A NOVEL FABRICATION TECHNIQUE FOR THE PRODUCTION OF RF PHOTOINJECTORS*

P. Frigola, R. Agustsson, S. Boucher, A. Murokh, RadiaBeam Technologies LLC, Los Angeles, CA, U.S.A.
J. Rosenzweig, G. Travish, UCLA Department of Physics and Astronomy, Los Angeles, CA, U.S.A.
L. Faillace, Universita degli Studi di Roma "La Sapienza", Roma, Italy; INFN, Frascati, Italy
D. Cormier, T. Mahale, NCSU Department of Industrial Engineering, Raleigh, North Carolina, U.S.A

Abstract

Recent developments in Solid Freeform Fabrication (SFF) technology may make it possible to design and produce near netshape copper structures for the next generation of very high duty factor, high gradient radio frequency (RF) photoinjectors. RF and thermal management optimized geometries could be fully realized without the usual constraints and compromises of conventional machining techniques. A photoinjector design incorporating SFF and results from an initial material feasibility study will be reported.

INTRODUCTION

Very high rep rate, high gradient photoinjectors are a critical component of the next generation of accelerators for high-energy electron beam applications [1-3]. The design of RF photoinjectors for advanced applications must take into account requirements of beam dynamics, RF power, and thermal management.

The first challenge of high gradient operation is how to achieving high fields without breakdown; this is answered with optimized cavity shape and coupling geometry, material quality, care in surface machining and handling, and maintenance of excellent vacuum. Beyond the issue of breakdown one finds further challenges associated with the handling of the high average RF power in these devices. Nearly all of the applied RF power input to the gun is deposited on the cavity walls, as the RF fields generate surface currents in the cavity walls that result in ohmic losses. These ohmic losses, which scale with the square of the accelerating gradient, present significant thermal engineering problems. First, the structure must be able to withstand transient pulse heating effects. Second, is the issue of handling the average dissipated power, as the cooling system must be robust enough to control the structure temperature to within 0.1° C. This tight temperature control is required to keep the system on resonance with minimal change in the RF phase response of the cavity that can arise due to general temperature-related expansion, or to local thermally-induced distortions.

The key limitation on the rep rate of photoinjectors is thus cavity cooling. The magnetic field magnitude B at the walls provides an indication of areas of high ohmic power loss density, which is proportional to the square of the surface current, and thus to B^2. Areas such as the irises and the RF couplers, due to their location and size, are exceedingly difficult to adequately cool in designs making use of conventional fabrication techniques. We are therefore led to explore new manufacturing methods when considering the next generation of high average power RF photocathode guns.

RadiaBeam Technologies' innovative design and use of SFF techniques allows for the fabrication of RF and thermal-management optimized photoinjector geometries without the usual constraints and compromises of conventional fabrication techniques[#].

FABRICATION PROCESS

SFF technologies employ so-called rapid prototyping layer methods to allow for virtually any geometry to be physically constructed. Rapid prototyping refers to a group of techniques used to quickly fabricate a part layer-by-layer using 3D computer aided design (CAD) data. These techniques are common today throughout industry, providing a quick and accurate way for designers and engineers to visualize, optimize, and fabricate parts directly from CAD models. However these methods have largely been limited to production of parts made from either thermoplastics or special sintered (not fully-dense) metals. The direct metal SFF technique explored in this paper, Arcam's Electron Beam Melting (EBM) [4], is similar to rapid prototyping technologies in its approach to fabrication. However, Arcam EBM is unique in that it can produce fully-dense metal components with properties similar to or better than that of wrought materials [5].

EBM Build Process

In the Arcam EBM process, powder metal is spread over a vertically adjustable surface. A computer guided electron beam then traces the cross section of the modeled part, first heating then melting and forming the first layer. The surface is then lowered and the process repeated for each successive layer, forming the three-dimensional object modeled. A video, showing the EBM process in action, is available for viewing in Ref. [6]. Table 1 shows the technical parameters for the Arcam EBM S12. Because an electron beam is used to melt the powder

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metal, the object must be built in vacuum. A benefit of this requirement is that the use of vacuum provides a clean environment, resulting in excellent material characteristics. Additionally the vacuum provides a thermally insulated and controlled environment, which improves part stability [7]. Two other features of the Arcam EBM process are particularly well suited to the fabrication of photoinjectors. The first is the significantly higher energy efficiency (lower operating cost and faster build times) offered by the use of an electron beam over a laser beam in the processing of highly reflective metals. The second is an attribute Arcam's EBM build procedure, where the surrounding loose powder serves as a support for subsequent layers, allowing for the generation of unsupported complex shapes with downward facing geometries. This feature is critical for the formation of the types of shaped, conformal cooling channels employed in our photoinjector design.

