DEVELOPMENT OF A CW NCRF PHOTOINJECTOR USING SOLID FREEFORM FABRICATION (SFF)*

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Abstract

A key issue for high average power, normal conducting radio frequency (NCRF), photoinjectors is efficient structure cooling. To that end, RadiaBeam has been developing the use of Solid Freeform Fabrication (SFF) for the production of NCRF photoinjectors. In this paper we describe the preliminary design of a high gradient, very high duty cycle, photoinjector combining the cooling efficiency only possible through the use of SFF, and the RF efficiency of a re-entrant gun design. Simulations of the RF and thermal-stress performance will be presented, as well as material testing of SFF components.

INTRODUCTION

NCRF photoinjectors have a proven track record in generating the high quality beams necessary for the next generation accelerator based systems, but are limited to relatively low duty cycle due to the ohmic losses on the cavity walls. We aim to combine the cooling efficiency possible through the use of SFF, and the RF efficiency of the re-entrant gun design, to develop a very high duty cycle, high gradient photoinjector.

FABRICATION PROCESS

EBM Build Process

The direct metal SFF process explored in this research, Arcam's Electron Beam Melting (EBM), is similar to rapid prototyping technologies in its approach to fabrication. However, the Arcam EBM process has been shown to produce fully-dense metal components with properties better than cast and comparable to wrought material [1, 2].

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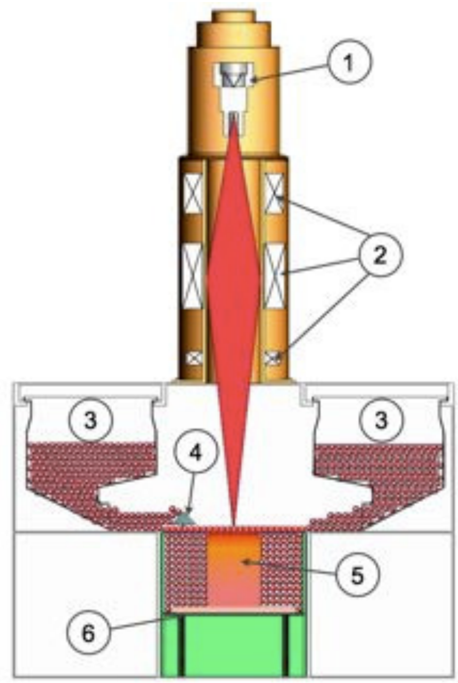

Figure 1: Arcam A2 EBM system schematic.

Figure 1 shows the Arcam A2 EBM system schematic. Powder metal, contained in two stainless steel hoppers (3), is gravity fed and raked (4) over a vertically adjustable surface (6). An electron beam, generated by a thermionic gun (1) across an accelerating voltage of 60 kV, manipulated by steering and focusing optics (2), pre-heats the entire powder layer (typically ~100 µm thick) with a low beam current and high scan speed. This step serves two important purposes. One, it lightly sinters the powder allowing it to hold firm during subsequent melting. Two, 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 electron beam current is increased and/or scan speed decreased. A computer-aided design (CAD) program guides the electron beam and traces the cross section of the modeled part (5), thus melting and forming the first layer. The surface is then lowered and the process repeated for each successive layer.

Several features of the Arcam EBM process are key to the construction of RF cavities. The use of an electron beam to melt the powder, as oppose to a laser used in other systems, makes it significantly more efficient when processing highly reflective metals. The lightly sintered powder serves as a support for subsequent layers, allowing for the generation of unsupported complex shapes with downward facing geometries, critical for the formation of internal cooling channels. Since an electron beam is used the build takes place in vacuum ($\sim 10^{-4}$ Torr), providing a clean environment, resulting in superior material characteristics.

Material Optimization

Samples of varying size and geometry were fabricated using an Arcam S12 EBM machine at NCSU, and an Arcam A2 EBM at UTEP. Starting from EBM process parameters generated in a previous studies [3], initial samples were EBMed from very high purity (99.99%), argon atomized, copper powder. These samples exhibited incomplete interlayer fusion and porosity due to poor powder flow and conglomeration during raking process. Optical and SEM analysis of the powder revealed a large percentage of the particles had smaller "satellite" particles attached, accounting for the poor flow characteristics. An electronic grade (99.8% purity) copper powder, with similar size distribution but much better flow characteristics, was then used with greatly improved results (see Figure 2).

Samples made using electronic grade powder had an as-EBMed density as high as 8.84 g/cm^3, 99% of the wrought material. The dark pores, present mainly at the grain boundaries, are thought to be Cu_2O precipitates. Additional observations revealed a novel dislocation architecture, illustrating the prospect for engineering microstructure by EBM parameter optimization [4].

