Metallurgical Analyses of Niobium for Superconducting Radio Frequency Cavities

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ABSTRACT

Superconducting radio frequency cavities have gained use in accelerator systems for particle physics research. Careful production of the cavities has the greatest influence on their efficiencies as uniform interior surfaces are required for high accelerating gradients. Small variations in the surfaces of these cavities, such as inclusions, voids, and cracks, cause large deficiencies in the accelerating gradients. Processes to remove such deficiencies usually include eddy current scanning, buffered chemical polishing, and electropolishing. These methods do not provide a consistent means of producing a uniform interior surface. The effectiveness of tumbling as a mass finishing technique was analyzed. This process completely removed the weld line. The effects of weld line removal on cavity efficiencies will be examined.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are widely used in particle physics to achieve high-quality beams. They are used in accelerator systems because of their high quality factor, low-energy dissipation, and potential for continuous wave operation. The material used to construct these cavities is niobium due to its relatively high-critical temperature and high-critical magnetic field. Superconductivity occurs at low temperatures in certain metals. When certain materials have been cooled below their critical temperature, the electrical resistance nearly vanishes [1]. Though resistance exists for any conductor with a temperature greater than 0K, the resistance is negligible when compared to that of regular conductors.

Greater surface roughness negatively affects the superconducting properties of the cavities [2]. For a more detailed explanation, see Appendix. Surface roughness of the lattice has been known to create hotspots as a result of electron multipacting. This causes an increase in the thermal energy of the lattice, meaning that a larger energy gap is required for superconduction. As the energy gap is increased, multipacting is increased [9,10,11]. This cyclical effect causes the superconductor to be less efficient. An increase in the thermal energy of the lattice also decreases the probability of Cooper pair electrons, which are responsible for superconductivity. If these deficiencies are eliminated or decreased in their frequency of occurrence, greater efficiency may be attained by future SRF cavities.

FABRICATION, DEFICIENCIES AND CORRECTION METHODS

Current methods of fabricating the niobium cavities create inclusions, pitting, and other deficiencies throughout the metal. The niobium for cavities is delivered in the form of 3-mm-thick rolled sheets. It is required to check these sheets to detect possible inclusions and mechanical damage before proceeding to the fabrication of the cavities. Eddy current scanning is performed as a nondestructive method to detect such deficiencies. Once the inclusions are detected, they are removed and the sheets are recreated. The next step in fabrication is to stamp the sheets into half-cells. Minor deficiencies are created at locations of maximum curvature as a result of stamping. The half-cells are lightly etched using HF acid and electropolished (EC) before they are welded together by a focused electron beam. This creates a large weld line and often causes spattering. Attempts to remove defects caused by welding include heavy buffered chemical polishing (BCP) and EC. These techniques remove approximately 100 μm from the surface of the cavity, but do not consistently ensure a uniform interior surface.

The effects of tumbling as a mass finishing technique have been examined. Though tumbling is a simple process, several things must be considered. Niobium is a soft metal. If the tumbling media is too hard, it will deposit itself in the surface of the cavities and may increase the surface roughness. Type TG conical media was used because it has a low hardness and was consumed in the tumbling process. The effects of varying the rotation speed and percent volume filled by the media were examined.

RESULTS AND DISCUSSION

Before tumbling techniques were used on SRF cavities, BCP and EP were the best methods of removal. These methods were successful in removing inclusions from the surface, but generally fail to remove the weld line. A consistent method is being developed for this purpose. The effectiveness of each variable was quantified by thickness testing. The weld line was inspected after an effective method was determined. Fourteen reference points were chosen for measurement and labeled on the cavity according to Figure 1.

Points 4, 9, 11, and 13 lay on the same longitudinal line. Points 5, 10, 12, and 14 lay on the same longitudinal line. The cavity is filled between 45–55% with media, water, and TS compound before tumbling. Typically, approximate quantities of 2200 g media, 1000 g H_2O, and 100 g of TS compound are added to the cavity. The effects of tumbling speed were tested. Results are shown in Figure 2.

