FABRICATION OF SEAMLESS SINGLE-CELL COPPER ELLIPTICAL CAVITIES THROUGH BULK-MACHINING

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Abstract

In the context of future accelerator studies, niobium coating of copper-based cavities plays a key role in achieving an optimal balance between RF performance and cost-effectiveness. Recent advancements have focused on the development of bulk-machined elliptical cavities, featuring a seamless, weld-free equator. By optimizing the design of machining tools, the machining strategy and processing parameters, fabrication of high-quality cavities with excellent shape accuracy and surface finish has been achieved, along with improved repeatability. This contribution presents the current status of fabrication for such seamless cavities, including the design of the specialized cutting tools. It also explores the relationship between cutting tool parameters, machining conditions and surface integrity, providing a deeper insight into the factors that may influence the future success of niobium coatings.

INTRODUCTION

Traditionally, SRF cavities are fabricated from bulk niobium sheets. However, an alternative approach pioneered at CERN in 1980 is to coat copper cavities with a thin niobium film [1]. This method offers advantages in thermal stability, lower material cost, and potential for improved performance. For more than three decades, literature has documented that weld defects can degrade the performance of such niobium coatings [2]. A clear example was seen at CERN during the development of niobium-coated quarter-wave resonators for the HIE-ISOLDE [3]. Performance issues in the produced cavities were traced to fabrication flaws, notably cracks in electron-beam welded regions [4]. Similar performance limitations due to weld defects also apply to elliptical niobium-coated copper cavities. Early attempts to eliminate the electron-beam equator weld in elliptical cavities relied on spinning or hydroforming full cells. In the past, machining cavities directly from bulk billets had been considered impractical for thin-shell geometries and consequently set aside [2]. However, despite potential economic limitations for large-scale production, this approach offers substantial advantages for prototyping and for R&D related to subsequent processes (such as surface treatment), including precise control over RF surface roughness, shape accuracy, consistent local wall thickness and less intensive surface treatment compared to traditional techniques. It enables the fabrication of reproducible reference substrates for coating development, where the additional machining time and material consumption are considered acceptable trade-offs.

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This paper reviews past CERN projects that have employed the seamless cavity approach through bulk machining for niobium-coated elliptical Oxygen-Free Electronic (OFE) copper (according to ASTM C10100) cavities, focusing on the substrate fabrication perspective. It also presents recent efforts to optimize the machining process and understand its impact on surface integrity, with the ultimate goal of enhancing the RF performance of the Nb-coated cavities.

FABRICATION OF SEAMLESS BULK-MACHINED CAVITIES AT CERN

1.3 GHz elliptical cavities

Direct machining of cavities from bulk copper billets was investigated and successfully implemented at the CERN main workshop [6]. The geometry posed a major challenge: a small aperture relative to the required undercut depth. The solution used indexed turn-mill operations at several machine angles, followed by internal and external semi-finishing and finishing with a custom cavity-conformal toolholder. For internal finishing, a polycrystalline diamond insert was used. This strategy achieved interior profile deviations of ±43 μm, wall-thickness uniformity of ±30 μm, and a surface roughness of $R_a \approx 0.16\,\mu$m. Roughly 95% of the billet volume was removed in about 20 h of machine time.

Cold tests on these bulk-machined cavities coated with Nb showed that they can comfortably meet RF performance targets scaled from the FCC 400 MHz specification at 4.2 K [5, 7]. Nevertheless, comparative tests across different post-machining surface preparations showed that removing the machining damage layer prior to coating is critical for achieving the best performance [7]. Overall, the first ever bulk-machined series demonstrates that precision-machined seamless copper substrates provide robust, reproducible reference platforms for Nb film R&D and support a systematic path to performance improvement.

400 MHz elliptical cavity

Building on the success of the bulk-machined 1.3 GHz cavities, the approach was extended to single-cell 400 MHz elliptical cells (Figure 1). Several modifications to the machining sequence and cavity design were made to accommodate the larger size and heavier workpiece.

