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ADDITIVE MANUFACTURING OF 6 GHz SEAMLESS SRF COPPER CAVITIES: PRINTING, SURFACE TREATMENTS AND PERFORMANCE INVESTIGATIONS*

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Abstract

Traditionally produced Superconducting Radio Frequency (SRF) cavities are characterized by many limiting drawbacks, such as welding lines and poor reproducibility of their properties. Additive Manufacturing (AM), and in particular Laser Powder Bed Fusion (LPBF), may overcome these issues: with this technology, it is possible to create seamless components with reproducible characteristics. 6 GHz cavities cannot see internal supports because of the impossibility to remove them mechanically. On the other hand, the down-skin self-supporting surfaces are extremely rough and unsuitable for the intended application.

Indeed, very smooth surfaces are required since copper cavities are internally coated with superconducting films (like Nb, Nb_3Sn, etc). In this work, several surface treatments have been performed and studied; tests like tightness, resonant frequency and internal inspections have also been carried out.

INTRODUCTION

6 GHz SFR cavities are very suitable as laboratory test prototypes. Typically, cavities are made of bulk niobium since it has the highest critical temperatures (9.25 K) [1] among the pure metal superconductors.

In this work, instead, Nb-coated cavities are concerned: the chassis of a cavity is made of copper, because of the excellent thermal conductivity, and only a thin layer of superconducting material, like Nb, is deposited internally via magnetron sputtering. Such cavities would potentially have superior performance with respect to the Nb cavities [2].

The employment of LPBF technology to build the copper chassis was investigated, in other to evaluate the pros and cons of the process.

Such a technology is not free of difficulties, starting from the raw material: pure copper is highly reflective, especially in the IR range. Thus, when the material is processed with machines provided with an IR laser (λ~1060 nm) the source energy is reflected almost entirely. Moreover, the excellent thermal conductivity of pure copper leads to a fast dissipation of energy, thus it is very difficult to realize very dense parts [3-5].

The surface roughness is high in LPBF-ed parts and this is peculiarly limiting in case smooth surfaces are needed.

Nowadays, the research in post-printing finishing processes is intense and many works can be found in the literature, for different materials and geometries. Specific investigations on the printability and smoothening AM-ed pure copper prototypes for 6 GHz SRF cavities can be found here [5]. In this work we have investigated the printability of full-length cavities, and post-printing processes were carried out to smooth the internal surfaces and optimize the procedure preliminary developed in [5], to evaluate also the reproducibility of the results in pieces obtained with different machines and printing parameters.

MATERIALS AND METHODS

For this preliminary study, two 6 GHz cavities were created using a commercially pure copper powder, the printing machine was the TRUMPF TruPrint 5000 (TRUMPF, Ditzingen, Germany), provided with a green laser of λ=515 nm and a maximum nominal power of 1 kW. The cavities will be indicated as T1 and T2 (as in Fig. 1).

Figure 1: Cavities T1 and T2.

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The prototypes were analysed and treated to smooth the internal surfaces. Many tests were performed also in between the different finishing stages:

- Computed Tomography (CT);
- Room-temperature frequency test;
- Vacuum leak test;
- Internal inspections (cavities were optically investigated thanks to a sonde equipped with a small camera, and pictures were taken to analyse the quality of the surface);
- Material loss estimate.

Surface Treatments

T1 cavity T1 was subjected to a traditional mass finishing process[1] (MF, details are reported in Table 1) at Rösler Italiana S.r.l. (Concorrezzo, MB, Italy). After this, other processes were performed at INFN-LNL (Legnaro, PD, Italy): electropolishing (EP) was carried out in two steps. The first step lasted 80 minutes, in which the chemical agent flowed inside the cavity, which was maintained in a vertical position. The second step was then performed for 67 minutes keeping the cavity upside-down with respect to the first step. The cavity was then treated with Vibro-tumbling (VT): the system worked at 190 Hz, and an etchant solution was used to increase the polishing rate: a first step was conducted for 60 minutes using cylindrical SiC as an abrasive part. For the second step of VT, SiC angle cut tristar abrasive was used. The second step lasted less than 30 minutes.

