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## High-power comparison among brazed, clamped and electroformed X-band cavities

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### ABSTRACT

We report the building procedure of X-band copper structures using the electroforming and electroplating techniques. These techniques allow the deposition of copper layers on a suitable die and they can be used to build RF structures avoiding the high temperature brazing step in the standard technique. We show the constructed prototypes and low power RF measurements and discuss the results of the high power tests at SLAC National Accelerator Laboratory.

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### 1. Introduction

The high-gradient RF breakdown phenomenon is still a problem. Dedicated research and development has been launched in this field in the linear-collider community [1]. The activity of testing high-gradient RF sections at 11.424 GHz for the next generation of electron-positron linear collider is in progress to investigate breakdown mechanisms, which limit the high gradient performance of RF structures [2].

The activity to design, construct and conduct high-power experimental tests on standing wave (SW) accelerating sections began at INFN-LNF in the framework of a collaboration with SLAC and KEK laboratories. The goal of the collaboration is to assess the maximum sustainable gradients with extremely low probability of RF breakdown in normal-conducting high-gradient RF accelerating structures for particle beam accelerators. An intense technological activity is therefore dedicated to building 11.424 GHz (X-band) accelerating structures, with different materials and methods.

We describe the construction of accelerating structures by the electroforming and electroplating techniques. These techniques allow the production of high-gradient normal-conducting structures without the production step of high temperature brazing. The breakdown rate of electroplated structure was similar to the rate measured in brazed structures of the same geometry and

slightly higher than clamped structures. From experimental results at high power, the best breakdown rates have been obtained using copper structures simply clamped (hard copper) and not brazed or realized by diffusion bonding (soft copper) [2]. More precisely the conclusions reported in the cited reference are that the structures made of soft copper and soft-copper alloys show similar and reproducible behaviour. The breakdown rate was highly correlated with peak pulse surface heating temperature. High power RF tests of the hard copper structures showed some improvement over soft copper but not as dramatically as we expected based on the tests of the pulse heating samples but, unlike the soft Cu structures, pulse heating damage in the hard Cu structures has not been observed.

In the first two sections of the paper we briefly illustrate the production techniques. In the third and fourth section we show the built structures and the low power RF measurement results, while in the last section, we report the results of the high-gradient test at SLAC and compare this structure performance with the performance of the copper clamped and brazed structures.

### 2. Electroforming technique for RF structure construction

Electroforming is an electrolytic procedure through which a layer of copper (Cu), or other metals, is formed on a die that is subsequently removed by a selective chemical etching [3].

Originally this procedure was used to obtain hollow metal structures with large dimensions, for example statues. Presently

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the electroforming is used to produce special components for the space industry, RF devices, waveguides and so on [4–14].

The main steps of the procedure are the following:

- (1) The die on which the Cu will be deposited is machined, including cavities, beam tubes and RF couplers with a surface finish as accurately as required. Generally Al is used to make the die because it can be easily machined and polished (Fig. 1a).
- (2) The die is immersed in an electrolytic solution containing water soluble Cu salts and other chemical compounds and then connected to a negative voltage (Fig. 1b). Some masks made of inert material (as an example polyvinyl chloride-PVC) are also inserted in the bath around the piece in order to homogenise the electric field distribution improving the micro-crystals quality on the device surface. In other words, these materials allow to avoid the Cu deposition of different concentrations around the device determining a uniform distribution deposition [19]. For the sake of completeness, we also inserted some aluminium masks around the stainless steel flanges in order to avoid the unwanted electro-deposition on those [19]. If very thick layers (many millimetres) of Cu are needed the die must be taken out of the bath and polished more than once to assure a Cu layer without defects;
- (3) At the end of the operation the copper–aluminium composite is extracted from the bath, washed and immersed in an etching solution (usually a strong alkaline like the sodium hydroxide, NaOH) to selectively remove the aluminium and leave the copper structure intact. The multi-cell cavity structure, which remains after the etching, with beam tubes and RF couplers, is shown in Fig. 1c.