To improve chip evacuation and minimize distortion, the machining sequence was adjusted so that rough milling was first performed on the outside volume, followed by rough milling of the inner volume. This was then completed with vertical finish turning of the outside surfaces, and finally, multi-axis finish turning of the inner surfaces. This revised sequence mitigates a deformation risk due to constraint relief distortion specific to the larger 400 MHz cavity. Rings were added to the design of the cavity to simplify clamping during both roughing and turning operations using soft jaws, and by providing threaded lifting points for safe handling.

Roughing was performed using the same turn–mill technique as for the 1.3 GHz cavity [6], employing indexed 5-axis orientations and continuous C-axis rotation. Unlike the 1.3 GHz case, the entire inner contour of the 400 MHz cavity was finished in a single continuous 4-axis turning pass. The cutting tool maintained uninterrupted contact from iris to iris, eliminating any tool repositioning marks. Finish turning of the inner surfaces was carried out using a custom toolholder with anti-vibration extensions. Metrology in the coordinate system defined by the cell axis and one side face revealed an overall shape accuracy of ±46 μm. At the moment, the cavity has now been fully assembled with its extremities and is awaiting Nb coating.

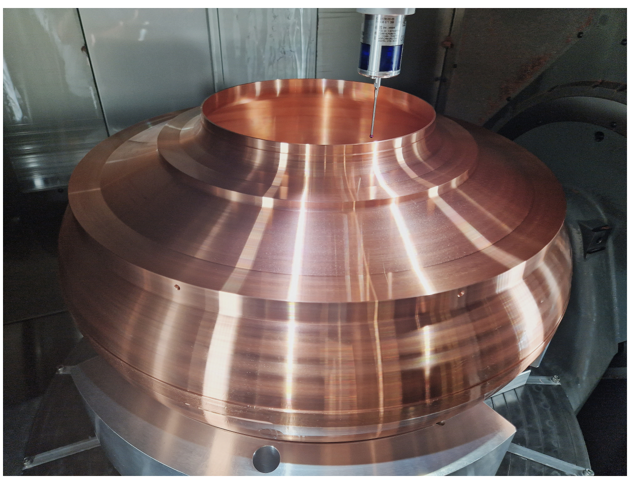


Figure 1: Fully machined 400 MHz seamless copper cavity.

1.3 GHz SWELL elliptical cavity

The Slotted Waveguide ELLiptical (SWELL) cavity differs from traditional elliptical cavities in its construction method, as it is assembled from four individual quadrants. This design results in a seamless cavity, with no weld at the equator, and its distinctive geometry allows for the inclusion of longitudinal slots. These slots function as high-frequency waveguides, enabling the extraction and propagation of transverse Higher Order Modes (HOMs) out of the resonator and thus facilitating efficient damping [8].

While the original concept was a 2-cell 600 MHz cavity, a 1.3 GHz subscale version was developed and fabricated as a demonstrator to enable performance evaluation (Figure 2). From a manufacturing perspective, the quadrant geometry meant that all material removal had to be obtained by milling. A fabrication strategy similar to that used for Radio Frequency Quadrupoles (RFQs) was adopted: each quadrant was machined individually with fully finished RF surfaces, while leaving extra material on the assembly interfaces [9]. After the quadrants were machined, their mating surfaces were adjusted based on coordinate measuring machine (CMM) measurements to ensure alignment within ±10 μm.

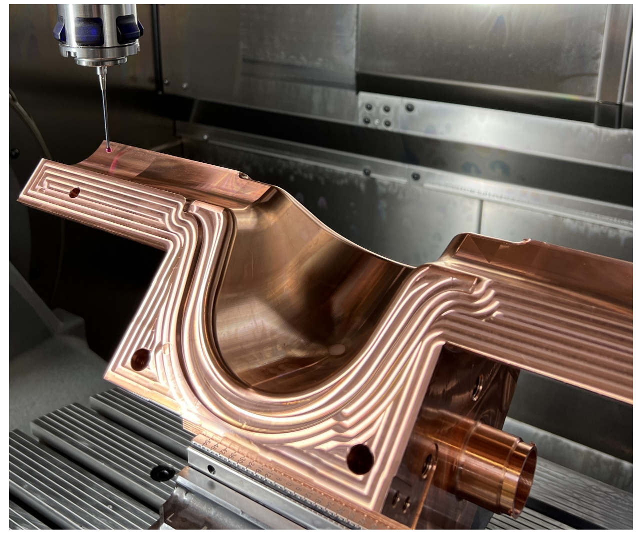


Figure 2: Machined quadrant of a 1.3 GHz SWELL cavity.

