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Mirror Smooth Superconducting RF Cavities by Mechanical Polishing with Minimal Acid Use

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Abstract

A new mechanical technique for polishing the inside surface of niobium superconducting RF (SRF) cavities has been developed. Mirror-like finishes, the smoothest observed in cavities so far, were produced after fine polishing, with < 15 nm RMS roughness over 1 mm^2 scan area. This is an order of magnitude less than the typical roughness produced by electropolishing. The processing equipment has advantages of modest installed and operating costs, simple associated technology, and no large quantities of acutely toxic chemicals or special handling procedures. Cavity quality factors above 10^{10} were maintained well above the 35 MV m^{-1} benchmark for electropolished cavities, and this was achieved with an intermediate finish not as smooth as the final polish. Repair of a weld defect, which is intrinsic to this process, was also demonstrated. These transformational aspects could enable a new SRF cavity processing paradigm for future large scale particle accelerators such as the International Linear Collider.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Niobium superconducting radio-frequency (SRF) resonating cavities are an enabling technology for efficient particle accelerators. They are central to physics machines that produce high-energy and high-intensity beams, and they enable other applications such as next-generation light sources, sub-critical nuclear reactors and spent fuel remediation, medical isotope production, emissions reduction, and screening for defense and security [1]. Important metrics of SRF cavity technology are the quality factor Q and the maximum electric field E_{Acc} to which high values of Q can be sustained [2]. These quantities drive cost and performance factors related to cryogenics, beam energy, and machine length.

The present state of cavity fabrication and processing art places strong emphasis on attaining a very smooth surface because both Q and E_{Acc} are improved as the surface roughness is decreased [3,4]. Penetration of RF magnetic fields at sharp points, edges, ridges, and other topographical features where the geometry imparts a local enhancement is a popular model why smooth surfaces perform better than rough surfaces [5]. While extremely smooth surfaces should, therefore, result in nearly ideal performance, sub-surface contamination cannot be introduced as a by-product of the surface polishing technique because of the negative impact some impurities have on superconducting properties [6-10]. Ideally smooth surfaces would permit a better evaluation of the impact of contamination on cavity

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performance. From a more practical point of view, surface polishing techniques that also prevent or reduce sub-surface contamination are highly desirable.

Electropolishing (EP) is presently the preferred route for preparing the cavity interior surface, due to the positive correlation between higher Q and E_{Acc} with smoother cavity surfaces [3] and the overall reduction of surface roughness when compared to buffered chemical polishing and mechanical abrasive techniques [4]. A well-controlled EP process can produce a typical root-mean-square average roughness R_A of approximately 0.1 μm for a 1 mm × 1 mm area scan using a profilometer [3,4].

Unfortunately EP has several drawbacks. Many are associated with the electrolyte that is typically used, 9 parts by volume 98% concentrated sulfuric acid and 1 part 49% concentrated hydrofluoric acid [11]. Extensive facilities and personnel protective equipment are needed for safe acid handling. Sulfur byproducts can form and deposit on the surface potentially limiting cavity performance [13,14]. Hydrogen is loaded into the cavity during EP, requiring several additional processing steps [11]. In addition, the complexity of the EP process makes it difficult to control the fluorine ion diffusion [14].

In this work, we describe how an alternate technique to polish the cavity interior by mechanical polishing achieved a truly mirror-smooth surface finish with $R_a < 15$ nm. This technique is derived from centrifugal barrel polishing (CBP) which has been applied to SRF cavities previously [15,16]. While CBP in this sense was also applied to the cavities reported here, new techniques were innovated to explore further improvement of the cavity surface beyond that obtained by traditional CBP alone. This includes the use of both traditional materials and novel media, which resulted in smoothing and polishing action more akin to the preparation of atomically flat metallography samples.

