AN ELECTROPLATING FABRICATION METHOD FOR ELECTRON ACCELERATOR STRUCTURES

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Abstract

An electroplating fabrication method has been used since 1962 for S-band frequency electron accelerating structures in Japan. The electrical contact between disk and cylinder, and the vacuum integrity are maintained by an electroplated copper layer 5 mm thick, without any metal brazing. The typical integrated phase error after plating was kept below ±2° without any frequency tuning. The mechanical straightness was within ±100 μm over the 2 m length of the S-band accelerating structure.

Since this method does not require any high-temperature processes, such as the metal brazing commonly used for accelerator fabrication, the copper material does not crystallize and maintains a higher tensile strength. That makes this method very attractive for fabrication of the high-performance structures which will be required in various future projects, and especially for e+e- linear colliders.

1 INTRODUCTION

A special requirement for a large scale e^+e^- linear collider for 300-500 GeV C.M. energy reasion is to be able to accelerate a low emittance beam while achieving a nano-meter size beam at the collision point in order to provide the required high luminosity. One R&D issue for the accelerating structure is how to control beam induced wakefield effects. The multi-bunch instability problem has been mostly solved by the Choke-Mode concept and the detuned-structure. However, single bunch instability due to short-range wake-field is still a problem. Trade-offs are involves since lower rf frequencies minimize these instabilities, while higher frequency bands provide higher shunt-impedance which is also preferable. From consideration of the required straightness tolerance, we chose a compromise at the C-band frequency (5712MHz), where the straightness tolerance becomes ±50 μm (maximum bow) for a 1.8 m-long structure. At the higher X-band frequency, straightness becomes on the order of ±10 μm for the 1.8 m-long SLAC Detuned-Damped-Strucure [2,3]. It is clear that no laboratory or industry group currently has any experience with fabricating so many structures at this extraordinary level of accuracy.

Mitsubishi Heavy Industries Ltd. (MHI) and Professor J. Tanaka of KEK developed an electroplating fabrication method (not to be confused with the prior electro-forming method) for electron accelerator structures [4,5]. Their motivation was to improve the accuracy in the phase-shift per cavity, while ensuring mass productability. They introduced a high-precision machining lathe, and succeeded in fabricating accelerating structures, which did not require frequency tuning of any method after the copper plating.

In 1978, 160 accelerating structures were made this method and installed in the 2.5 GeV PF-injector at KEK. Recently, 68 more structures were added for an energy upgrade to 8 GeV for the KEK-B project [6,7].

Figure 1 shows the temperature dependence of the tensile strength, and also the dimensional elongation of high purity Oxygen-Free-High-Conductivity (OFHC, 99.996%) copper.

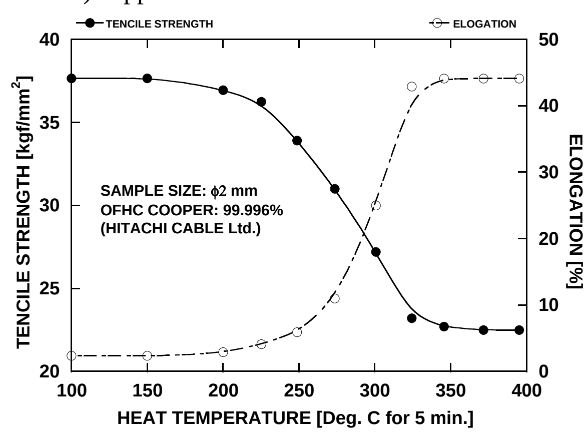

Figure 1: Mechanical properties of OFHC copper as a function of temperature. Each sample was heated up to a target temperature, and held there for 5 minutes.

As can be easily seen in the figure, at temperatures over 200 °C the tensile strength drops sharply and elongation becomes pronounced.

It is very clear that conventional brazing methods, which require temperatures of around 700-900 °C, present difficult problems with respect to mechanical performance. On the other hand, when using electroplating to join the cavities, the maximum temperature raise is only about 40 °C. From this fact, we believe that the electroplating method is a very attractive candidate for the preferred fabrication method for high-performance accelerators requiring tight mechanical tolerance and frequency control.

In this paper, we will describe the elector-plating fabrication method, and its related techniques.

