ELECTROFORMING PROCESS DEVELOPMENT FOR A 33 GHz HIGH-GRADIENT ACCELERATOR

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Abstract

A method has been developed for fabricating an electroformed 33.3 GHz accelerator section. Tolerances of ±50 millionths of an inch are required. This approach has been pursued in the interest of simplifying the construction of these small, high-precision assemblies. This work is part of our two-beam accelerator research program.

Introduction

An initial goal of our two-beam accelerator (TBA) program has been to demonstrate the high accelerating gradients, e.g., 200 - 500 MV/M, which are feasible in disc-loaded waveguide structures at frequencies in the 35 GHz range.[1,2] An earlier seven-cavity copper test structure achieved an equivalent accelerating gradient of 180 MV/m during a 15 ns pulse at 34.6 GHz with only routine metallurgy and relatively poor vacuum involved.[3] This paper describes the development of one of two identical very high quality 33.3 GHz high gradient accelerator (HGA) sections. These were intended to be comparison-tested at the LLNL Electron Laser Facility (ELF)[2] at high vacuum (e.g., $.10^{-8}$ Torr). The other is a machined and brazed structure whose fabrication and microwave design is described in a companion paper.[4] The HGA dimensions were determined in that work. Figure 1 shows a diagram of the basic cylindrically-symmetric disc-loaded waveguide cavity. The final structure requires a 10 cm long assembly of 34 of these with input/output coupling structures at the first and last cavities. Vacuum pumping for each cavity is provided by six 0.028 in diameter radial pumpout holes. From the input to the output end of the assembly, the dimensions of the holes in the discs, 2a, and the cavity outer diameter, 2b, decrease. The 2a dimension ranges from 0.10254 in to 0.08540 in; the 2b dimension ranges from 0.28619 to 0.28100 in. The tolerance on these diameters and other critical dimensions is ±50 millionths of an inch.

The maximum achievable accelerating gradient is ultimately limited by electrical breakdown (arcing) in regions where the microwave electric field is maximum. In these structures, this region is on the curved surface of the radiused disc-hole edge. It is most important that these surfaces be exceedingly smooth and free of gross tool marks, whiskers, inclusions of foreign materials, and pits caused by voids in the copper. Our specification calls for a 3 microinch (R_A) surface finish on all interior cavity surfaces. To ensure that the ELF tests would be comparing only the two accelerator sections and not just the input/output couplers, the couplers for this HGA were made identical to those of the brazed structure (by Haimson Research Corporation). Moreover, each included five machined cavities in a brazed subassembly. These were to be joined to the HGA later by plating.[5] The electroformed section described in this paper therefore has 24 cavities.

Fabricating the Mandrel

The required cylindrical mandrel has 25 slots of width 0.01972 in, spaced by 0.09839 in, and cut to varying depths of approximately 0.100 in. The rounded slot-root was permitted to be fully radiused, to simplify preparation of the cutting tool. Because of the limited usage necessary, a carbide tool was selected and prepared as shown in Figure 2. The circular nose of the tool was precision ground. Measured with a Sheffield small radius gauge having a 5 microinch maximum error, the tool nose had a best-fit circular radius of 0.009848 in with a maximum deviation of 19 microinches from this radius.

For the mandrel material, we investigated an aluminum alloy, type 7050,[6] which reportedly has the lowest porosity of any Alcoa product. However, machining tests revealed that it had an unacceptable number of unidentified inclusions. The common 6061-T6 alloy was used for the mandrels. We intended to microscopically inspect finished units for voids before plating them. The mandrels were machined at LLNL on a Pneumo precision T-base lathe which had an air-bearing spindle, vibration isolation system, laser feedback, and an Allen-Bradley computerized numerical control system capable of one-microinch resolution. During machining, the mandrel and chuck were bathed in temperature-regulated cutting fluid. The entire room was temperature regulated to < ±0.1° F. The lathe setup included a carbide roughing tool as well as the slotting tool described above. The lathe speed was 1200 rpm. The cross-feed rate was 0.0005 in/rev. The machining proceeded as follows. A 1.25 in diameter rod was placed in the lathe and left protruding approximately 6 in out of the chuck. The roughing tool machined a two-groove section (farthest from the chuck) to the required 2b finish diameter plus 0.0005 in. The slotting tool then machined the first finish diameter, plunge-cut the slot, deburred the corners, machined the second finish diameter, then plunge-cut the second slot. The roughing tool then cut the third and fourth finish diameters plus 0.0005 in, moving toward the chuck, and the process was repeated through the 25th slot. Occasionally, chips leaving the part would scratch a finished diameter or nick the outer slot edge, ruining the part. The initial acceptable part yield was poor. As problems were overcome, however,

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the yield increased to at least two "good" mandrels per day with perhaps one out-of-tolerance mandrel being produced every day or two. Nine good mandrels were finally produced. We anticipated that the numerous possible pitfalls in handling and in subsequent electroforming steps might require several re-starts with new mandrels. The machining computer program was checked by carefully measuring the key diameters and spacings on test mandrels. Subsequent mandrels were first checked on an optical comparator, then precision measured by a granite slab-mounted Laseruler[7] capable of one-microinch resolution and two-microinch repeatability. Optical interferometry was employed to confirm the three-microinch surface finish of the curved slot-root, the slot sidewalls, and the outer finished diameters. No final polishing of surfaces was permissible since this might leave small, irregular particles embedded in the mandrel. These could, in turn, become embedded in the copper plating and reduce ultimate arcing thresholds. A finished mandrel is shown in Figure 3 along with three lucite masks, discussed below.