Other parameters of interest are

- (1) *Deposition rate*: For complex shapes only one micron per hour is used to obtain about  $\pm 2.5 \mu\text{m}$  dimensional tolerances and a 150–200 nm surface roughness. Usually the applied voltage is about 1 V.
- (2) *Surface roughness*: The Al die can be easily polished to a roughness of  $< 0.4 \mu\text{m}$ . If a smoother surface, close to a mirror finishing, is needed, the main issue would be to maintain the finish after the chemical polishing of the die surface.

The chemical polishing of the die before the electroforming is compulsory to produce a good Cu adhesion. The chemical polishing of the die is more important than the Al die preparation itself. To obtain a mirror like surface finish, the company producing our accelerating structures [19] suggested to put a thin approximately 100 nm layer of gold on the die by sputtering, causing a very nice

adhesion of the copper to the die without the need to etch the die surface. The NaOH alkaline solution does not etch gold. Some dedicated preliminary tests with very thin ( $< 1 \mu\text{m}$ ) gold layer showed a 20% lower surface roughness. We believe that this is due to possible micro-fissure in the inter-diffusion region between the gold and the substrate. Additional investigations are in progress increasing the thickness of the gold layer to be deposited too.

This technique allows for the attainment of an accelerating structure in a single piece without the need for a high vacuum brazing procedure. As a result, due to the absence of brazing planes where the brazing alloy would flow, the possibility of mechanical gaps between the surfaces disappears and the RF exposed surfaces will have pure copper. In principle both multi-cell structures and couplers can be produced using this procedure. Further machining of the cell inner surfaces, which will be exposed to high electric fields, is avoided. Machining can be foreseen only on the outer surfaces of the accelerating structures to modify the cell shapes for tuning by deformation or for inserting a cooling system.

### 3. Electroplating technique for RF structure construction

Electroplating is a slightly different technique than electroforming. In the case of electroplating, Cu material is used to encapsulate previously machined bulk Cu structures [12,14]. The deposited Cu material is used, in this case to assure the vacuum tightness of the accelerator.

More precisely the procedure consists of

- (a) machining the single cells, couplers, beam pipes and flanges (Fig. 2a). The machining can be done with lathe machine and using diamond monocrystal tools, reaching very high precision dimensions (within  $\pm 1.5 \mu\text{m}$  of tolerances) and high surface roughness quality ( $< 30 \text{ nm}$ );
- (b) assembling all components with special tools that clamp the cells on the longitudinal axis (Fig. 2b);
- (c) covering the structure with a thick Cu electrolytic layer (of about 4 mm) to assemble the pieces in a single structure (Fig. 2c). Ribs have also been inserted in order to assure the device mechanical stability.

This mixed electroplating process is attractive since it allows the cells machining with standard techniques and high surface qualities. It is also attractive because it allows building structures with different types of materials, for example, molybdenum irises and copper cells (Fig. 5b).

The most critical point in this procedure is to assure the RF contact between cells before and after the electroforming

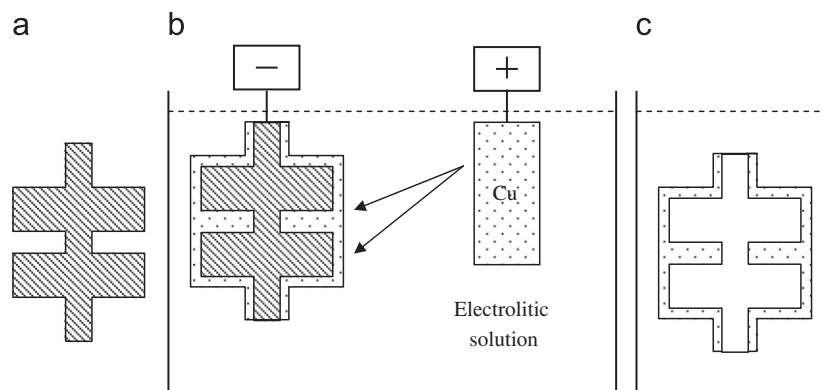


Fig. 1. Basic scheme for the electroforming procedure.

