Design and Test of Copper Printed RF Cavities

Christopher Nantista, Diana Gamzina; SLAC National Accelerator Laboratory, Menlo Park, CA 94025
Christopher Ledford, Timothy Horn; CAMAL, North Carolina State University, Raleigh, NC 27695
Paul Carriere, Pedro Frigola; Radiabeam Technologies, Santa Monica, CA 90404

Abstract: *Additive manufacturing of high-quality copper using electron beam melting techniques has demonstrated significant progress toward suitability for production of vacuum electronics components. Additively manufactured low oxygen level copper wafers, as printed and annealed, have been tested in an RF cavity designed for surface resistivity measurements. Strings of coupled cavities for S-band and X-band traveling wave tubes have been designed for vertical additive manufacturing in powder bed systems, enabling significant cost reduction. The S-band RF cavity string design has been additively manufactured, processed and RF tested.*

Keywords: RF cavities; additive manufacturing; oxygen free high-conductivity copper, design for additive manufacturing.

Introduction

Current manufacturing of vacuum electronics requires machining of individual RF cavity sections, precise alignment and assembly of manufactured sections, and bonding of sections through high temperature brazing. Additive electron beam copper melting has a potential to dramatically reduce manufacturing time and cost by eliminating the need for manufacturing of components individually (conventionally manufactured coupled cavity travelling wave tube requires over 100 sections). Minimizing the need for skilled technical labor at assembly and bonding stages as well for high temperature hydrogen environment brazing operations. Additive manufacturing has a potential to reduce cost of coupled cavity travelling wave tubes by 50% or more.

Copper additive manufacturing has gained significant attention over the last few years, with multiple groups in U.S., Germany and U.K. developing the process utilizing laser as well as electron beam melting techniques: near full density (99.9%) copper has been demonstrated. Furthermore, commercial machine suppliers are starting to support pure copper as a development material. Thus far, electron beam melting has been the most successful at producing low oxygen (~50 ppm) copper suitable for manufacture of ultra-high vacuum components. Demonstration of full material density and low oxygen content has led to demonstration of ultra-high vacuum and hydrogen environment brazing compatibility. This provided a foundation for considering manufacture of RF cavity strings suitable for RF testing.

Copper Quality

Density: Near full density (99.9%) copper has been manufactured from 25-50 micron sized copper powder utilizing spot melting technique. Remnant porosity consisted of few micron sized pores distributed through the material, most likely resulting from porosity within the starting copper powder material. Helium leak tests of 2 mm thick copper samples show 2×10^{-11} Torr-l/s leak rates. Further improvement in copper powder quality as well as thermal material post processing can be employed to achieve full copper density.

Oxygen Content: Through significant development effort oxygen content of additively manufactured components has been reduced to 50 ppm. Ledford, *et al.* [1] reported a study on the mechanism of oxygen content reduction in additively manufactured copper components. Their findings conclude that pretreatment of copper powder in hydrogen can reduce oxygen content in manufactured parts significantly. The authors also suggest that there is an opportunity to reduce oxygen content during the printing process itself. This approach may benefit spreadability of the powder: surface oxides help keep the copper powder from agglomerating during the powder spreading process.

Surface Resistivity

Skin depth for microwave to millimeter wave frequencies varies between a few microns and a few hundred nanometers in copper. As a result, surface features such as surface roughness that are larger than the skin depth can have a significant effect on surface losses. Optimized copper electron beam melting techniques produce an average surface roughness on the order of 20 microns. To quantify effects of surface roughness on RF losses, a dome-like cavity [2] originally developed for SRF studies was employed to deduce from the measured quality factor the loss contribution from high surface roughness samples.

It was found that additively manufactured surfaces can be up to six times as lossy as highly polished copper at ~11.4 GHz. Sonication to remove loose particles stuck to the surface can bring this loss ratio down to about five. High temperature (900 °C) annealing in ultra-high vacuum can reduce surface resistivity losses to two to three times that of highly polished copper. Addition of chemical or mechanical polishing or utilization of smaller copper powder have the potential to reduce the losses even further. RF test set up for evaluation of the surface roughness effects on RF losses is shown in Fig.1.