2. Mechanical Polishing Process

The mechanical polishing of single-cell and 9-cell SRF cavities was done using a machine custom built for this purpose by Mass Finishing Inc. [17]. Cavities were secured in buckets. Each bucket rotated around the central shaft at up to 115 rpm, and each bucket counter-rotated around its own axis at the same rate. The cavities were filled 50% by volume with media and capped for each step. The cavities were rinsed with tap water between polishing steps.

The extended mechanical polishing process consisted of one bulk material removal step and 4 polishing steps, all conducted at ambient temperature. The first 2 steps follow earlier CBP work: In the first step, 9 mm × 9 mm KM ceramic angle cut triangle media, purchased from Kramer Industries, Inc., was spun inside the cavity to remove approximately 80 μm of material at a removal rate of 11 μm hr^{-1}. The second step ran for 12 hours at a material removal rate of 3 μm hr^{-1} using 12.5 mm RG-22 cones from Mass Finishng, Inc. Both steps used enough de-ionized (DI) water to just cover the media and a surfactant called TS Compound provided by Mass Finishing, Inc. (1 TS Compound : 40 parts water).

The final 3 steps diverged from previous CBP work and followed metallurgical sample preparation guidelines. They all used 4 mm cubic hardwood blocks (Raytech Metal Finishing, part number 41-363) to hold various polishing slurries. The blocks were found to be superior to other fibrous organic and inorganic media. The third step used -400 mesh alumina, the fourth step -800 mesh alumina (both from Kramer Industries, Inc), and the final step used 40 nm colloidal silica (Allied High Tech Products Inc., part number 180-25000). The alumina was mixed as powder into DI water until the water was saturated. The wood blocks were soaked in the alumina-water and colloidal silica for 12 hours before use. Processing times were 15 hr for step 3, 20 hr for step 4, and 35 hr for step 5.

3. Results & Discussion

Two 9-cell and seven 1-cell 1.3 GHz Tesla type cavities have been processed by this mechanical polishing procedure. All of the cavities were processed with the first 4 steps, but only three of the cavities were polished to step 5. Figure 1 shows pictures of the equatorial weld of two different cavities taken by a special camera system [18]. In all pictures, the weld bead is approximately 10 mm wide. Figure 1a shows the surface of a 9-cell cavity named TB9ACC015 that received bulk EP (i.e. > 100 μm material removed) and contained a large weld pit. Multiple repair attempts to remove the pit with light EP (i.e. < 40 μm material removed) failed, and the cavity was never able to operate without quench above 19 MV m^{-1}. Subsequently, the first 4 steps of the process were applied, resulting in an intermediate finish. Figure 1b shows the same surface location as in 1a; there is no remaining sign of the pit, and the weld itself is somewhat difficult to discern. This repair resulted in improved performance of this cavity, as will be discussed shortly.

Figure 1c shows the weld bead area that is representative of a high-quality EP, resulting in E_{Acc} of >40 MV m^{-1} [19]. Figure 1d shows the surface of a different single cell cavity (TE1AES005) after polishing with colloidal silica. The surface looks mirror like with no evident scratches. The weld zone is nearly invisible. Magnification is required to observe features, which are on the order of 1-2 pixels wide.

Coupons were co-processed with the cavities using end flanges for support perpendicular to the media rotation axis. Surface roughness of the coupons was measured on a KLA Tencor P-16 surface profilometer. Figure 2a shows the finish after the first 4 polishing stages, where R_A improved to 0.07±0.005 μm. Figure 2b shows the effect of the fine polishing with colloidal silica, where R_A improved to 0.014±0.002 μm. This is an order of magnitude less than the typical roughness obtained by EP when measured by comparable equipment over a similar scan area [14].

