with 2.10 A, 143 V. The pulse frequency was 350 kHz, the dual time was 1.1 µs for 3 hours at 3.9×10^{-2} mbar of krypton at room temperature (RT).

Cavity 'C' was coated after EP using DC sputtering at 300 W with 1.01 A at 297 V for 4 hours with 3.3×10^{-3} mbar of krypton at RT. An image of the cavities after coating can be seen in Fig. 2.

RF MEASUREMENTS

The surface resistance (R_s) measurements were performed in the facility described in Refs. [14, 15]. The surface resistance was calculated from the Scattering (S) parameters of the cavity, measured using two antennas connected to a Vector Network Analyser (VNA). Traces of the S_{11} and S_{21} parameters with a span of 10-20 MHz were taken. The bandwidth was then measured using the 3 dB points below the resonant frequency of the S21 trace. The measurement were performed at RT and cryogenic temperatures in the range 4 K $\leq T \leq$ 11 K

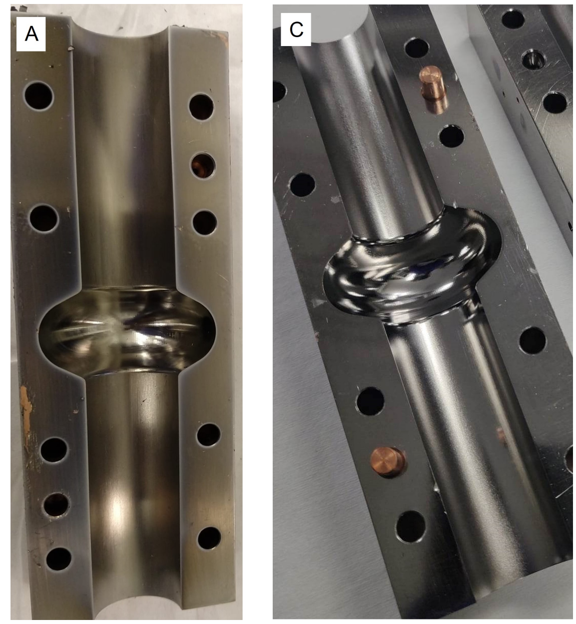

Figure 2: Cavity 'A' coated with Nb after second machining and Cavity 'B' coated after EP.

RESULTS AND DISCUSSION

Uncoated Copper Cavity

The results of the measurements of the NC cavities after each stage of polishing at RT and 4.2 K can be found in Table 1. The measurements of surface resistance were made as a way to quantify the surface roughness of the cavity.

Cavity 'B' was measured after it had been unpackaged at DL, and was then put into the cryogenic facility for cryogenic measurements. It can be seen in Fig. 1 that the finish is more reflective after machining with the smaller, faster bore nose and has a mirror-like finish after EP.

No R_s measurements prior deposition were performed with Cavity 'C' to avoid contamination after EP.

One can see that for each cavity the surface resistance decreased after each stage of polishing which was expected. However, this R_s is higher than copper cavities of a similar frequency measured SLAC. SLAC measured R_s of a 5.7 GHz copper cavity to be $1.6\times10^{-2}\,\Omega$ at RT and $4\times10^{-3}\,\Omega$ at 4.2 K [16]. Thus, our best results for mechanically polished cavity surfaces are 37% higher at RT and 17% higher at 4.2 K that could be explained by the better surface finish of the copper cavities at SLAC. Our cavity after EP had a surface resistance 18% higher at RT and the same surface resistance at 4.2 K as those measured at SLAC [16].

Nb Coated Cavities

Cavity 'A' was coated with a Nb film after it had undergone a second machining and was tested at 4.2 K. The heaters attached to the cavity were then used to obtain the surface resistance at higher temperatures. The surface resistance as a function of temperature of both of these cavities is reported in Fig. 3.

