DEVELOPMENT OF SOLID FREEFORM FABRICATION (SFF) FOR THE PRODUCTION OF RF PHOTOINJECTORS*

P. Frigola, R. Agustsson, S. Boucher, A. Murokh, RadiaBeam Technologies LLC,
Los Angeles , CA, U.S.A.
H. Badakov, A. Fukasawa, P. Musumeci, 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

Electron beam based additive fabrication techniques have been successfully applied to produce a variety of complex, fully dense, metal structures. These methods, collectively known as Solid Freeform Fabrication (SFF) are now being explored for use in radio frequency (RF) structures. 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 RF photoinjectors. The SFF process discussed here, Arcam Electron Beam Melting (EBM), utilizes an electron beam to melt metal powder in a layer-by-layer fashion. The additive nature of the SFF process and its ability to produce fully dense parts are explored for the fabrication of internal cooling passages in RF photoinjectors. Following an initial feasibility study of the EBM SFF process, we report on the results of recent material optimization, plans to fabricate a copper photocathode and new designs for a high duty factor photoinjector utilizing SFF technology.

INTRODUCTION

Very high average power, high brightness photoinjectors are a critical component of the next generation of accelerators systems, such as X-ray free-electron lasers (FELs) [1], inverse Compton scattering (ICS) [2], and energy recovery linacs (ERLs) [3,4]. Normal conducting RF photoinjectors have a proven track record of generating the high quality beams necessary in these systems, but are limited to relatively low repetition rates due to the ohmic losses on the cavity walls. Thus a key issue for high average power, normal conducting photoinjectors is effective structure cooling.

RadiaBeam has been exploring an innovative design and use of Solid Freeform Fabrication (SFF) techniques allowing for the fabrication of RF and thermal-management optimized photoinjector geometries without the usual constraints and compromises of conventional fabrication techniques[#].

EBM FABRICATION PROCESS

SFF technologies employ so-called rapid prototyping layer methods to allow for virtually any geometry to be physically constructed. The direct metal SFF technique explored in this paper, Arcam's Electron Beam Melting (EBM) [5], is similar to rapid prototyping technologies in its approach to fabrication. However, Arcam EBM SFF is unique in that it can produce fully-dense metal components with properties similar to or better than that of wrought materials [6].

EBM Build Process

In Arcam's EBM process, powder metal is scraped over a vertically adjustable surface. An initial pre-heating of the entire powder layer is performed at 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. It should be noted that this process is fast, taking only a few seconds. After the preheating is complete, the electron beam current is increased and/or scan speed decreased. A computer guides the electron beam and traces the cross section of the modeled part, thus melting and forming the first layer. The surface is then lowered and the process repeated for each successive layer. A video, showing the EBM process in action, is available for viewing through the link Ref. [7]. Table 1 shows the technical parameters for the Arcam EBM S12. Because an electron beam is used to melt the powder 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 [8]. 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

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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 [8]

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 are expected to outweigh the increased pumping pressures needed to overcome the added flow resistance.

PHOTOINJECTOR DESIGN

The advantages afforded by using Arcam's EBM SFF to manufacture RF photoinjectors are considerable. The addition of embedded, conformal cooling channels will be an immediate improvement to many current designs. Although some state-of-the-art photoinjectors currently use conformal cooling channels [9, 10, 11], such features come at a very high price and complexity due to the desire to avoid water-vacuum transitions and numerous circuits and brazing cycles required to accomplish them using conventional manufacturing techniques. In Figure 1 a conceptual design of a photoinjector gun is shown with shaped conformal cooling channels. Such shaped, conformal, axysymmetric 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.

Designs for a 500 Hz RF Gun utilizing SFF technology are currently being developed in a RadiaBeam/UCLA/INFN collaboration. The photoinjector design will be described in detail in Reference [12].