FABRICATION TOOLING DESIGN AND OUTLOOK FOR FUTURE PROJECTS

Machining shell-like cavities is challenging due to the extreme aspect ratio between the small iris opening and the deep undercut of the cavity shape (which limits tool accessibility), as well as the large amount of material that must be removed. These challenges were addressed through a combination of advanced toolpath strategies and custom tooling solutions.

Designing custom tools for these operations is typically an iterative process: an initial tool geometry is defined, the toolpath is simulated in CAM to check for insufficient clearance, and the design is subsequently refined based on the simulation results. To streamline this process, a geometry-based method was developed to directly compute the maximum allowable tool envelope based on the part geometry and the planned toolpath (Figure 3). This computed envelope is then imported into CAD software, where the custom tool is designed to fit precisely within those boundaries. This method eliminates much of the trial-and-error in tool design and ensures that the final tool geometry is optimized for maximum stiffness and stability, thereby improving machining performance.

Using this envelope-guided design approach, it was shown that the entire inner surface of a 1.3 GHz cavity can be machined in a single continuous pass, maintaining contact from iris to iris. This also confirms the feasibility of producing two-cell 1.3 GHz cavities entirely through bulk machining.

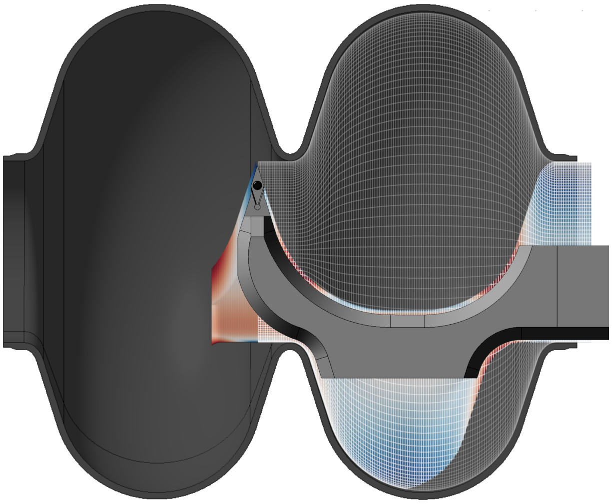


Figure 3: Schematic illustration of a 2-cell 1.3 GHz cavity geometry, the computed maximum tool envelope ensuring collision-free finish turning, and a custom tool designed to fit within these constraints while maximizing rigidity.

IMPACT OF PROCESS PARAMETERS ON SURFACE INTEGRITY OF OFE COPPER

Bulk-machining cavities offers a seamless approach, uniform wall thickness, smooth and accurate surfaces. While post-machining treatment is less intensive than those required by other standard fabrication methods, they remain essential to reach optimal RF performance [5]. This requirement arises because the cutting process generates plastic deformation and thermal loads that can lead to microstructural changes such as grain refinement, recrystallization, grain elongation, and oxidation on the copper surface.

To address this, studies have been conducted to quantify the depth of material affected by machining and to predict the copper microstructure that will be exposed after post-machining treatments. Although a direct correlation between dislocation density and RF performance has not yet been clearly established, the goal, by minimizing the thickness of the affected layer is to recover the properties of the bulk material after electropolishing (EP). These efforts require correlating the affected depth with process parameters. Investigations have been carried out for both turning and milling operations to reflect the range of fabrication approaches used in current and future cavity designs.