Electroplating Studies

The electrochemistry of copper-plating processes as well as other details of our studies is described elsewhere.[8] There it is shown that a maximum theoretical plating rate exists, known as the limiting current density, i_ℓ, which is a function of several electrical and fluid mechanical parameters including the rotation speed. Dendritic growth, void formation and surface roughness increase as i_ℓ is approached or exceeded. First studies centered on achieving successful deep-slot plating. The ratio of slot depth to width excess 5:1 and was recognized as presenting a challenge. The first plating bath used was the acid-sulfate type, consisting of 28 oz/gal copper sulfate and 10 oz/gal sulfuric acid. To this was added various concentrations of Udylites "UBAC No. 1" and other additives to enhance brightening, leveling, and wetting. Plating tests were conducted on aluminum mandrels 0.25 in in diameter and 4 in in length. These included three machined slots 0.020 in in width and 0.100 in deep. Figure 4 shows the cross-section of a plated slot at a magnification of 200. Direct current plating was done at a rate of 20 A/ft^2 for 20 minutes, then 5 A/ft^2 for 44 hrs. i_ℓ was about 185 A/ft^2. The bath included 0.2% UBAC organic brightener. The part was rotated at 30-60 rpm. As can be seen, the slot root was indeed plated but a large void was formed. This is unacceptable since the trapped fluid can cause excessive pressure and resulting distortion during bakeout. In addition, the "seam" where the plating joins is not likely to be vacuum tight. This would cause later vacuum problems. Also, as the photograph indicates, the adhesion between the copper and aluminum was not good. Figure 5 shows a slot plated in a different acid-sulfate solution, "Cubath", with no brightener. The dc plating rate was 30 A/ft^2 for 15 min, then 5 A/ft^2 for 19 hrs. The part was rotated at 30-60 rpm. The plating inside and outside the slot is more uniform although the adhesion still appears to be poor. To avoid the "seam" problem and trapped fluids, we decided to leave the slots open as shown by .0.006 in. This would permit later cleaning and evacuation of the slots, improving the vacuum environment. If no further plating were done, however, the electroform would be weak and flexible, like a long bellows, after the mandrel was chemically etched out. To provide the necessary strength, we planned to electroform three longitudinal strengthening ribs onto the plated mandrel. These would be equally spaced in azimuth. Figure 6 shows a ribbed HGA, produced to demonstrate feasibility. In the final HGA, however, the rib width and radial thickness were to be larger. Microwave power loss considerations required the radial pumpout holes to be $\geq$ 0.110 in long in copper. Also, deep counterbored holes were required in the ribs to facilitate the microwave tuning of cavities. Thinned cavity wall regions thus produced would be intentionally deformed in the tuning process. The lucite masks shown in Fig. 3 were designed to produce the larger electroformed ribs.

To improve the adhesion of copper to the aluminum, the mandrels were zincated. In this process, the anodic aluminum surface is displaced by zinc from the cathode to a depth of about 100 angstroms. It is done in a solution of sodium hydroxide at 500 g/l and zinc oxide at 100 g/l concentration. There was concern that this process and the subsequent etching out of the mandrel by a hot caustic solution would result in the degradation of the surface finish of the copper electroform. Tests were performed on several diamond-turned aluminum discs. These showed that a 1.5-1.7 microinch finish would usually be exactly replicated on the copper surface providing the zincating had been done at 30° C. At 20 or 40° C the copper surface was degraded. In other later tests, however, some 12 microinch features did appear in the copper, even when 30° C zincating had been performed. This process thus requires further study. At worst, there may be a yield problem.

In the acid-sulfate baths, attempts were made to fill the slots with copper using periodic reverse plating and pulse plating. The periodic reverse plating resulted in mandrel dissolution during the reverse portion of the plating cycle, so it was abandoned. With no organic additives, the pulse plating produced a finer grain size than was achievable with dc plating. The growth was columnar, however, therefore brittle. This approach was also abandoned in favor of dc plating. Although the copper electrodeposited from the acid-sulfate bath with UBAC No. 1 additive had very small grain size, the microstructure was unstable during heat treatment. Significant void formation occurred at 450° C and higher.