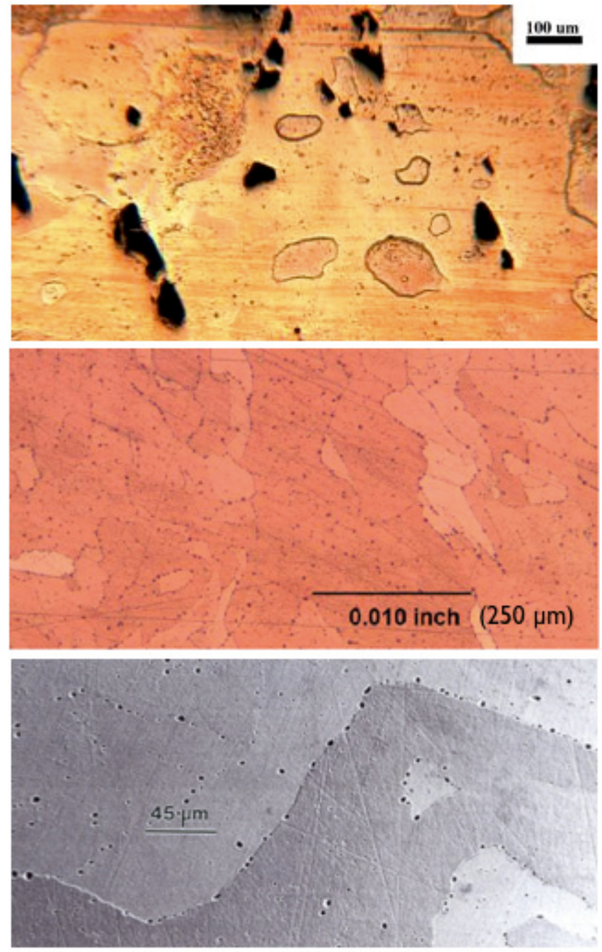

Figure 2: Micrograph of the initial high purity copper sample (top) and lower purity copper sample (middle and bottom) at different magnifications.

Post Processing

Currently the Arcam EBM process produces parts with a rough surface finish, typically >200 µm. Although tolerable for external surfaces, and beneficial for the cooling channel surfaces, it is not suitable for internal RF surfaces, typically requiring secondary machining. Additionally, access to internal surfaces usually requires the cavity to have a joint. For these reasons we have explored secondary finishing and joining techniques.

Initial electron beam glazing and welding test, using JLab's modified Sciaky electron beam welder, had mixed results. EB glazing, or re-melting of the surface layer, has been shown to improve surface finish in copper and niobium cavities [5]. A defocused electron beam was used to melt the surface layer of an OFE copper plate and, using the same parameters, a smaller EBMed copper plate. As can be seen in Figure 3 the EBMed plate responded quite differently, with significant outgassing occurring. Test welds (also visible in Figure 3) were more encouraging, behaving similarly to the wrought OFE material.

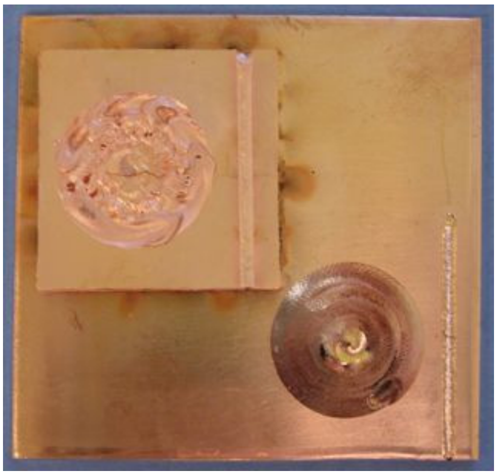

Figure 3: EB surface melting (overlapping spirals) and weld test (vertical lines) conducted on an OFE copper plate (lower right) and EBMed copper plate (upper left).

PHOTOINJECTOR DESIGN

An existing re-entrant gun design [6], scaled to 1497 MHz, and fitted with shaped, conformal cooling channels, was used to conduct preliminary thermal/stress analysis using Ansys coupled with HFSS. Twelve axisymmetric shaped channels and one around the pumping port provide cooling. SFF allows the use of shaped, conformal cooling channels resulting in enhanced heat transfer. Additionally the ability to place, and realize, complex cooling channels allows the addition of large dedicated pumping ports while keeping stresses low.

Two different thermal boundary conditions are applied: free (natural) convection on the copper cavities' outer walls, with a room temperature of 22 °C; and forced convection on the channels' inner walls, with an input water temperature of 22 °C flowing with a velocity of 4 m/sec. The average power inside the gun is 36 kW, considering the power source parameters at cw operation. Figure 4 shows a maximum temperature rise of 43°C, and peak stress of 70 MPa. This, however, occurs in a very small localized area on a sharp corner. Otherwise cavity stresses are well below 50 MPa.

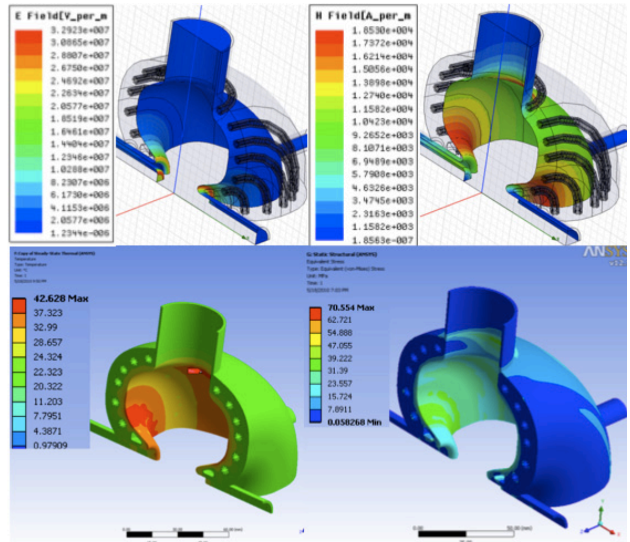

Figure 4: (Top) HFSS model showing cathode electric field of 20 MV/m (left), and surface magnetic field (right). (Bottom) Ansys model of the cavity temperature (left) and stress (right) distribution at P_{ave}=36 kW

Material analysis of EBM copper samples and simulations utilizing shaped cooling channels possible through the use of SFF provide encouraging results for the realization of a very high duty factor, high gradient photoinjector.

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