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Machining of bulk 1.3 GHz cavity

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Abstract

This work describes the machining process of the first 1.3 GHz radio-frequency (RF) accelerating cavity prototype machined entirely from a bulk material. The RF cavities are a thin-wall complex shape structures fabricated from superconductive materials such as niobium. The standard fabrication process is a combination of sheet metal forming of cut-offs and half-cells and electron-beam (EB) welding of iris and equator. To avoid EB welding in the most critical equator area, some seamless cavities have already been fabricated by spinning or hydroforming. While the final cavity shape was achieved, their shape accuracy, thickness uniformity, and surface roughness could still be improved. Therefore, the seamless cavity manufacturing by machining from an entire bulk was tested at CERN. The main issue was the surface accessibility for machining of inner form. For this purpose a custom toolholder was designed, manufactured and tested. Then, the manufacturing process was done in several steps: turning roughing, 5-axis milling roughing, turning finishing of inner and external shape. As an outcome of our development a prototype from aluminium alloy EN AW-6082 was successfully fabricated. The metrology and the thickness measurement of the inner RF form were performed and the surface roughness was also evaluated to show the potential of 1.3 GHz cavity manufacturing by machining from a bulk material.

1.3 GHz cavity, Machining

1. Introduction

The standard fabrication process of the accelerating RF cavities is a combination of metal sheet forming, machining and EB welding [1-4]. The half-cells are usually formed by spinning or deep drawing with tubes manufactured by rolling and longitudinal welding. These assemblies require several EB welds including the main risk of equator weld contamination [5]. Therefore, some different techniques have been investigated in order to avoid the equator weld, where the risks of performance loss caused by the porosities is very high. In last years INFN in [6] investigates spinning of whole iris-equator-iris form from one disc. The spinning method is not a very accurate technique and it requires several intermediate heat treatments to achieve the final form [6]. Then the hydroforming of multiple-cells was investigated and established in DESY [7] from copper and niobium tubes. The disadvantage of spinning and hydroforming is varying wall thickness along the profile and the necessity to perform polishing to obtain a satisfactory surface finishing.

The cavity machining from bulk is a challenging task, which involves machining thin walls, difficult to reach internal surfaces, and complex workpiece clamping. The main motivation was the possibility to control the profile thickness and achieve a cavity with the most accurate shape with high surface quality. The bulk fabrication method has been successfully developed on the aluminium prototype at CERN in 2019.

2. Materials and methods

The raw material for the prototype is an aluminium AW-6082 bar. The bar initially measures 220 mm in diameter and 140 mm of length. The machining is performed using Hermle C42U 5-axis milling centre and Biglia B750Y turning machine. The finishing of cavity was performed using Sandvik Coromant VCMW110204FPCD10 polycrystalline diamond (PCD) turning plates for interior and Masnada monocrystalline diamond (MCD) inserts for exterior surfaces. The manufacturing process of the prototype consist the following steps:

- Roughing turning of exterior diameter and boring of interior to permit access for the milling tool;
- Precise finishing of two parallel extremity surfaces, which are used as a reference planes for each of further operations;
- 5-axis roughing milling of interior of cavity to allow access for the finishing turning tool;
- Finishing turning of inner shape from both sides using the custom toolholder;
- Finishing turning of external shape from both cavity sides.

2.1. Concept of a toolholder for inner turning

A particular difficulty of the inner cavity turning is the limited access to the machining areas. The inner diameter on the iris surfaces is equal to 78.1 mm, while the largest inner diameter (in the equator area) is equal to 206.6 mm. There are no existing tools on the market which could reach the equator of the Cavity. The custom toolholder was designed and manufactured at CERN. In order to reinforce the holder and minimize chatter during machining, the toolholder shape aims to follow the cavity profile (see Fig.1). For this reason, the toolholder is designed to perform only semi-finishing and finishing machining process. The simulated gap between tool and finished inner cavity surfaces in the nearest point is equal to 2 mm. The toolholder is manufactured from one block of C45 steel and assembled with the standard Sandvik Coroturn 107 insert holder by four M8 screws. The customized copper cooling nozzles are added to ensure the emulsion propagation directly on the insert cutting edge.