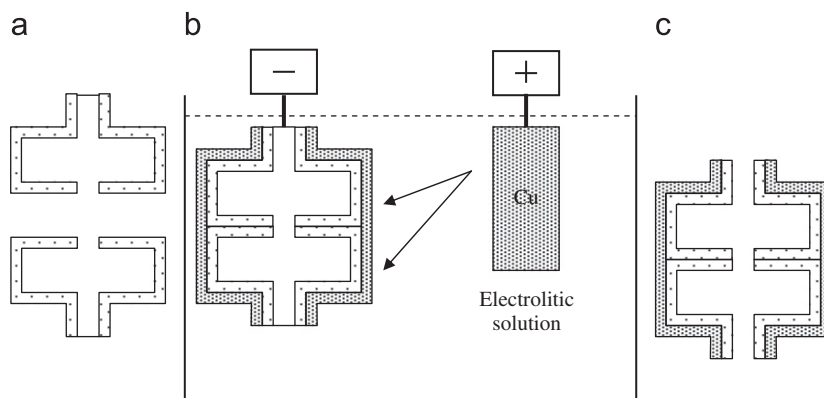


Fig. 2. Basic scheme for the electroplating technique.

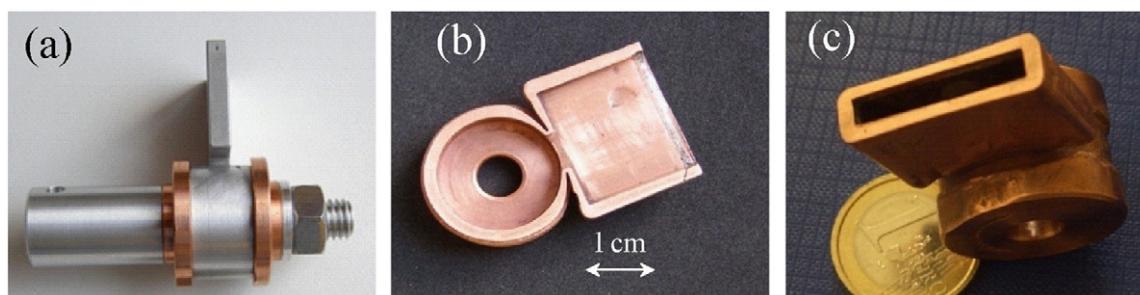


Fig. 3. Coupler constructed by electroforming: (a) aluminium die; (b) and (c) final electroformed structure.

procedure. Additionally this contact must be very good to prevent the electrolytic solution used in the galvanoplastic bath from penetrating inside the cells. One way to create this good contact is to machine the surfaces between cells with a very fine smoothness ( $\leq 50$  nm). This will create a vacuum tight contact, as seen from some preliminary tests on properly machined Cu components. Such surfaces are vacuum tight with a leak rate of about  $10^{-10}$  mbar l/s when a pressure of a few N/mm<sup>2</sup> is applied.

#### 4. Structures built by electroforming

Several prototypes have been built using the electroforming procedure. Fig. 3 shows the Cu coupler prototype by electroforming. In this case the deposition layer was  $\approx 3$  mm thick after 6 days of deposition. The goal of producing this prototype was to demonstrate the feasibility of constructing a coupler by electroforming, and the results were completely satisfactory. The shape was reproduced within the size specifications of a few micrometers.

Fig. 4 shows a couple of cells and the beam tube: the holes in the cells have been done after the electroforming to test the possibility to thread copper. The structure shows the presence of cracks and fissures. This has been the first realized prototype. The cracks and the fissures have been caused by the fact that in order to check and control the copper growing during deposition, the structure has been taken away from the bath several times to look at it. This caused air contamination during the deposition.