Analysis of surface integrity in finish turning

Surface integrity during finish turning was investigated in the context of developing niobium-coated QWR cavities for HIE-ISOLDE. A Kistler dynamometer was used to record cutting forces and a thermocouple was placed 0.5 mm below the tool's rake face to provide comparative measurements of the thermal loads between different tests [10]. Tests were conducted on 3D-forged OFE copper samples, varying the cutting speed, feed per revolution, and depth of cut. The cutting tool was a single uncoated carbide insert with a rake angle of 18°, an edge radius of 9 μm, and a cutting edge angle of 93°. It was observed that stable cutting required a minimum depth of cut of about 0.1 mm. This is consistent with earlier findings that, for OFE copper, the ratio of uncut chip thickness to tool edge radius must exceed approximately 5 to avoid a sharp increase in specific cutting force [11]. Temperature measurements did not reveal significant differences when crossing this chip-thickness threshold. However, as the depth of cut increased further, a rise in specific cutting force was observed, indicating the transition to a different cutting regime [10].

To evaluate how these cutting conditions affected the material below the surface, samples were analyzed using transmission electron microscopy (TEM), focused ion beam (FIB) cross-sections, and electron backscatter diffraction. Under typical finishing parameters, three distinct layers beneath the machined surface were identified:

- A recrystallized surface layer about 0.6 μm thick.
- A second layer, up to 4 μm deep, composed of highly elongated grains formed by mechanical deformation, but without sufficient energy input to induce recrystallization (Figure 4).
- A third layer, up to 60 μm deep, still exhibiting a slightly different, and notably lower, dislocation density than the bulk material.

An important observation was that the combined thickness of the recrystallized and deformed layers increased by a factor of three when inappropriate tools or cutting conditions (such as ploughing) were used [10].

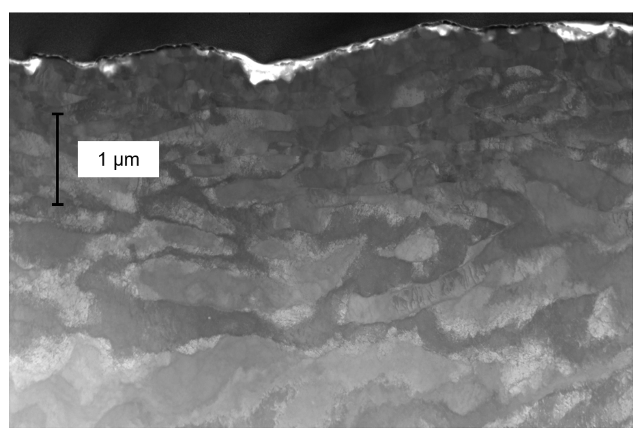


Figure 4: TEM analysis of a FIB-prepared lamella, showing the effects of ploughing during finish turning.

Analysis of Surface Integrity in Finish Milling

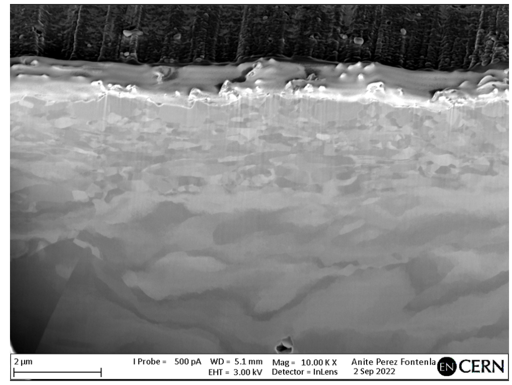
The development of the SWELL cavity has motivated to expand the investigation into the relationship between milling parameters and surface integrity. To this end, a set of analysis samples replicating the geometry of the cavity equator were machined [12]. These samples underwent the same subsequent treatments as the actual cavity, including an EP step (removing about 12 μm of copper) and the deposition of a niobium film using high-power impulse magnetron sputtering (HiPIMS) [13]. A matrix of milling conditions was tested, varying factors such as the tool material (carbide versus diamond ball-end mills), tool wear (new versus worn tools), cutting parameters (feed per tooth and cutting speed), toolpath pattern (parallel passes versus a spiral path), and the use of a spring pass (a light final pass to improve finish).