2 MANUFACTURING

The regular section of the accelerating structure is composed of disks and cylinders. They are stacked alternately in series and held in place as a single structure by the electroplated outer copper layer as shown in figure 2. The disks and cylinders are made of high purity OFHC copper, and machined by a high-precision turning lathe. The electroplated copper layer is 5 mm, which provides good enough electrical contact as well as vacuum tightness without further metal bonding, such as the high-temperature brazing process.

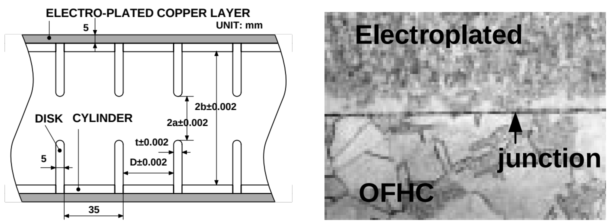

Figure 2: Figure 2: Left: cut away view of the structure. The thickness of the electroplated copper layer is 5 mm. Right: an expanded view of the electroplated layer (top), and OFHC copper (bottom). A horizontal dark black line shows boundary of electroplated copper and OFHC.

2.1 Disk and Cylinder Manufacture

The disk, cylinder, and the coupler cavity are made of the high purity OFHC (>99.99%) copper. Figure 3 shows a photograph of the machining of the disks for KEKB 8 GeV linac. The final machining uses a very high-precision tuning lathe with a diamond cutting tool of round shape (R0.5).

The dimensional accuracy was kept within 2 µm, except for the rounded part of the beam hole, where it is 5 µm. The surface roughness was kept to 30 nm at disk flat surfaces and within 500 nm around the beam hole. The inner surface of the cylinders have 30 nm of roughness. Figure 4 shows the typical surface roughness at the disk surface measured by an optical interferometer using a 600-nm wavelength monochromatic light source.

2.2 Assembly Accuracy Check

The dimensional tolerances for the disk and cylinder are ±2 µm as shown in figure 2, which corresponds 80 kHz in frequency error, and 0.34 degree of the phase error at vg of 0.01c at the S-band frequency. This result made it possible to eliminate the final phase adjustment such as the dimpling procedure which is needed after brazing the structure. The target resonant frequency of each cavity was intentionally lowered by 200 kHz from the operating frequency to allow for the mechanical compression effect associated with the electroplating process. The electroplated copper tends to shrink, and produces a small change in the resulting mechanical dimensions, mainly in that the cylinder diameter becomes smaller.

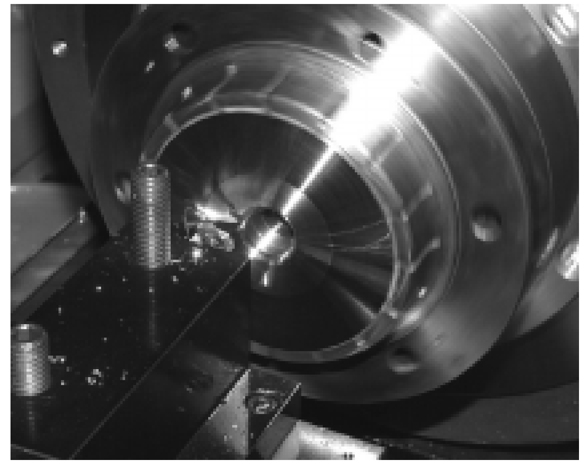

Figure 3: Figure 3: The final machining of a disk with a diamond tool.

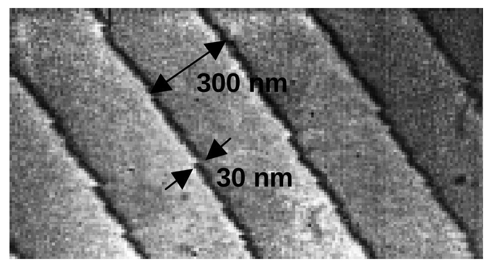

Figure 4: This photograph, taken by an optical interferometric method, shows the typical surface roughness of a copper disk machined on a precision turning lathe. The distance between dark lines is 300 nm (half-wavelength). Any deviation of the dark line from straightness shows the surface roughness. The peak to peak surface roughness is about 30 nm in this case.