A third prototype consisting of a five-cell structure with beam pipe tubes is shown in Fig. 5. The irises of the structure have been previously built with molybdenum. In this case the deposition layer was  $\approx 4$  mm thick ( $\sim 8$  days deposition time) and the obtained surface roughness was  $\approx 200$  nm. RF measurements of this structure show a quality factor of 5400, 10% lower than the theoretical value computed for that same geometry built with high purity copper. This result is an indication of the good quality

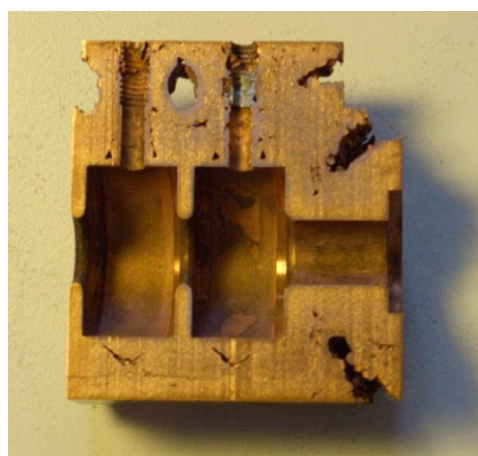


Fig. 4. Two cell structure and beam tube constructed by electroforming.

of the joints between the cells and the irises, and also of the good electrical properties of the electrodeposited copper.

A substantial open problem in constructing structures with this technique is the poor quality of the Cu surface due to the alkaline solution used to remove the die. Several techniques are being explored to mitigate this problem, such as the deposition of a silver layer on the mandrel and chemical treatment to clean the surfaces.

#### 5. Structures built by electroplating

Several prototypes have been built using the electroplating technique. A three-cell Cu OFHC structure is shown in Fig. 6. Having planned to test our structures at the high power RF test-station at SLAC, this accelerating structure has the same internal dimensions and RF properties as other prototypes already built

using different materials and constructing procedures and tested at high power at SLAC [15]. The structure has 3 cells fed by a circular waveguide. The central cell is foreseen to have high gradient while the adjacent cells are used to match the RF power from the input circular waveguide. The excited mode in the structure is the  $\pi$ -mode.

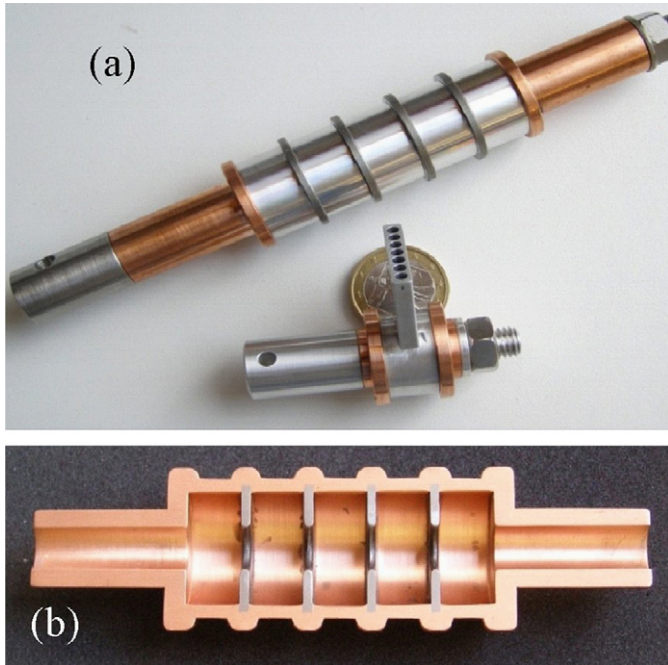


Fig. 5. Five cell structure with molybdenum irises constructed by electroforming: (a) mandrel and (b) prototype structure.

