ADVANCE ADDITIVE MANUFACTURING METHOD FOR SRF CAVITIES OF VARIOUS GEOMETRIES*

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Abstract

An alternative fabrication method for superconducting radio frequency (SRF) cavities is presented. The novel fabrication method, based on 3D printing (or additive manufacturing, AM) technology, capable of producing net-shape functional metallic parts of virtually any geometry, promises to greatly expand possibilities for advanced cavity and end-group component designs. A description of the AM method and conceptual cavity designs is presented along with material analysis and RF measurement results of additively manufactured niobium samples.

INTRODUCTION

SRF accelerating cavities are commonly used in a variety of particle accelerators for research applications, as well as emerging industrial applications. These applications place enormous demands on the development of more reliable and economic methods for fabrication of SRF accelerating cavities and end-group components such as fundamental power couplers (FPCs) and high order mode (HOM) dampers.

RadiaBeam Technologies LLC (RadiaBeam), in collaboration with Thomas Jefferson National Accelerator Facility (JLab), the University of Texas at El Paso (UTEP), and North Carolina State University (NCSU), has been developing the use of Electron Beam Melting (EBM) AM for the production of normal conducting radio frequency (NCRF) and SRF accelerating cavities and end-group components [1, 2, 3]. A review of the fabrication of copper (NCRF) components using EBM is available in reference [4]. A detailed account of the EBM fabrication and characterization of niobium can be found in reference [5].

FABRICATION PROCESS

AM (a.k.a. rapid prototyping or 3D printing) encompasses a group of technologies used to fabricate a part layer-by-layer using 3D computer aided design (CAD) data. AM is increasingly being use throughout industry, providing a quick and accurate way for designers and engineers to visualize, optimize, and fabricate functional parts directly from CAD models in a variety of materials including metals.

EBM is a so-called powder-bed fusion AM technology, originally patented and commercialized by Arcam AB, Sweden. EBM AM is unique in its use of an electron beam to fully melt powdered metals in a layer-by-layer fashion, and has several advantages compared to other AM techniques, such as reduced residual stresses, fast build rates, and better material homogeneity from the vacuum process when compared to laser based powder bed fusion technology (i.e. selective laser melting, SLM).

EBM Fabrication Process

Figure 1 shows a schematic depicting the main components of the Arcam EBM system.

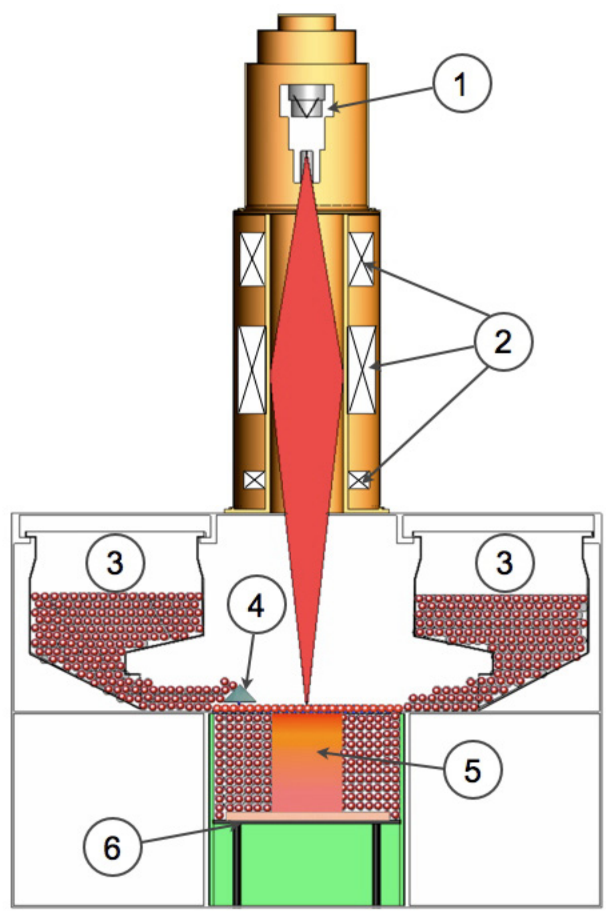

Figure 1: Arcam EBM system schematic.

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Metal powder (30µm – 120µm diameter), contained in two stainless steel hoppers (3), is gravity fed to a raking mechanism (4) which spreads the powder forming a uniform layer on a vertically adjustable platform (6). An electron beam (e-beam), generated by a thermionic cathode (1), is accelerated to a typical energy of 60 keV. The e-beam is collimated and steered by magnetic optics (2), and used to pre-heat the entire powder layer (50-120µm) with a combination of low beam current and high scan speed. This step serves two important purposes: 1) to lightly sinter the powder allowing it to hold firm during subsequent melting and 2) by imparting heat to the part, it helps reduce thermal gradients between the melted layer and the rest of the part. After the preheating is complete, the beam current is increased and/or scan speed decreased and the e-beam is quickly and accurately steered selectively melting regions of the powder bed corresponding to a cross-section of the part being fabricated. The surface is then lowered and the process is repeated for each successive layer until the entire part in complete (5).

