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ADDITIVE MANUFACTURING OF COPPER RF STRUCTURES FOR PARTICLE ACCELERATOR APPLICATIONS*

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Abstract

Particle accelerators, employs many complex rf structure made of copper. These structures are used for particle acceleration, and deflection. Recent advances in additive manufacturing are opening the possibilities of building these copper structure with the help of additive manufacturing. Additively manufactured (AM) copper structures offer the usual well-known advantages in terms of relaxation of physical design (shape) constraints, and thus hold the promise of making complex shaped rf structures. To rapidly demonstrate the potential to additively manufacture accelerator structures with existing technology, a bound metal deposition (BMD) metal 3D printer is used to build a c-band structure and scaled model of 201.25 MHz RFQ structure.

INTRODUCTION

Many particle accelerators use normal conducting accelerator structures for charged particle acceleration. These copper structures can be challenging and costly components of an accelerator facility. Cavities are mostly fabricated in half cells and then joined by complex processes (brazing, welding). The shape of these cavities is well-optimized for electromagnetic fields keeping in mind conventional manufacturing methods. Design changes as a result of measured versus modelled RF response may require scrapping and starting over.

Recent advances in additive manufacturing open the possibility of optimizing the shape without concern about the manufacturing. Additive manufacturing provides the opportunity to manufacture faster, with more flexibility in design, cooling channel optimization, and potentially lower cost. The challenges are i) UHV compatibility ii) Mechanical strength iii) Surface roughness iv) Electrical conductivity v) Dimensional accuracy vi) RF properties at higher power.

Several particle accelerator labs have R&D efforts to print accelerator components and test them for accelerator environments. A Radio Frequency Quadrupole (RFQ) of 750 MHz and 4 vane type was additively manufactured and getting tested [1,2], a 433 MHz IH-type cavity was 3-D printed, and tested for accelerator applications [3], a klystron circuit has been designed, 3-D printed and tested [4], and mechanical properties of metal printed with additively manufactured techniques were explored [5,6].

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Additive manufacturing produces three-dimensional parts with the help of a computer-aided design and adding materials layer by layer. Currently, there are two main methods to additively fabricate the metallic structure: i) Laser powder bed fusion method [7], where laser power is used to melt the metallic powder and print a structure. Process parameters (layer thickness, scanning speed, laser power, and scanning strategy) have a significant effect on printed materials' properties. This method has some challenges associated with it particularly the absence of mechanical pressure which leads to the discontinuous melting of tracks and the generation of poor and uneven surfaces [7]. Due to the high reflectivity of copper, most of the laser power is reflected and a green laser source was chosen to print a copper RFQ [1,2]. ii) The second method is the electron beam melting method where a high-power electron beam is used to fuse the metallic powder and print a layer-by-layer structure out of it [8]. There are some promising advantages of (EBPF) such as 99% purity copper fabrication and electrical conductivity close to conventionally fabricated copper [9]. There are a few challenges associated with this process like the smoke phenomenon which results in the spatial resolution and the surface finish inferior to L-PBF parts.

The surface of additively manufactured components must be chemically treated as this structure has a roughness on the order of microns while accelerator components (particularly cavities) require much smoother surfaces. A chemical procedure such as electropolishing (EP) has to be developed for additive manufacturing technology similar to the development of subtractive manufacturing technology for producing a defect-free and smooth surface [10].

Multiple accelerator applications accelerate particles to significant energies within a limited footprint, naturally calling for a high acceleration gradient. AOT division at Los Alamos National Laboratory (LANL) has recently commissioned CERF-NM, the C-band high gradient test facility. The purpose of the facility is to conduct a comprehensive study of the material science and physics of high gradient operation of C-band NCRF accelerating cavities and identify materials and fabrication methods that would allow us to produce accelerating cavities operating at ultra-high gradients [11,12]

We are additively manufacturing a 2-cell C-band accelerating structure with distributed RF coupling. It is designed to accelerate protons at 1.6 GeV ($\beta = v/c = 0.93$) [13]. A traditional copper version of the structure was fabricated using precise machining. It was tuned to 5.712 GHz and tested at high gradients [13] at the LANL C-band RF test stand. We plan to test the AM version of the structure for high vacuum and resonance frequency

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accuracy. This structure would later be electropolished and tested for high gradient RF performance.

EXPERIMENTAL SETUP

The experiment is conducted on multiple additive manufacturing machines to evaluate the advantages and challenges unique to each printing method on the direct manufacture of accelerator structures.

The first experiment is conducted at one of the additive manufacturing centres at Los Alamos National Laboratory. The designed C-band structure is adapted to a thin-walled structure suitable additive manufacturing using the Bound Metal Deposition (BMD) method. The BMD filament consists of metal powders suspended in a polymer and wax binder. This method extrudes the heated filament onto a build plate to form a green part, which is then chemically washed and sintered to remove the binder constituents and fuse the metal powder to form a consolidated metal part.

BMD processing requires significant support structure for surfaces of the part at angles of more than 45° from vertical. This support structure can be difficult to remove, especially in blind passageways as in the C-band structure and leaves residual surface roughness at connection points. As a result of this constraint, the C-band structure is split into two halves that are then fused during post processing.