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Table 1: Surface Resistance Measurements at each Stage of Polishing for Uncoated Cavities

Cavity	Initial Machining		Second Machining		After EP	
	RT	4.2K	RT	4.2K	RT	4.2K
	$R_s(\Omega)$					
A	2.6×10^{-2}	1.1×10^{-2}	2.2×10^{-2}	6.3×10^{-3}	-	-
B	2.4×10^{-2}	6.8×10^{-3}	2.2×10^{-2}	6.7×10^{-3}	1.9×10^{-2}	4.0×10^{-3}
C	2.5×10^{-2}	9.5×10^{-3}	2.5×10^{-2}	4.7×10^{-3}	-	-

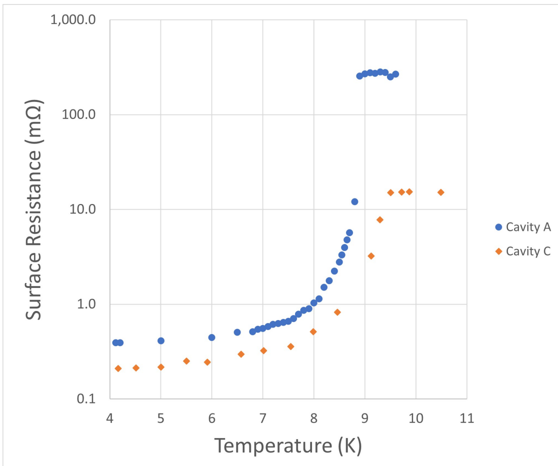

Figure 3: The surface resistance R_s as a function of temperature in the range $4\ \text{K} \leq T \leq 11\ \text{K}$ of Cavity 'A' (after second machining) and Cavity 'C' (after EP).

The critical temperature, T_c^{RF}, in this section will be quoted as a value where the surface resistance begins to decrease sharply (at least 10%) from its normal conducting value in $R_s(T)$ results, see Fig. 3. The critical temperature of the Nb coating on Cavity 'A' is a $T_c^{RF} = 8.9 \pm 0.05$ K, and on Cavity 'C' is a $T_c^{RF} = 9.3 \pm 0.1$ K.

A relation of T_c^{RF} to values measured with DC methods such as the resistance at 90, 50 and 10% of the resistance value before the superconducting transition, will be explored in a future by measuring the same samples with both RF and DC techniques.

The value of the critical temperature of the thin film on Cavity 'A' is below the expected values for bulk Nb (9.2 K), however, the values for Cavity 'C' are within the expected range. This suggests that the film quality was better for Cavity 'C'.

The surface resistance of Cavity 'A' at 4.2 K was measured to be 5.32×10^{-1} mΩ. The surface resistance of Cavity 'C' at 4.2 K was measured to be 2.10×10^{-1} mΩ. The difference in surface resistance between Cavity 'A' and Cavity 'C' is likely due to the improvement in surface roughness. The Bardeen–Cooper–Schrieffer (BCS) resistance for Nb at 4.2 K at 6 GHz is 1.15×10^{-2} mΩ, which is significantly lower than the measured resistance of both Cavity 'A' and Cavity 'C'.

The coating has been improved for the split cavities since the first coating at DL. The measured surface resistance has improved by a factor of 2.5 which brings the measured surface resistance within a factor of 20 of the BCS resistance. The critical temperature of the new coating is also within range of the critical temperature for bulk Nb further demonstrating an improvement in the coating.

CONCLUSION

Superconducting thin film radio frequency cavities based on the concept of a longitudinal split have been explored by our team. Three OFHC copper cavities were designed, manufactured, and mechanically polished at DL, following EP at INFN on two of them to improve the surface finish.

One of the advantages of this open geometry design is that the cavities can easily be manufactured, polished, cleaned, coated and examined at every stage.

The first Nb coating had a lower T_c than pure Nb and a higher surface resistance. It is expected that this is due to defects within the coating. The second Nb coating had a T_c in the range of that of pure Nb but a surface resistance a factor of 20 higher than BCS resistance.

Future work will include testing of other coatings and upgrading the system to perform measurements at higher power. A study on the effect of the sharpness of the edges where the two halves of the cavity meet on the performance of the cavity will also be undertaken.

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