The results of this test show that if removal occurs at a point, it is more likely to occur at a higher rpm. The maximum limit was 115 rpm for the mass-finishing device. This rate was used for the rest of the process. The effect of varying the volume of the cavity filled by tumbling media was tested. Results are shown in Figure 3. The results of this test show that a higher removal rate is most probable when the cavity is filled between 50–55% of its total volume. This corresponds to the addition of approximate quantities of 2300 g media, 1100 g H_2O, and 150 g TS compound.

After 40 hours of tumbling the cavity, between 7–15μm were removed from the inner surface of the cavity. This process should remove large deficiencies on the surface.

Chemically polished and electropolished SRF cavities have been visually inspected. Figure 4 shows the weld line of a cavity that has undergone BCP and EP with no tumbling. The weld line in this image is approximately 5 mm. This cavity has undergone BCP and EP, but still has large deficiencies on its surface. It is clear that the electron beam welding process produces significant cracks and spatters that are not removed in previous polishing techniques. Mechanical methods of polishing are employed using the tumbling process yielding more favorable results. Figure 5 shows the weld line of the same cavity after the tumbling process.

This process has almost removed the weld line and other surrounding deficiencies. Though these mass finishing techniques seem to have succeeded in removing large deficiencies, they produce minor inclusions of media residue on the cavity surface. These inclusions and other minor deficiencies can be removed during light BCP. The exclusion of deficiencies eliminates electron multipacting, decreases hotspots, and increases the quality factor. Once this cavity undergoes BCP and EP, the quality factor will be tested after the mechanical polishing. An average roughness (Ra) of 100 nm has been achieved by BCP. This corresponds to about 25 MV/m accelerating gradient for 1.3 GHz single-cell cavities. An Ra of about 10 nm has been achieved through EP. This corresponds to accelerating gradients of 35 MV/m and higher, but these results have not been consistent. The addition of mechanical polishing is expected to increase the quality factor significantly.

CONCLUSIONS AND FUTURE GOALS

It has been shown that surface roughness negatively affects the superconducting properties of SRF cavities. Problems in manufacturing techniques have been addressed and are currently being modified for improvement. One such technique is the polishing process examined in this paper. The addition of mechanical polishing has improved the surface roughness and will be quantified after BCP and EP. The exclusion of deficiencies should be able to increase the quality factor and accelerating gradient. Though improvements can be seen visually, the effect of mechanical polishing on the quality factor merits further analyses. Future goals include the improvement of welding techniques and the development of an expedited polishing process. These methods will be applied to the fabrication of nine-cell structures for the international linear accelerator.

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FIGURES

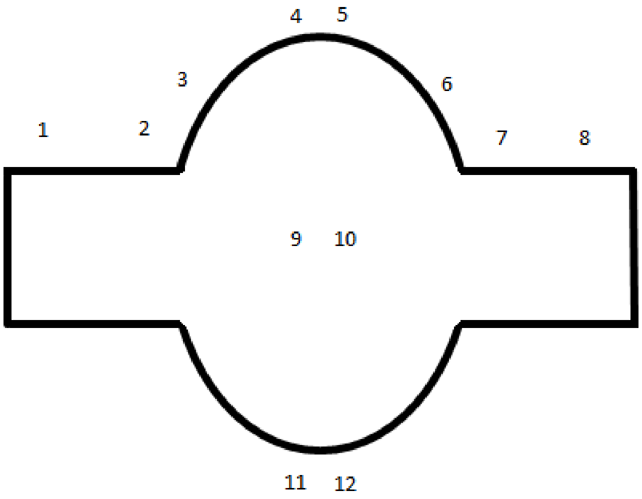

Figure 1. Cavity with labeled reference points.