The on-axis electric field profile for a Cu structure as computed by HFSS simulations [16] is shown in Fig. 7a. It shows good matching at the nominal RF frequency of  $\sim 11.424$  GHz and the maximum field intensity in the central cell. The quality factor for the Cu structure obtained by simulations was 8300.

The cells of the structure constructed by electroplating have been machined with a surface  $R_a < 80$  nm, they have been assembled and tightened at a torque of several  $N/mm^2$ . Vacuum and RF tests have been conducted after assembling and, finally, they have been sealed by electroplating with the deposition of a  $\sim 4$  mm thick copper layer obtained during the 1-week deposition.

This structure has been characterised at low power after the final copper deposition. The result of the  $\pi$ -mode on axis electric field measurement by the bead-pull method is given in Fig. 7(b). The measured quality factor was 7700 for the operating mode,  $\sim 10\%$  lower than the simulated value for a Cu structure.

### 6. Results of high power test on the structure realized by electroplating

High power RF tests have been conducted at SLAC on the electroplated structure. The results are reported in Fig. 8 where the breakdown probability as a function of the accelerating gradient and the peak pulse surface heating in the cavity are shown for different accelerating structures. The vertical error bars on the graphs are inversely proportional to the square root of the number of breakdowns, and the horizontal error bars are proportional to the standard deviation of the corresponding value during the experiment. All four structures shown in Fig. 8 have the same geometry to eliminate the effect of the structure geometry on the breakdown probability [15]. The electroplated structure is compared with two brazed, soft copper structures and one structure made of hard copper, which was not annealed at high temperatures. Cells of this

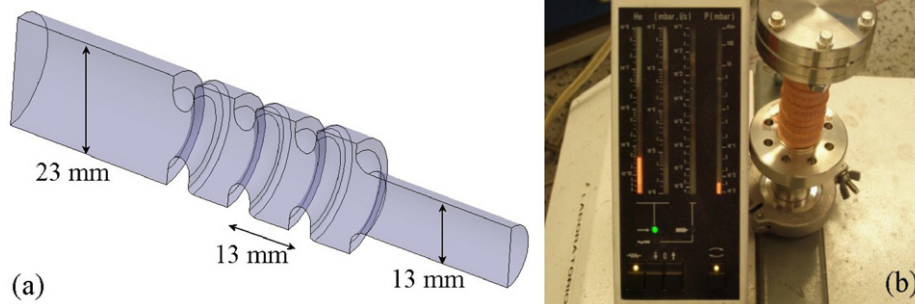


Fig. 6. (a) Sketch of the three-cell structure constructed by electroplating and (b) structure realized by electroplating technique.