Table 1: ARCAM EBM Technical Data [7]

Max build size	200 x 200 x 180mm
Accuracy	+/- 0.4 mm
Melting speed	Up to 60 cm^3/h
Layer thickness	0.05-0.2 mm

Secondary Machining

Arcam EBM process produces parts with a texture resembling that of a sand casting, therefore conventional machining is needed to bring the part to final dimensions and surface finish. Note, however, that the surface of the internal cooling channels will be left in the as-EBMed condition. Benefits from the increased surface area and roughness are expected to enhance turbulent flow, and thus enhance heat transfer. These benefits will far outweigh the increased pumping pressures needed to overcome the added flow resistance.

PHOTOINJECTOR DESIGN

An initial design for a 100 Hz RF Gun utilizing SFF technology has been developed in a RadiaBeam/UCLA/INFN collaboration. The photoinjector design will be described in detail in Reference [8]. In Figure 2 a rendering of the photoinjector gun is shown with shaped conformal cooling channels. Such shaped, conformal channels would result in greatly enhanced heat transfer and more uniform cooling (no hot spots). Furthermore, the cooling channels can be designed and built to avoid going through braze/vacuum joints. These are features that are possible only with SFF techniques.

Thermal analysis of the 100 Hz RF SFF Gun has been carried out by using ePhysics2 [9] coupled with HFSS [10]. Six axisymmetric, conformal channels and four around the coupling iris region provide cooling, as shown in Figure 2. Two different thermal boundary conditions are applied: free (natural) convection on the copper cavities' outer walls, with a room temperature of 24 °C; and forced convection on the channels' inner walls, considering an input water temperature of 24 °C flowing with a velocity of 4 m/sec. The average power inside the gun is 3 kW, considering the power source parameters and a 100 Hz repetition rate.

Comparing the case of a fairly standard geometry, with circular cross-sectional dia. of 6 mm, to that of the shaped, conformal and "snake" geometry available only through SFF, we see that star-shaped cross section and snake geometry allows cavity wall temperatures to be kept significantly lower than the case with cylindrical channels, by 25 °C. Assuming the same overall temperature increase, this yields the immediate possibility of pushing the rep rate up to 170 Hz.

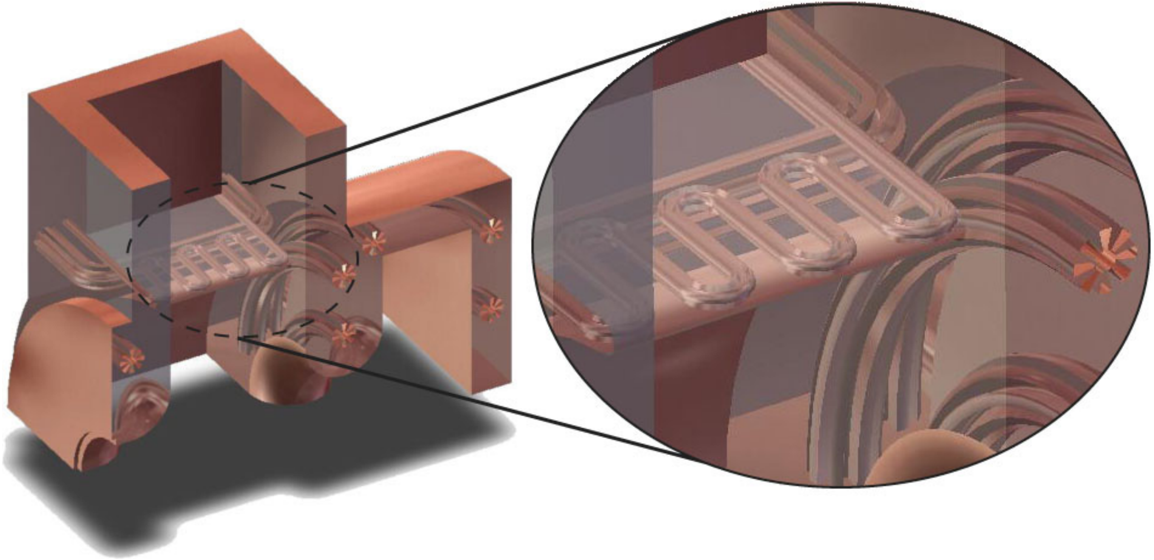

Figure 2: 3D CAD rendering of a photoinjector gun incorporating shaped, conformal cooling channels. Detailed image shows complex cooling geometry placed on the input coupler.