Several features of the EBM process are key to the fabrication of SRF cavities. The use of an e-beam to melt the powder, as opposed to a laser used in other systems, makes it significantly more efficient when processing highly reflective or refractory metals such as copper and niobium. The lightly sintered powder serves as a support for subsequent layers, allowing for the generation of unsupported complex shapes with downward facing geometries. Since an e-beam is used the build takes place in vacuum, and for most materials a build chamber pressure of ~10^{-3} Torr in maintained. For niobium processing, the EBM system was modified in order to achieve a chamber pressure of <10^{-4} Torr, and the pressure was monitored using a residual gas analyser (RGA). Figure 2 shows an RGA plot of the residual pressures in the build chambers. The spikes in hydrogen, which correspond to EBM heating and melting cycles, are believed to be caused by outgassing of the niobium and/or the result of the decomposition of water by the e-beam.

Material Characterization

Samples suitable for material and mechanical testing were fabricated using a modified Arcam A2 EBM machine at UTEP. Type 1 reactor grade (ASTM B392) unalloyed niobium wire was purchased from ATI Wah Chang, and plasma atomized by Advanced Powders & Coatings (Raymor). Table 1 summarizes the measured material and mechanical properties of EBM samples.

Table 1: Comparison of Measured Material Properties for the Wrought and EBM Niobium

	EBM Nb (from reactor grade feedstock)	**Wrought reactor grade Nb**
Density	8.55 g/cm^3	8.57 g/cm^3
RRR	19 -24	~ 40
Thermal conductivity	50 W/m*K	53.7 W/m*K
YS (Rp 0.2)	141 MPa	135 MPa
UTS (Rm)	225 MPa	205 MPa
Elongation	34%	45%

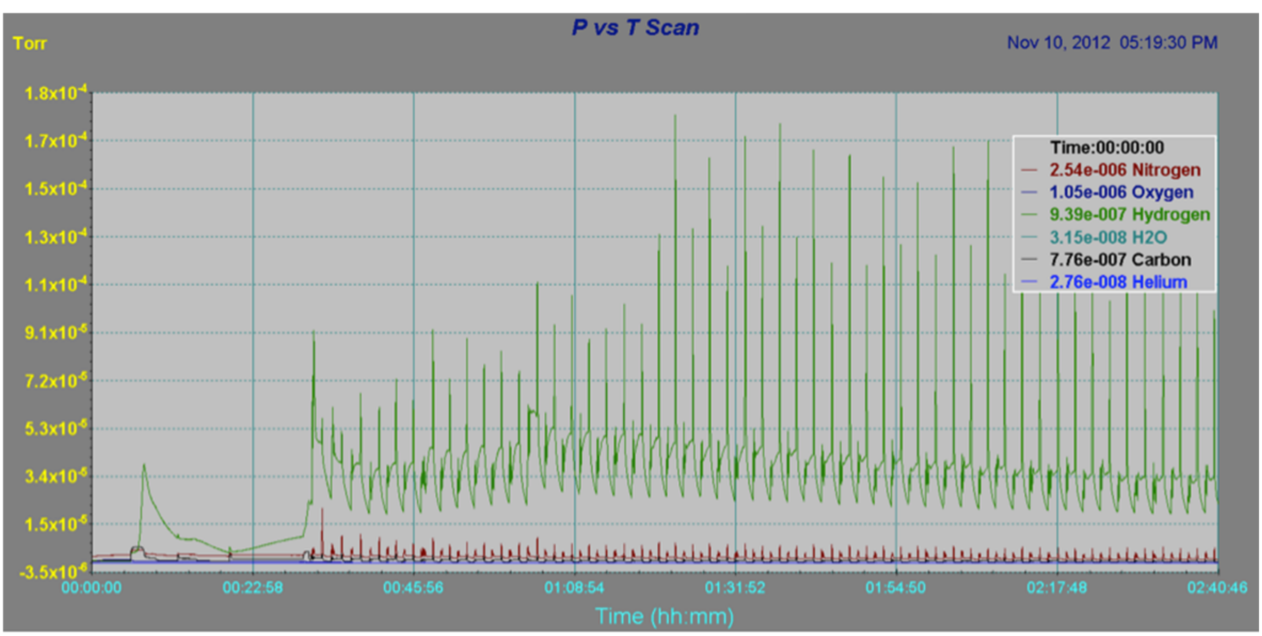

Figure 2: RGA plot showing the partial pressure in the build chamber during the EBM processing of reactor-grade niobium.