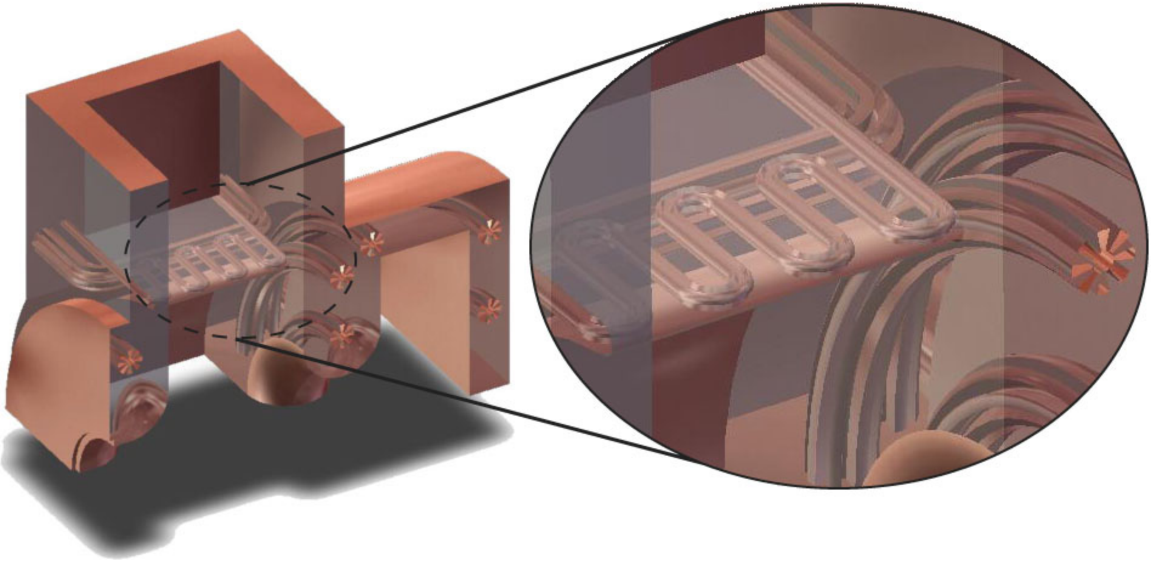

Figure 1: Conceptual 3D CAD of a photoinjector gun incorporating shaped, conformal cooling channels. Detailed image shows complex cooling geometry placed on the input coupler.

MATERIAL OPTIMIZATION

Initial feasibility studies, conducted at NCSU's Edward P. Fitts Department of Industrial and Systems Engineering using an Arcam EBM S12 machine under a RadiaBeam Phase I DOE SBIR, were successful in fabricating pure copper parts using the EBM process [13]. It is worth noting that this was the first time pure copper parts have been fabricated using Arcam EBM process. Although full density was not achieved in the initial feasibility study, microstructural examination showed complete interlayer fusion in the fabricated samples. This led us to believe that the porosity exhibited was a correctable problem given more time to conduct additional optimization of process parameters.

A new set of runs, carried out at NCSU, and internally funded by RadiaBeam, benefited from the installation of a residual gas analyzer (RGA) in the Arcam EBM machine, not present during the initial feasibility study. With further fine tuning of process parameters, this last set of runs resulted in a marked improvement in the density of the EBM copper. Figure 2 shows an optical micrograph taken during the final runs showing virtually fully dense EBMed copper.

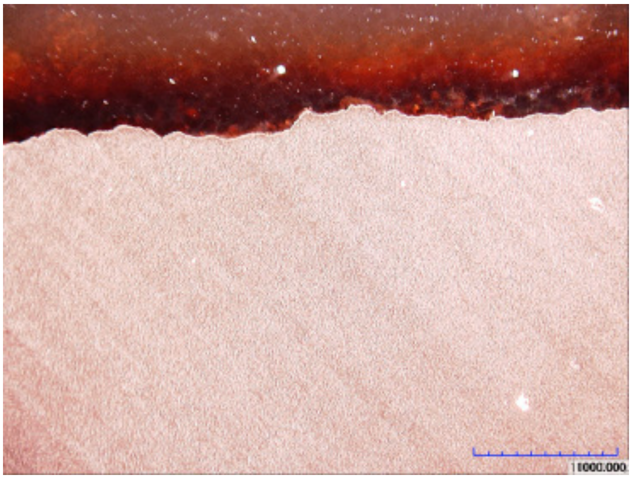

Figure 2: Optical micrograph of EBMed copper sample, shown with 1000 µm reference scale. The top of the sample shows the edge of the mounted copper piece.

Detailed metallographic examination has not yet been performed. However, comparison of our latest results with those taken in the feasibility study serve to illustrate the vast improvement in decreased porosity of the copper using the new EBM process parameters (See Figure 3).

While there is still a certain amount of development work needed to optimize the processing parameters for arbitrary work piece geometries, the current copper process parameters appear to be nearly optimized.

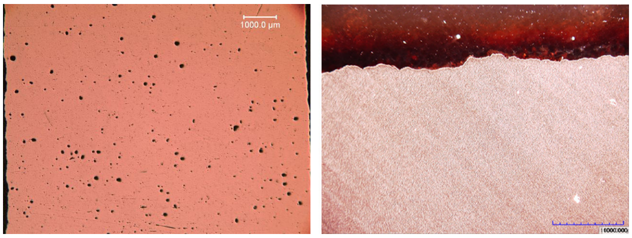

Figure 3: Comparison of copper microstructure (both shown with 1000µm scale) from the original feasibility study (left), and the virtually fully dense microstructure from the latest set of runs (right). Note that the original micrograph (right) was taken after polishing and waxing (but before etching), while the one on the left was only roughly polished.

CONCLUSIONS/FUTURE PLANS

Future plans will include the fabrication and RF testing of an EBMed cathode suitable as a drop-in replacement in the UCLA 1.6 cell photoinjector. Additional testing will also be carried out to quantify the extent of channel erosion as a function of water flow speed.

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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