MATERIAL FEASIBILITY STUDY

A number of samples were successfully fabricated at NCSU’s Edward P. Fitts Department of Industrial and Systems Engineering using an Arcam EBM S12 machine. To the authors’ knowledge, this is the first time the feasibility of manufacturing very high purity copper parts using EBM SFF has been shown. An initial visual inspection of the samples showed successful melting of layers with no obvious voids or cracks. Figure 3 shows a photograph of the EBMed samples.

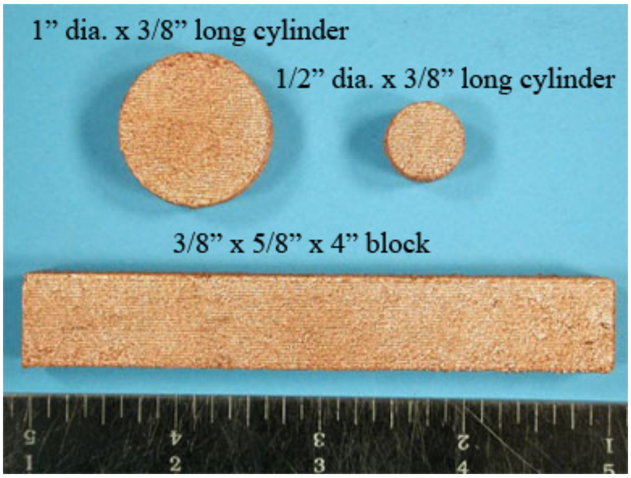

Figure 3: Photograph of the fabricated samples in the as-processed condition. Note the “sand” texture appearance.

Metallographic analysis was carried out on a ½” dia. x 3/8” cylinder to reveal its microstructure. A cut parallel to the flat face of the cylinder (transverse cut) is made revealing the internal surface. An additional cut, across the diameter (longitudinal cut), is made splitting the cylinder in two.

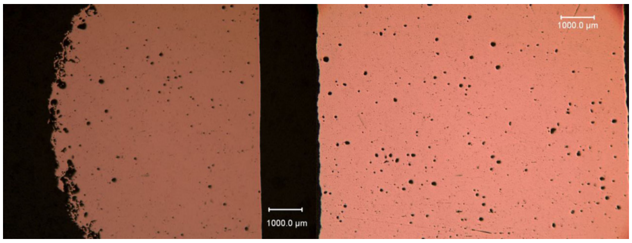

Figure 4: Microstructure of the EBMed copper cylinder showing transverse (left) and longitudinal (right) cross sections.

As evident in Figure 4, the initial samples exhibit significant porosity. However, close microstructural examination appears to show complete interlayer fusion. Additional runs, each having slightly different EBM process parameters, were carried out to reduce porosity. Although full density was not achieved in the initial feasibility study, evidence of decreased porosity was observed. Based on these results and previous experience with the successful fabrication of GRCop-84 (a copper based alloy) by NCSU [11], we are confident that the porosity exhibited in the samples is a correctable problem.

Having successfully demonstrated the feasibility of producing copper parts using Arcam’s EBM process, future work will focus on optimizing the EBM process parameters and powder material properties to obtain fully dense, high purity copper parts. These process improvements will be followed by additional optimization of microstructure, grain size, and material properties, with the ultimate goal of producing EBM copper parts comparable to those made from wrought OFE class 1 copper.

CONCLUSIONS

The use of EBM SFF can provide wide, unmatched flexibility in cooling channel design and fabrication of high average power RF structures. Although further work is necessary to bring the EBMed material properties inline with RF and vacuum requirements for high gradient operation, innovative features such as star-shaped cross-sections, and arbitrary channel paths, allow us to consider RF photoinjector operation approaching 1kHz.

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