T2 cavity The cavity T2 was subjected to the MF treatment, but also a chemically-assisted mass finishing treatment was performed (C-MF, in Table 1). In order to furtherly improve the quality of the surfaces, an extra-polishing process (ExP) was done. The cavity, as the T1, was subjected to the EP treatments, two steps of 60 minutes each.

Table 1: Details of the Several Processes

Process	Media	Time
MF	Cu needles (2mm x 10mm) + Synthetic diamond powder	80 h
C-MF	RMBD1 05 G + CMP 03/21 L	48 h
ExP	RKH/4 + ZF 322 1% by wt.	32 h
EP	H_3PO_4 + Butanol in 3:2 v.r.	varied
VT	SiC + oversaturated ammonium persulfate	varied

RESULTS AND DISCUSSION

CT scans

The CT scans revealed a weak region in correspondence of the internal fillet (iris), in the down-skin region (Fig. 2). This has been observed in both the T1 and T2 cavities. Such a defect was surely due to the printing process, the layer thickness too high, and/or the printing parameters not properly optimized for the down-skin region of these prototypes, as long as the minimum inclination angle is only 18° with respect to the building platform plane. The most delicate part of the cavities is the upper iris since the region is not supported by any structure.

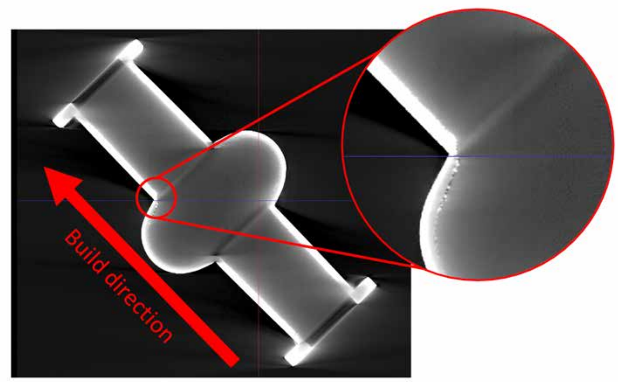

Figure 2: CT scan of the cavity T1, the lack of material in correspondence on the internal fillet can be clearly seen. This was observed also in cavity T2.

Room Temperature Frequency Measurements

Cavities showed very similar frequencies (Table 2), very close in value to the traditionally manufactured cavities.

Table 2: Frequencies Measured at Room Temperature

Cavity	Frequency (GHz)
T1	5.9871875
T2	5.9862500

Surface Treatments

For a better analysis, the discussion must be done separately for each cavity.

T1 cavity This cavity was subjected only to the traditional MF process because the internal inspection showed very deep and punctual defects on the cell surface, such defects were attributed to the aggressivity of the treatments first, but after a detailed inspection we established that the imperfections were concentrated just on one half of the cavity, thus, they were displaced on the down-skin region. The cavity was then tested for leaks detection, and after the tightness has been proved, it was processed at INFN-LNL with EP treatments: after the first step, the sonde inspection revealed very reflective, but still rough surfaces, especially towards the cell equatorial. The down-skin part was evidently rougher than the up-skin side. Surfaces presented also pointy defects, like pitting.

The inspection then showed a very shiny and smooth surface, even if it was still characterized by the presence of macro-roughness and pitting-like defects. The equatorial region was still very rough compared to the other regions. A leak test was repeated and passed.

The cavity was then treated with VT: the resulting surface quality improved significantly and most of the macro-defects were removed with the first stage. A leak test was carried out and once again the cavity proved its tightness

[1] All the media and chemicals used for the mass-finishing and extra-polishing treatments are commercial products sold by Rösler Italiana S.r.l..