PROTOTYPE SINGLE-CELL CAVITY

A prototype EBM cavity design, based on the Fermilab 3.9 GHz 3rd Harmonic Cavity Design [6], was developed incorporating stiffening 3D lattice supports.

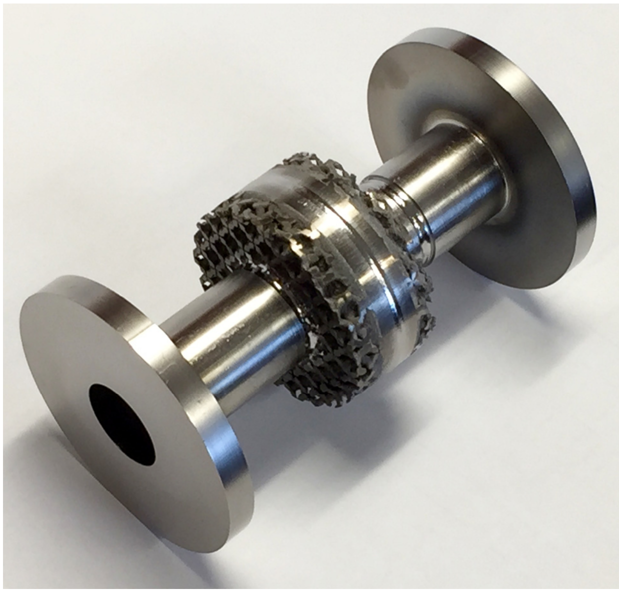

Figure 3: Photograph of the 3D_1 single-cell cavity.

Single Cell Fabrication

Two single cell 3.8 GHz prototype cavities were successfully fabricated (3D_1 and 3D_2). Four half cells were made using EBM AM from reactor grade niobium powder. The half cells fabricated by EBM were oversized (thicker walls) to allow machining (turning) of the RF surface in order to improve the surface roughness. The half cells were then e-beam welded at the equator to form the two single cell cavities (see Figure 3). After fabrication the cavities were etched by buffered chemical polishing (BCP), removing ~100µm surface layer, followed by annealing at 800˚ C for 3 hours and additional removal of ~ 20µm surface layer by BCP. The cavities were then rinsed with ultra-pure water and Liquinox in an ultrasonic tank for 30 minutes, followed by another rinse with ultra-pure water only in an ultrasonic tank for 30 minutes. The cavities were dried in an ISO 4 clean room and assembled with input and pick-up antennae, and evacuated to ~10^{-8} mbar. Figure 4 shows a picture of cavity 3D_1 attached to the vertical test stand.

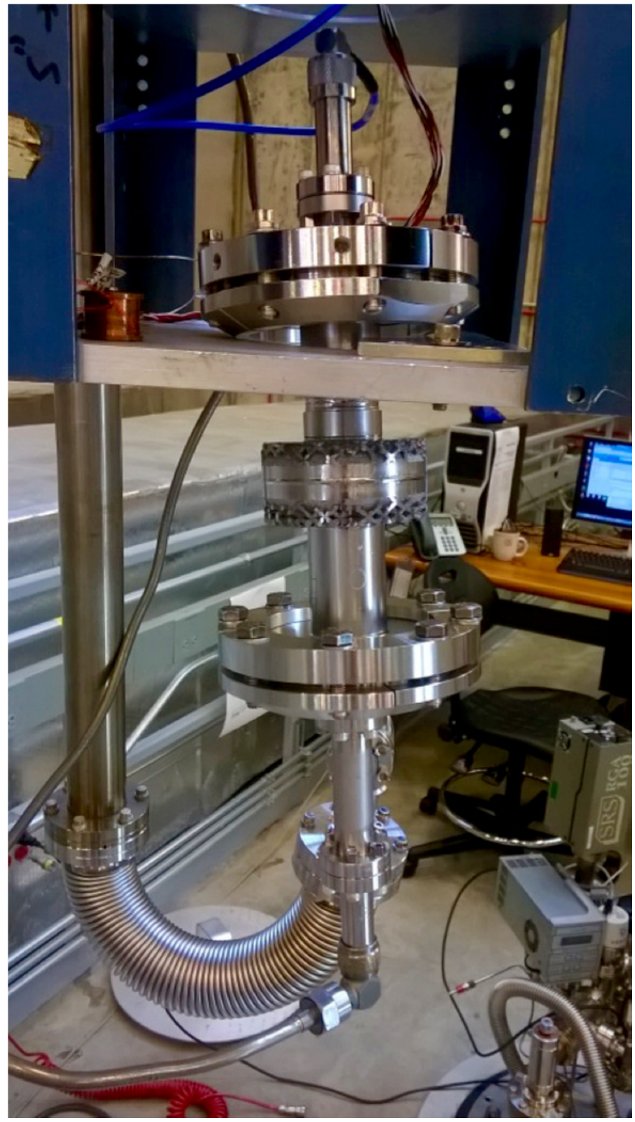

Figure 4: 3D_1 attached to the vertical test, under vacuum.