Analysis of the results using FIB–SEM imaging and Grazing-Incidence X-Ray Diffraction (GI-XRD) revealed a strong correlation between surface roughness and the depth of the affected layer, consistent with earlier observations for machined pure copper [14]. In particular, spiral toolpaths and the use of worn tools resulted in poor surface finish and a significantly increased thickness of the affected layer. Conversely, machining with a diamond tool produces the best surface finish, which also corresponds to the thinnest damaged layer (Figure 5). The superior performance of the diamond cutting tool can be attributed to its extremely sharp edge, low chemical affinity for copper (which prevents material build-up), and exceptional thermal conductivity (approximately five times higher than copper and twenty times higher than typical carbide tools).

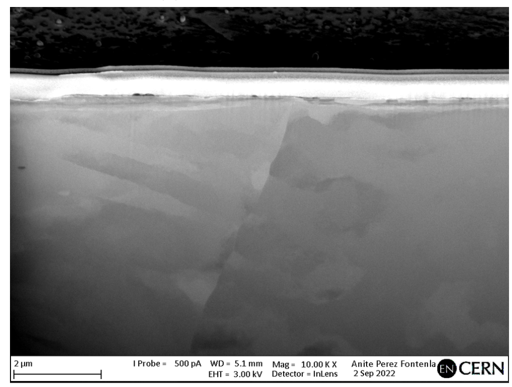
An exception to the observed correlation between surface roughness and the thickness of the affected layer was found in samples machined under reduced cutting conditions. Although these samples exhibited good surface finish, they also showed the highest dislocation densities in the niobium coating and an important thickness of the damaged layer. This phenomenon was attributed to ploughing, underscoring the importance of maintaining a feed per tooth well above the tool edge radius.

Regarding dislocation density, this study also demonstrates a clear relationship between the dislocation density present in the machined copper substrate and that subsequently observed in the niobium coating after EP.

Given that the best results were achieved with diamond tools, future work will broaden the investigation to include several monocrystalline and polycrystalline diamond tools, as well as diamond-like coated carbide tools from various suppliers.



(a) Worn carbide tool



(b) Diamond tool

Figure 5: FIB-SEM cross-sections of samples milled with (a) a worn carbide tool and (b) a diamond tool [12].

CONCLUSION

The development and fabrication of seamless single-cell copper elliptical cavities through bulk machining at CERN have demonstrated clear advantages over traditional methods, especially for prototyping and research applications. This approach has been successfully applied to both 1.3 GHz and the larger 400 MHz elliptical cavities, enabling the elimination of the equator weld while delivering exceptionally smooth RF surfaces, highly accurate geometries and uniform wall thickness.

Furthermore, the process reduces the subsurface damaged layer compared to other standard shaping processes. Both turning and milling investigations highlight the strong influence of tool material, wear, and process parameters on the thickness and properties of this affected layer. In particular, diamond tooling consistently yields superior results, producing both the thinnest damaged layers and the lowest dislocation densities, due to its sharpness, thermal conductivity, and low chemical affinity with copper.

However, the results also demonstrate that a good surface finish alone is not sufficient: under certain reduced cutting conditions, ploughing can occur, leading to increased subsurface damage and higher dislocation densities, both in the copper substrate and in the subsequent niobium coating. This finding underscores the need for careful selection and optimization of cutting parameters.

A clear relationship was observed between the dislocation density present in the machined copper substrate and that found in the niobium coating, even though EP step removes a few microns of the affected material. Although a direct correlation between dislocation density and RF performance is still under investigation, minimizing the thickness of the affected layer remains a key objective to restore the favorable properties of bulk copper at the surface and to support high-quality niobium films.

Looking ahead, efforts will focus on exploring advanced tool materials such as monocrystalline and polycrystalline diamond tools, as well as diamond-like coated carbide tools. The advances described in this work provide a solid foundation for continued improvement in seamless copper cavity fabrication and support the development of high-performance, cost-effective superconducting RF structures across a wide range of frequencies.

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