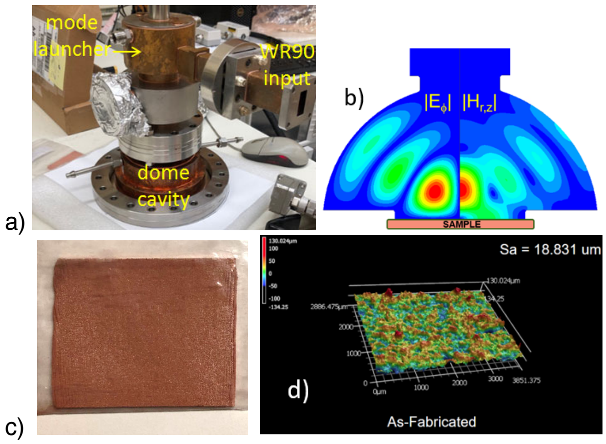

Figure 1. a) Hemispherical cavity test set-up, b) Electromagnetic field patterns in the hemispherical cavity, c) Printed copper sample, d) Surface roughness measurement of as-fabricated copper sample.

RF Cavities: Design and Test

Electromagnetic design is generally driven by optimization for highest device performance (power, efficiency, field gradients) and suitability for conventional manufacturing processes. Additive manufacturing promises to open opportunities for more complex designs than have been possible to date. While this advantage will come to fruition in the future, presently RF cavities must be designed to accommodate restrictions imposed by the additive manufacturing process. For example, each melted copper layer must be supported and heat-sunk to a layer underneath it: this limits possibility of creating surfaces horizontal to the printing platform and rules out downward hanging features that would initially be disconnected. As development of additive manufacturing for vacuum electronics matures, the need for engineering that encompasses knowledge of electromagnetic design as well as printing platform capabilities will grow.

Initial steps to address Design for Additive Manufacturing (DfAM) have been taken in designing a string of cavities for a coupled-cavity travelling-wave-tube (CCTWT) amplifier. Starting with a conventional design, the downward nose-cones were eliminated and the horizontal disk faces have been conically angled, allowing the RF cavity string to be fabricated in a vertical manner on the machine platform. Corners and edges had also to be reasonably rounded. Capability of printing RF cavity strings vertically is one of the key enablers of over 50% cost reduction: six X-band cavity strings can be printed on a 4 inch diameter experimental machine platform (see Fig. 2 (a) and (b)). As advances in additive manufacturing platforms and processing techniques improve, horizontal surfaces may become easier to produce. Fig. 2 (c) shows an additively manufactured cavity string printed in a vertical manner and sliced open to evaluate its quality. Features supported only near their tops (e.g. symmetric beampipe iris extensions) remain challenging to produce.

S-band RF cavity strings were tested to verify their performance: there was a good agreement between designed and measured operational frequency. Transmission parameters measurements are in progress for S-band and X-band cavity strings.

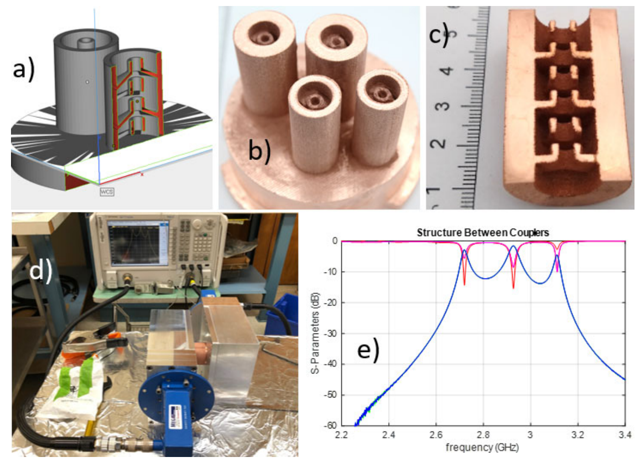

Figure 2. (a) 3D model of X-band RF cavity strings, (b) Printed copper cavities, set of four with space for two more, (c) Sectioned coupled cavity string demonstrating horizontal surface printed in a vertically oriented structure, (d) S-band periodic cavity structure on network analyzer with roughly matched launchers, (e) Electromagnetic passband response of S-band cavity string.

Conclusion

Significant progress has been made in development of RF design techniques of manufacturing processes for production of RF cavities via electron beam melting of copper. Further focus is needed on evaluation of outgassing parameters, surface roughness improvements and powder quality improvements to offer high-quality verified vacuum electronics components suitable for operation in high-power or high-gradient environments.

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References

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