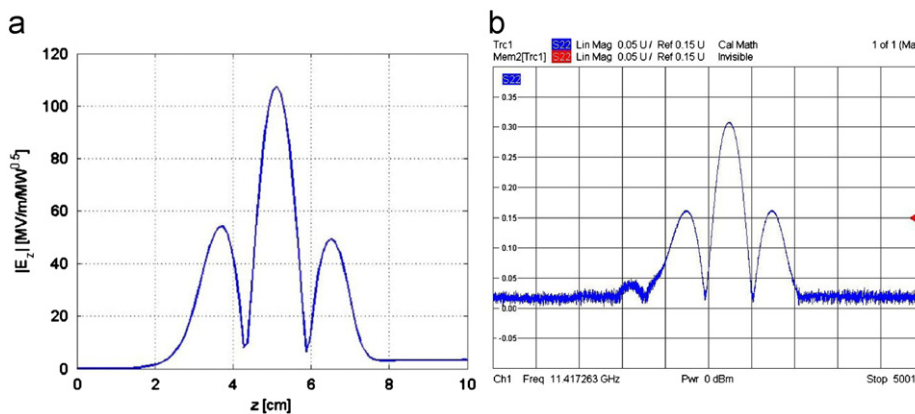
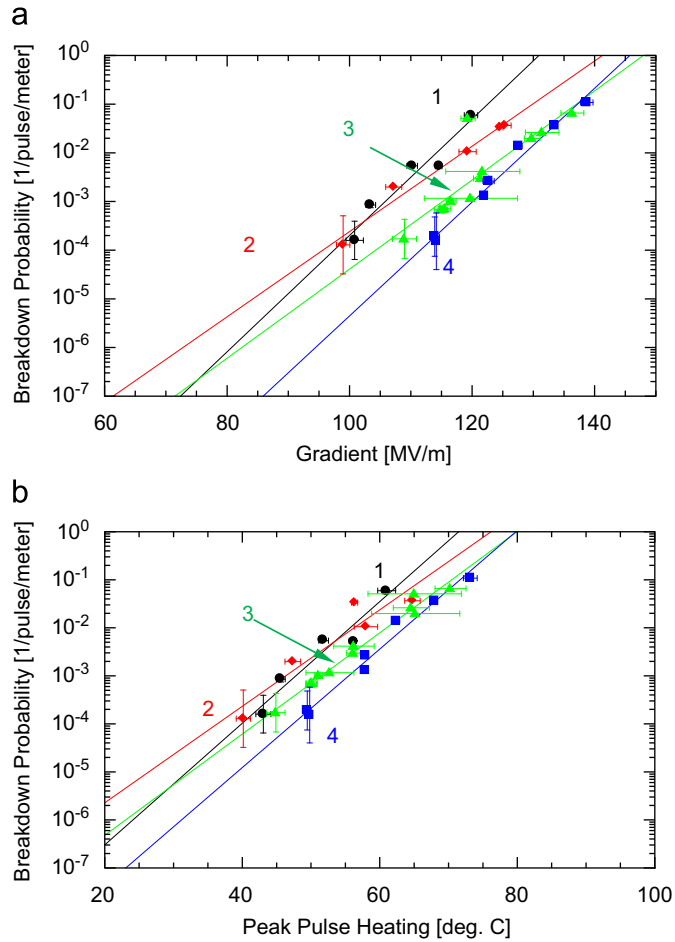


Fig. 7. Electric field on axis for the  $\pi$ -mode three-cell structure: (a) simulated and (b) measured on the electroplated prototype by bead-pull technique.

hard copper structure were clamped together to ensure electrical contact, and then placed in a vacuum vessel to preserve vacuum integrity inside the structure. This clamped-structure setup was developed at SLAC for tests of accelerating structures made of hard copper, hard copper alloys and coatings [17].

Even if the performances of this first prototype, realized by electroplated technique, were not comparable with the clamped



**Fig. 8.** Breakdown rate as a function of (a) the accelerating gradient and (b) the peak pulse heating for the electroplated structure compared with two brazed structures and one clamped structure: (1) electroplated structure (black circle), (2) brazed KEK-#4 (red diamond), (3) brazed Frascati-#2 (green triangles) and (4) clamped SLAC-#1 (blue square). The structures are powered with shaped pulse with flat part of 150 ns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

one but with those of the brazed structures, these results are very promising.