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successfully. After the second step, the quality of the surface was furtherly improved and the discrepancies between one half and the other (down-skin and up-skin) decreased distinctly. Internal finishing is visible in Fig. 3.

Up to now, the combination EP+VT seems the best choice, the mass finishing treatments are less effective in reducing the AM defects (porosity) and discrepancies.

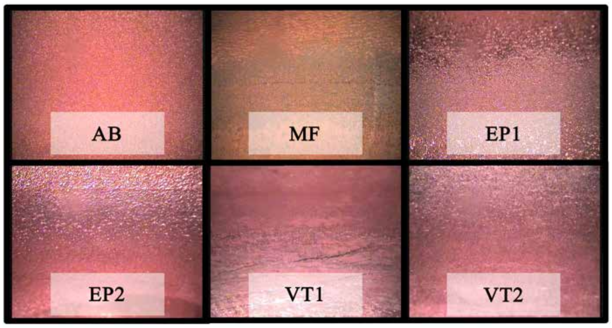

Figure 3: Internal surfaces of T1 in As-Built (AB) conditions, after the mass-finishing treatments (MF), after the EP treatments (EP1 and EP2), and after the VT steps (VT1 and VT2).

T2 cavity As said in the previous section, this cavity has seen also a chemically-assisted mass finishing treatment. Also in this case, after the treatments, the internal surface was still characterized by defects like pores, especially on one half of the cavity (the down-skin). Pores were certainly due to the manufacturing technique, but the finishing process contributed to creating some damages: indeed, in the cut-off region, close to the flange, the abrasive powder created pitting-like holes. Thus, in order to improve the quality of the surfaces, an extra-polishing process was performed. After this treatment, defects were less evident.

The visual inspection revealed a smooth and bright surface with some non-reflective regions in correspondence of the cell (like the one visible in Fig. 4, inside the dashed circle). Some small defects were still present. The smoothening process for this cavity was interrupted since a leak was detected in the iris region after the treatment.

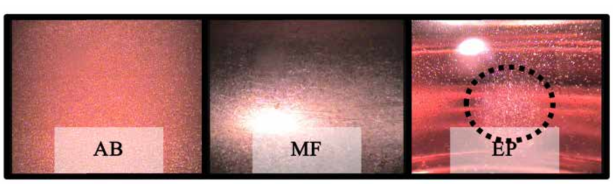

Figure 4: T2 internal surface in As-built conditions (AB), After the mass-finishing (MF) and the EP steps (EP).

The iris is probably the most critical region of an elliptical cavity: it represents a weak point that can easily break during the surface treatments, especially if vibrations are involved during the processes. A reinforcement needs to be introduced to prevent leaks and fractures that make the cavity useless.

Material Loss Estimate

The material loss was quite important, cavities were weighted after each process and the results are reported in Table 3.

Table 3: Material Removed After the Treatments

	Treatment	Removed mass [g]	Removed thickness
T1	MF	3,30	~40 µm
	EP1	4,86	~220 µm
	EP2	4,37	
	VT1	1,24	~38 µm
	VT2	1,96	
T2	MF	3,56	~43 µm
	C-MF	13,56	~165 µm
	EP	3,94	~94 µm

CONCLUSIONS

Due to the peculiar geometry, 6 GHz copper cavities are very difficult to machine and process for making the internal surface ready for the Nb sputtering. After different combinations of mass finishing treatments, EP and VT, the examined AM-ed cavities reached a very smooth and shiny internal finish (especially the T2 cavity), even if some defects due to the additive manufacturing process remained. Porosity is very difficult to remove, thus a thick layer of material must be removed by the finishing treatments. Unfortunately, the geometry makes impossible the roughness measurement in the cell region, thus only the optical evaluation of the surface quality was performed in this preliminary work.

A modification in the original cavities design needs to be done in order to strengthen the iris region.

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