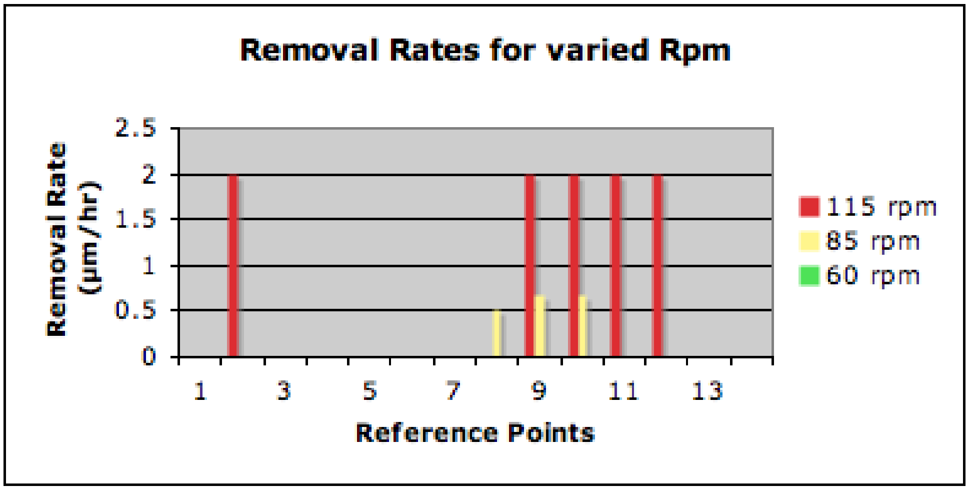

Figure 2. Removal rates for varied revolution speeds.

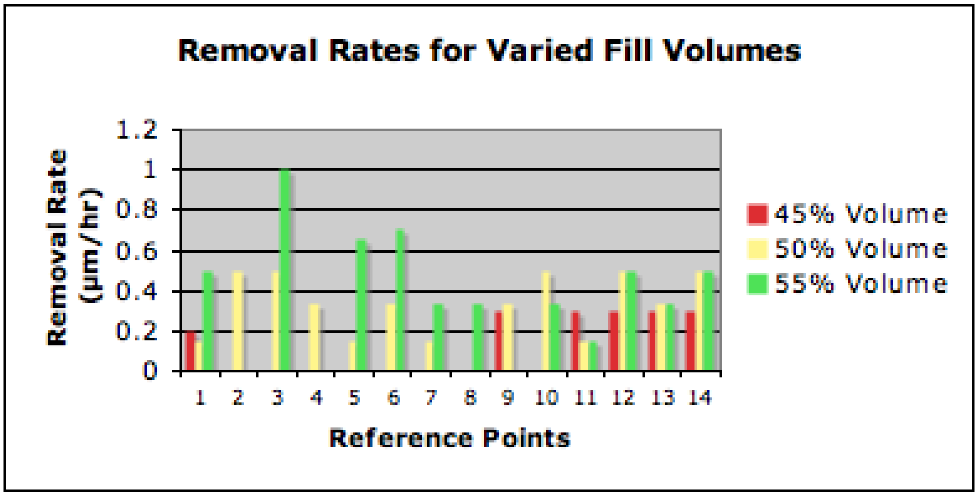

Figure 3. Removal rates for varied fill volumes.

Figure 4. The weld line after initial BCP and EP, with no mechanical polishing.