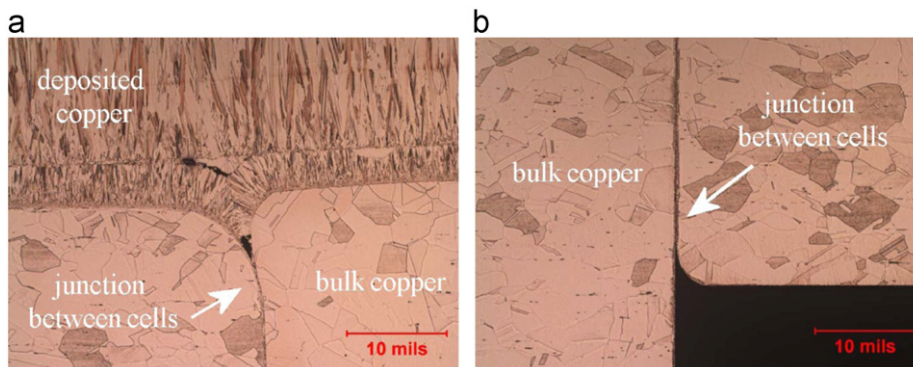
After high power tests the metallographic examination [18] was performed on the prototype before and also after hydrogen annealing treatment as shown in Figs. 9 and 10. In the first case the junction between the cells is visible and also the junction between the bulk copper and the deposited layer. The electroformed material consisted of small narrow radial grains. Another important point to be remarked is that this analysis shows that the contact between the copper pre-machined cells is very good, contributing to the good results in the high power RF tests.

After annealing the microstructure consisted of equiaxed recrystallised grains, containing twinned areas within the disc-cell material. The electroplated portion consisted of large radial grains. Significant voids and fissures were observed along the electroplating to cell interface and also inside the bulk and electroplated copper. The oxygen contamination in the electroplated copper was caused due to the inspection during the electroplating process. These inspections were conducted to control the deposition process but in principle can be avoided in the final procedure [19].

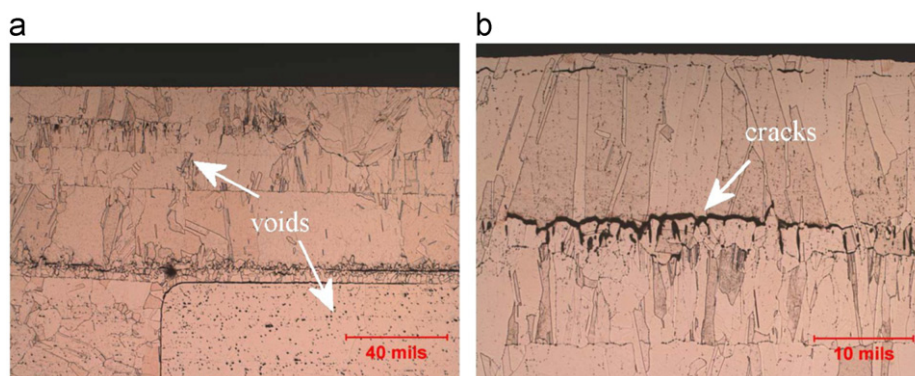
## 7. Conclusions

Electroforming and electroplating techniques for constructing high gradient accelerating structures have significant advantages. Electroforming is an electrolytic procedure through which a layer of copper is obtained on a mandrel that is subsequently removed by chemical etching. RF structures with multiple accelerating cells and couplers can be constructed this way as we have demonstrated with some prototypes. In the electroplating procedure, the copper is deposited on pre-machined bulk cells and the deposition is used to mechanically assemble the structure and assure vacuum tightness. These techniques allow the construction of accelerating structures by avoiding the high temperature brazing steps. From the results of the high power tests at SLAC on the hard copper, electroplated structure, it has been demonstrated that the breakdown performance of this structure is similar to that of brazed soft Cu structures. Hard Cu clamped structures tested at SLAC performed somewhat better than the brazed soft Cu structures. We note that these are first experiments and we expect further improvements in the breakdown performance as we improve the construction techniques of hard Cu structures. Therefore, both electroforming and electroplating are very promising techniques to avoid the brazing step in structure construction, while maintaining the mechanical soundness and the vacuum tight properties of the brazed structures.

Several prototypes were built and the results of low and high power tests have been reported.



**Fig. 9.** Pictures of the electroplated structure: (a) junction between the bulk copper cells and the deposited copper and (b) junction between bulk copper cells.



**Fig. 10.** Pictures of the electroplated structure after hydrogen annealing: (a) junction between the bulk copper cells and the deposited copper and (b) detail of fissures in the electroformed copper.

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