SRF Test Results

Figure 5 (top) shows the results of the measurement of the low-field surface resistance as a function of temperature. The residual resistance is (170 ± 10) nΩ and (2493 ± 93) nΩ for 3D_1 and 3D_2, respectively. The ratio between the energy gap and the critical temperature, Δ/kT_c, is 1.84 ± 0.06 for 3D_1, whereas it could not be determined for 3D_2 because of the high residual resistance. The critical temperature was determined by tracking the resonant frequency between 5-10 K and it was ~9.0 K for 3D_1 and ~9.1 K for 3D_2.

The pressure sensitivity coefficient was determined from a linear fit of the resonant frequency as a function of He bath pressure and it was -84 Hz/Torr for 3D_1 and -114 Hz/Torr for 3D_2.

The quality factor, Q_0, as a function of the accelerating gradient, E_{acc}, was measured for both cavities at 2.0 K.

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The results are shown in Figure 5 (bottom). 3D_1 quenched at 3 MV/m, whereas Q_0 of 3D_2 decreases rapidly with increasing field, up to a quench field of 2 MV/m. The quench fields correspond to peak surface magnetic field values of 13 mT and 9 mT for 3D_1 and 3D_2, respectively. No X-rays were detected during the high-power test at 2 K.

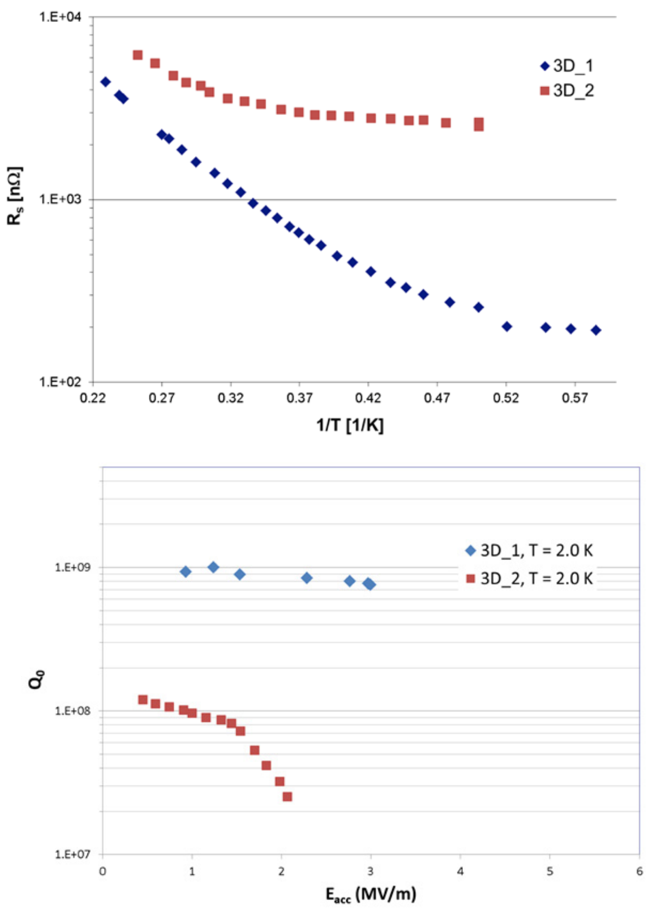

Figure 5: $R_s(1/T)$ measured at ~ 1 MV/m (top); $Q_0(E_{acc})$ measured at 2.0 K (bottom).

CONCLUSION

EBM AM process parameters have been developed yielding nearly fully dense reactor grade niobium components with mechanical properties comparable to wrought reactor grade niobium. A single cell prototype cavity, with integrated stiffening supports highlighting the design freedom afforded by EBM AM, was successfully fabricated and tested.

Although test results show that the EBM single-cavities underperformed compared to conventionally fabricated wrought reactor grade single-cell cavities previously tested by others, the results are nonetheless encouraging. The measured quench field corresponding to ~10 mT, along with the tremendous design freedom afforded by EBM AM, show promise for the development of end group components.

Further improvements to the EBM AM process are envisioned to optimize surface roughness, microstructure, and density. Such improvements, along with the use of higher RRR feedstock material, make it worthwhile pursuing EBM AM for SRF applications.

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