All of the cavities processed thus far have attained E_{Acc} higher than 32 MV m^{-1} and exhibit improved Q over typical results obtained by EP. This is interesting because different types of polishing media were used before the optimum formulation reported above was achieved. Figure 3 shows the performance data of cavities which were processed to an intermediate finish with the first 4 steps followed by light EP as a precaution to remove any residual grit. The necessity of final etching is presently being evaluated because this degrades the mirror-like finish; we expect this to be not more than a brief dilute acid rinse akin to that used for niobium metallography. An impressive 40 MV m^{-1} quench field and high Q $\sim 10^{10}$ is seen for single-cell cavity TE1ACC004, close to the theoretical quench limit of ~45 MV m^{-1} [20]. Repaired TB9ACC015 reached nearly double the E_{Acc} than from before, at 34.5 MV m^{-1} and at the ILC benchmark.

The present mechanical processing technique offers many advantages over EP at comparable performance. Paramount are low cost (~$200k for the processing machine and minor modifications to lab space, vs. ~$2M for an equivalent chemical facility) and safety (little to no acutely toxic acids). The extension of CBP to a fine polishing stage promises great results for large projects in the future because of the mirror like finish now achievable. From a more basic point of view, the ability to apparently surpass the R_A where jagged features limit cavity performance allows more detailed study of the roles of contamination.

4. Conclusions

Centrifugal barrel polishing was extended to intermediate and fine polishing stages with alumina and colloidal silica. This produced mirror like finishes that have not been seen before for polycrystalline SRF cavities. Profilometry determined < 15 nm R_A over 1 mm^2 scan, an order of magnitude less than the typical roughness obtained by electropolishing. Surfaces polished to an intermediate stage still resulted in comparable performance as attained by existing techniques, with only minimal use of toxic acids. Repair of a cavity weld defect was also demonstrated, resulting in restoration of performance to desired levels. Such repair is intrinsic to the polishing process, thereby mitigating weld errors and improving yield.

Acknowledgments

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References

[1] Henning W and Schank C *Acclerators for America's Future* Report of the U.S. Dept. of Energy Workshop www.acceleratorsamerica.org/files/Report.pdf

[2] Padamsee H 2008 *RF Superconductivity* Vol. II *Science, Technology and Applications* (Weinheim: Wiley-VCH)

[3] Saito K, Inoue H, Kako E, Fujino T, Noguchi S, Ono M and Shishido T 1998 *Part. Accel.* **60** 193.

[4] Tian H, Sommer W, Trofimova O, Reece C E, and Zhao L 2009 *Proc. of SRF2009, Berlin, Germany* (published online at http://accelconf.web.cern.ch/AccelConf/SRF2009/papers/tuppo081.pdf).

[5] Knobloch J, Geng R L, Liepe M, and Padamsee H 1999 *Proc. 9th Workshop on RF Superconductivity* Santa Fe USA (published online at http://laacg.lanl.gov/rfsc99/rfsc99_web/TUA/tua004.pdf) 77

[6] Koch C C, Scarbrough J O, and Kroeger D M 1974 *Phys. Rev. B* **9** 888.

[7] Halbritter J 1987 *Appl. Phys. A* **43** 1; Halbritter J, Kneisel P, Palmieri V, and Pekeler M 2001 *IEEE Trans. Appl. Supercond.* **11** 1864.

[8] Romanenko A and Padamsee H 2010 *Supercond. Sci. Technol.* **23** 045008.

[9] Ciovati G, Kneisel P, and Gurevich A 2007 *Phys. Rev. Special Topics Accel. Beams* **10** 062002.

[10] Dzyuba A, Romanenko A, and Cooley L D 2010 *Supercond. Sci. Technol.* **23** 125011.

[11] Lilje L *et al* 2004*Nucl. Instrum. Methods Phys. Res.* A **524** 21

[12] Saito K and Furuta F, 2009 *Proc. of SRF2009, Berlin, Germany* (published online at http://accelconf.web.cern.ch/AccelConf/SRF2009/papers/tuppo090.pdf)

[13] Zhao X *et al.* 2010 *Phys. Rev. Special Topics Accel. Beams* **13** 124702.

[14] Tian H and Reece C E 2010 *Phys. Rev. Special Topics Accel. Beams* **13** 083502.