2.3 High Speed Electroplating

After frequency checks of all the cavities for an acceleration structure, they are stacked together horizontally (56 cavities for 2 m length) on a precision support-bed. A steel mandrel is inserted through the staked cavities and tightened to a tension of 2500 kgf to which will be held during the electroplating. The mandrel has a bar-shape and is made of high-tensile-strength steel to maintain the tension throughout the electroplating procedure.

The oxide layer on the outside of the structure is removed by mechanical brushing, and then it is rinsed in pure water to remove any foreign matter such as dust which may be stuck on the surface. The structure is then immersed in the electroplating process fluid in a vertical bath.

A high-speed electroplating method is chosen [8,9]. In order to plate the copper at high current densities of 10 A/dm^2 or more, additives are included to the copper-sulfate. It takes 70 hours to deposit a layer 5 mm in thickness. The processing fluid mainly consists of copper-sulfite, sulfuric-acid (H_2SO_4, >95%), hydrochloric-acid (HCl, >35%) and ion-exchanged-water. During the plating the plating fluid temperature was controlled at 30 °C ± 1 °C. Also, close purity control of the plating fluid is very important to prevent defects in the copper crystal structure such as the so called star and wrinkle defects.

The possibility of fluid leakage through a gap between disk and cylinder is very low. A key point in this is the surface smoothness. It is around 30 nm after the precision machining and the dimensional accuracy is also 2 μm. When the disk and cylinders are compressed with an appropriate contact pressure, the resulting vacuum tightness reaches the order of 10^{-4} Torr.

After the electroplating, the surface of the plated copper is machined to back to a 5 mm thickness. The hardness of the plated copper layer is really high, and is comparable to iron. This is due to the compaction force of ionized copper. During the plating the temperature rises, but only to 40 °C.

2.4 Assembling the Completed Accelerating Structure

After assembling, an accelerating section has a coupler attached at each end by electron beam welding (EBW) while pressure is applied by the mandrel. The position for the weld is designed to avoid excessive stress concentration and to obtain a good electrical contact. The structure is cooled with a water-jacket type pipe, which has both ends TIG welded to the couplers.

3 RF MEASUREMENT RESULTS

The structure is assembled from highly accurate disks and cylinders; it is easily checked for the specified resonance frequencies, thus in principle we see that it is possible to mass produce a high precision accelerating structure. However, the proof is in the final check to measure the phase shift of the all the cavities by Nodal-Shift method. Figure 5 shows the typical measured Nodal-Shift data before and after the electroplating process. The three solid lines in figure 5 are the specified phase-shifts (0°, 120° and 240°), the measured phase shifts of the cavities for $2\pi/3$ mode at the operating frequency are marked with open circles. As can be seen from figure 5, the integrated phase errors are within ±2° for the 2 m-long structure (two couplers and 54 regular cavities). After the electroplating process, the integrated phase errors slightly increase, but still only to 0.86 degree in rms. From this we conclude that the electroplating effects can be controlled quite precisely.

4 CONCLUSIONS

We conclude that the electroplating method is a attractive candidate for fabrication of the next generation advanced accelerators. As for the related technology, we have also shown that the simple frequency measuring of the assembly check can be use to obtain the same accuracy of the Nodal-Shift method. Finally, the straightness of the structure can be improved to within less than 30 μm of the target value.

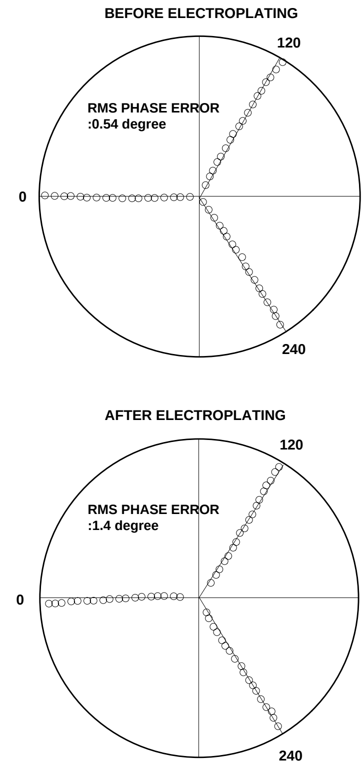

Figure 5: Typical phase characteristics of an electroplated S-band 2 m-long structure as measured by the Nodal-Shift method.

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