As an alternative to the acid-sulfate process, we planned to use a cyanide copper bath. Our choice was reinforced by the knowledge that this process is in common use at the Stanford Linear Accelerator Center (SLAC).[9] Our bath consisted of 8.6 oz/gal copper cyanide, 15 oz/gal sodium cyanide, and 2.5 oz/gal sodium hydroxide. The organic additives were Allied Kelite Isobrite Nos. 625 and 630 at 3.1 and 0.5 vol. %, respectively. Plating tests were run at current densities of 2 A/ft^2 (25% i_ℓ), 4 A/ft^2 (50% i_ℓ), and 10 A/ft^2 (125% i_ℓ). In all of these cases, a hyperfine, velvet grain structure developed. At the highest current density, a severe surface texture with dendrites developed. Figure 7 shows a metallograph of cyanide-plated copper from a slot at a magnification of 200. During the plating the current density had been stepped from 2 A/ft^2 to 4 A/ft^2. Afterward, it was heat treated for two hours at 650° C. The 2 A/ft^2 region showed columnar grain growth. The grains in the 4 A/ft^2 layer, on the other hand, remained nearly ideal: fine and randomly oriented. Consequently, we chose this technique and a 4 A/ft^2 current density to produce our electroforms.

Some outgassing studies were performed. The acid copper electroforms produced significant outgassing of carbonaceous species. The cyanide copper parts outgassed relatively little by comparison. Further tests are required to quantify these results.

Present Status and Conclusions

Budget restrictions and the cessation of ELF operations forced the termination of this effort before the final HGA could be electroformed, joined to the input/output couplers, tuned and baked out. We believe that the most difficult remaining tasks were the joining of the electroform to the coupler subassemblies, with adequate dimensional control, and the thorough cleaning of the final assembly.

This project was undertaken to determine (1) the feasibility of electroforming these precision structures, (2) to determine whether or not the high-gradient performance of these units is superior to that of an identical brazed structure, and (3) to gain a basis for judging whether or not this HGA fabrication approach has any significant cost or other advantage over that of the machine-and-braze method. We conclude that (1) is nearly completely demonstrated with the remaining tasks probably being achievable. The testing required for (2) must await the availability of a new high-power microwave source. ELF is presently being rebuilt. With regard to (3), it has now been demonstrated that a 33 GHz HGA can be machined, brazed, and tuned in a straight forward manner.[4] Moreover, these have the considerable advantage of using superior copper with low gas content so that they may be baked out at a temperature of 900° C. The resulting cleanliness and purity of critical copper surfaces might be difficult to match in an electroformed HGA and would likely permit higher ultimate gradients. With machined input/output coupler sub-assemblies, the electroformed HGA would not appear to have a significant cost or other advantage. With electroformed couplers (as in Reference 3), the cost factor improves somewhat but probably not enough to outweigh the advantages of the brazed HGA structure.

Acknowledgments

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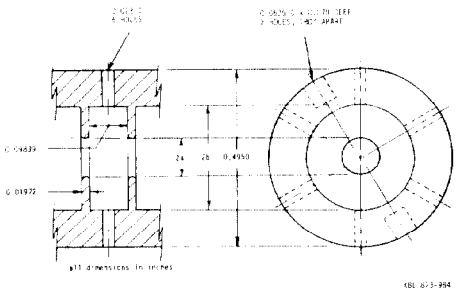

Fig. 1 HGA Cavity

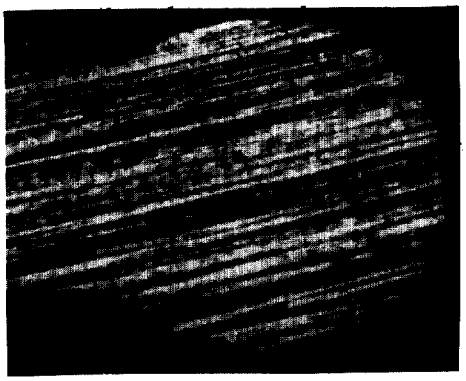

Fig. 2 Slot Cutting Tool

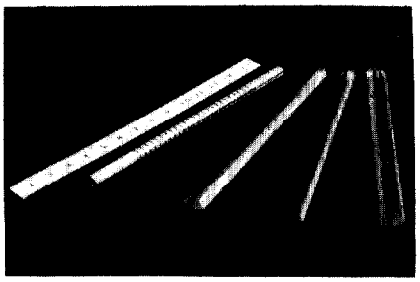

Fig. 3 Mandrel and Masks

Fig. 4
Early Plated Slot

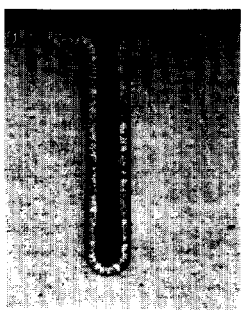

Fig. 5
Final Plated Slot

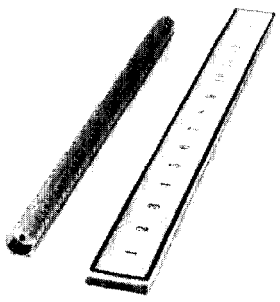

Fig. 6
Ribbed HGA Prototype

Fig. 7 Cyanide Copper
Grain Structure