[15] Higuchi T *et al.*, 1995 *Proc. 7th Workshop on Superconductivity* (Saclay, Gif sur Yvette, France) p. 723.

[16] Issarovitch G, Proch D, Singer X, Reschke D, and Singer W 2003 *Proc. 11th Workshop RF Supercond.* Lübeck/Tavemünder, Germany, p.482 (published online http://accelconf.web.cern.ch/accelconf/SRF2003/papers/tup56.pdf)

[17] Cooper C *et al.* 2009 *Proc. of SRF2009, Berlin, Germany* 806-10 (published online at http://accelconf.web.cern.ch/AccelConf/SRF2009 papers/tuppo076.pdf)

[18] Iwashita Y, Tajima T and Hayano H 2008 *Phys. Rev. Special Topics—Accel. Beams* **11** 093501

[19] Ginsburg C, Fermilab, private communication.

[20] Shemelin V, Padamsee H, Geng R L 2003 *Nucl. Instr. and Meth in Phys. Res. A*, **496** 1-7.

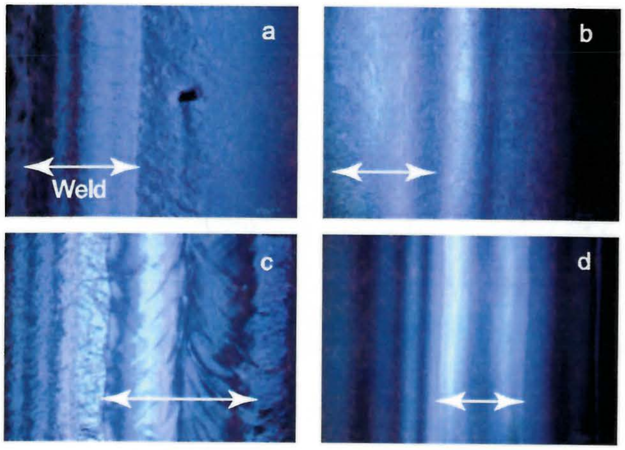

Figure 1. Pictures of weld bead: (a) Electropolished surface near cavity equator weld with a pit; (b) Same region as (a) showing improved polish and removal of pit after step 4 and light EP; (c) Typical high-quality EP polish; (d) Mirror-like finish obtained on a different cavity after step 5 polishing with colloidal silica.

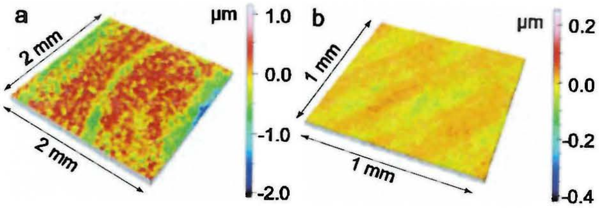

Figure 2. Surface profilometer scans of witness coupons from (a) intermediate polishing and (b) fine polishing.

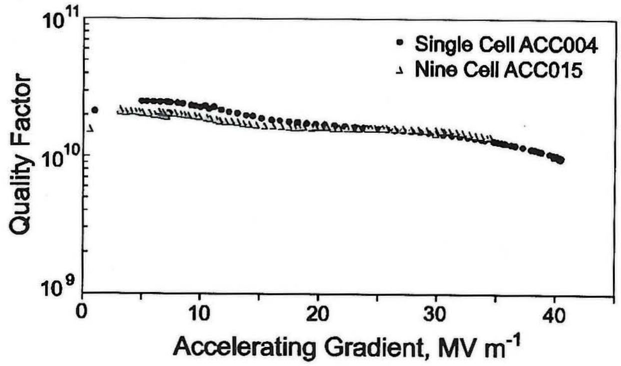

Figure 3. Quality factor is plotted versus accelerating gradient for single-cell ACC004 and the repaired 9-cell cavity ACC015, each after the fourth polishing step.