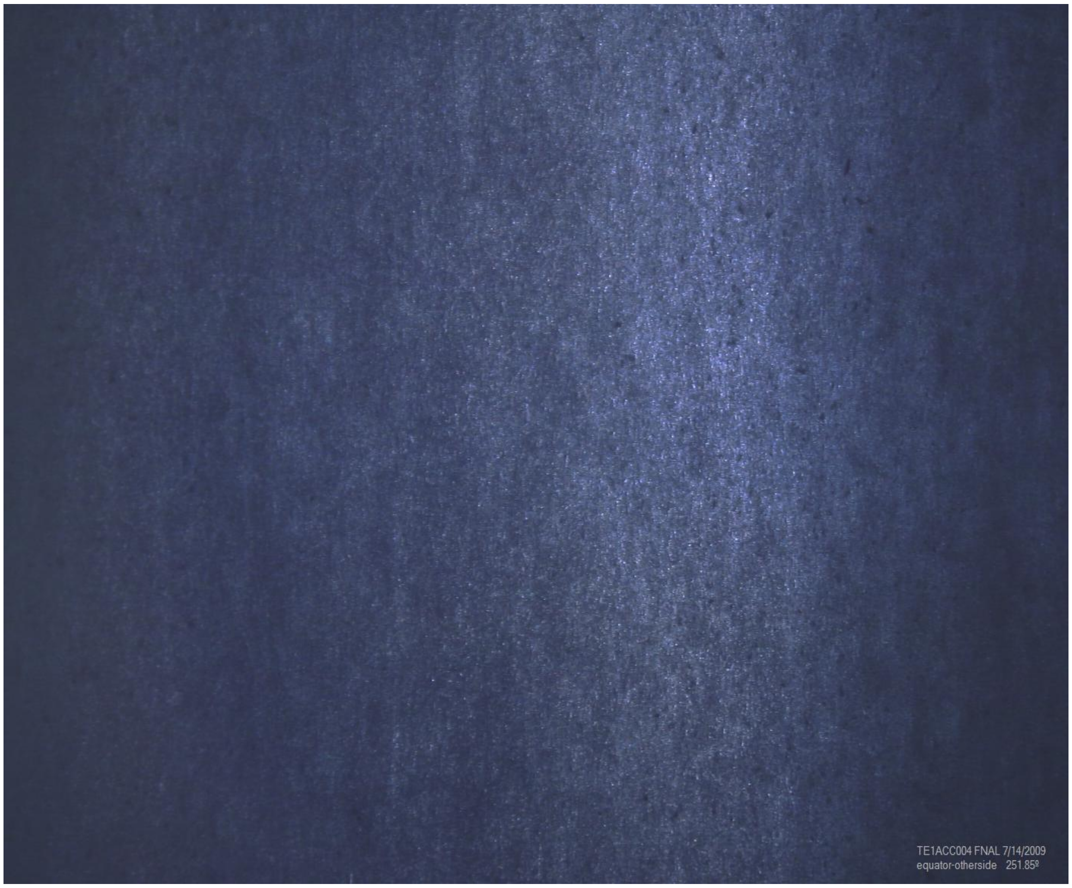

Figure 5. The weld line after mechanical polishing.

APPENDIX

Greater surface roughness negatively affects the superconducting properties of the cavities because less electron pairs (Cooper pairs) form. Cooper pair electrons are responsible for superconductivity. The reason that Cooper pairs are responsible can be examined by analyzing interaction forces at low temperatures.

Though resistance exists for any conductor with a temperature greater than 0K, the resistance is negligible when compared to that of regular conductors. The expression for RF surface resistance can be simplified as

$$R_s \propto A(1/T) f^2 e^{-\Delta/kT} + R_0 \qquad (1)$$

where Δ is half of the energy gap as a function of temperature, k is Boltzmann's constant, T is the temperature, R_0 is the lowest intrinsic resistance, and A is a constant, dependant upon the material parameters of the superconductor, such as the penetration depth, λ_L, coherence length, ε_0, the Fermi velocity, v_F, and the mean free path, l [1, 2, 3]. This phenomenon occurs because of strange electron rearrangements on the surface of the lattice.

In a normal conductor, an electrical current can be visualized as a fluid of electrons moving across a heavy ionic lattice. The electrons constantly collide with the lattice. During each collision, some of the energy carried by the electrons is absorbed by the lattice and converted into heat. As a result, the energy carried by the current is constantly being dissipated [4].

In superconductors, the electronic fluid cannot be resolved into individual electrons. It consists of bound pairs of electrons, called Cooper pairs. Electron pairing occurs when the attractive forces of the interactions between electrons and phonons become greater than the repelling forces between the two electrons [5]. In order for Cooper pair fluids to exist, a minimum amount of energy must be supplied to excite the fluid. The Cooper pairs will form if that energy, is much larger than the thermal energy of the lattice, kT as

$$\Delta >> kT. \tag{2}$$

According to BCS Theory of Superconductivity, the electron pairs have an interaction distance of approximately 100 nm. This interaction distance disallows the scattering of the fluid by the lattice. Therefore, Cooper pair fluid can flow with negligible energy dissipation. Negligible energy dissipation allows current to continuously flow through the circuit without a constant power supply. Therefore, this Cooper pair state is responsible for superconductivity [6, 7, 8].