The second experiment is conducted on an LPBF machine. Manufacturing is performed on an EOS M290 using IN718 feedstock. Post printing the IN718 component is stress relieved and then machined off-of the build platform. Internal support structure is mechanically removed from the component. The component is then electroplated with copper and the surface is electropolished to application requirements.

The third experiment is conducted on an Electron Beam Melting (EBM) machine. An Arcam Q10plus v2.0 was used to print high purity copper. The resulting component does not require support structure but does have a worse overall surface finish compared to LBPF and BMD methods.

Printed and finished components are then characterized at specified temperatures for radio frequency performance under high vacuum conditions.

EXPERIMENTAL RESULTS

C-Band structures have been printed using BMD printing using whole component and particle component approaches. The green components have notable surface roughness associated with the minimum filament deposition diameter and are expected to require significant surface finishing to maximize the quality factor of the structure. Further, the BMD process was observed to linearly scale the CAD geometry by approximately 15% about the centroid of the part. This scaling accommodates for anticipated component shrinkage during the binder removal and sintering processes. The impact of this scaling on final cavity geometry will be evaluated as prototype components are fully processed and tested for resonance frequency accuracy.

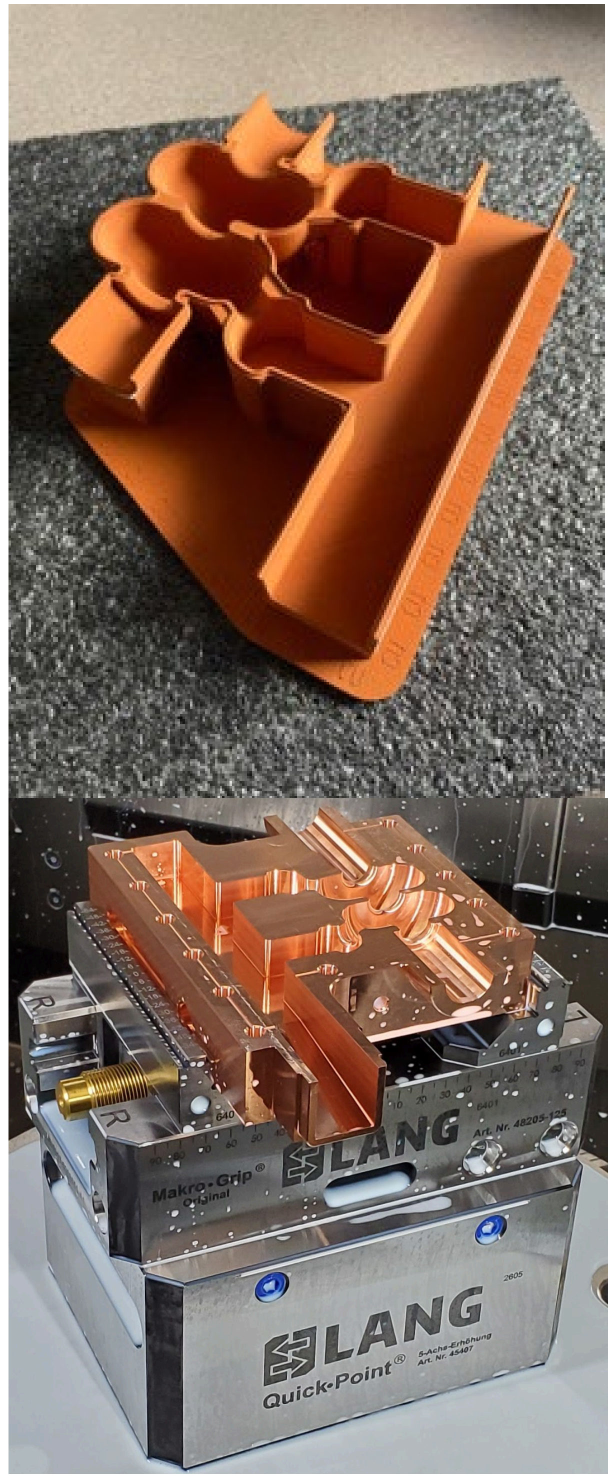

Figure 1: Half printed C- Band cell (Top) Conventionally fabricated C-band cell (Bottom).

Components from the second and third experiment have not yet been produced, however, both LPBF and EBM yield components with high expected surface roughness and will likely require similar post processing rigor. The C-band cavity printed from the

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first method (BMD) is shown in Fig.1. The 3-D printed cavity is shown in top while conventionally manufactured cavity is shown in bottom.

CONCLUSION

We are additively manufacturing copper rf structure to use in particle accelerators. We have chosen to build a C-band TM_{010}-type cavity of 5.712 GHz frequency. The infrastructure to test these cavities at high power exists at LANL. Initially, these structures will be tested for vacuum compatibility and resonance frequency accuracy. Once these parameters are established a chemical procedure will be established and optimized to obtain smooth surfaces on these structures and finally these structures will be tested for their rf performance at high powers.

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