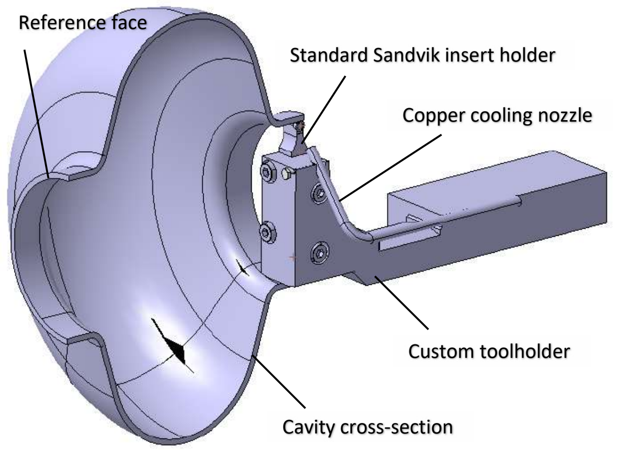

Figure 1. Custom toolholder illustrated on the cavity cross-section.

During the first semi-finishing pass, it occurred that in some areas the offset between the cavity and the toolholder was not sufficient. The chips are sticking between toolholder and cavity and are locally marking the workpiece surfaces. To improve these issues, additional chamfers had to be re-machined on the toolholder (Fig. 2).

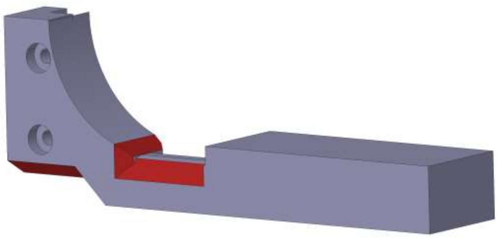

Figure 2. Final design of the special toolholder with additional chamfers.

3. Machining

3.1. Turning roughing and milling

During the roughing turning, the piece is machined according to the drawing below (see Fig. 3). At the same time, both surfaces (the references A and B) are finished. The position and parallelism of these planes is essential, as they will later be used for referencing origin of each subsequent machining operation (roughing milling and the final interior and exterior turning are performed from both sides of the cavity).

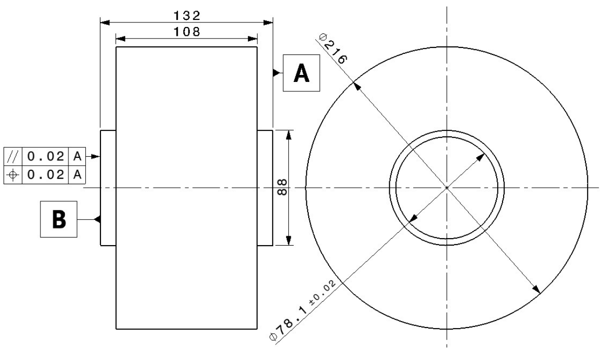

Figure 3. Rough turning sketch.

Once the part is turned, the milling operation is performed. The milling of the inner shape is a challenging process due to the large volume of the material that has to be removed, poor chips evacuation, limited tool access and the high tool diameter/length ratio required.

The toolpath programming is done directly on the machine control command. The program is performing constant spiral machining using fixed inclined A-axis with C-axis in rotary and Z-axis in linear motion. The gradual increasing of the A-axis angle allows to remove more and more material in the cavity equator direction. The Figure 4 shows exemplary positions inside the workpiece to which the tool is tangent. The positions are calculated using Catia software by prepositioning of tool model on the cavity profile in multiple angle configurations. The roughing milling is divided in two operations, using 29 different A-axis angles. First one is done with toroidal insert type mill of Ø 40 mm and the corner radius of 6 mm and the second one is a toroidal mill Ø 25 mm with the corner radius of 4 mm. The operation is repeated from both sides of cavity extremities.

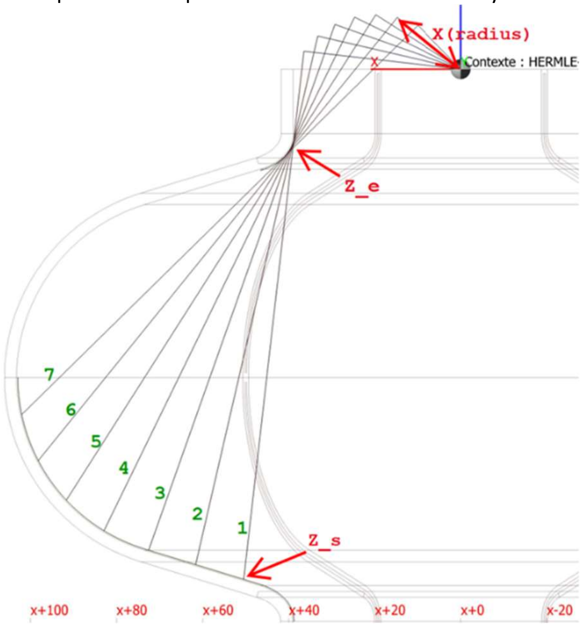

Figure 4. Definition of increasing of the tool angle inside the workpiece (for the tool of Ø 40 mm).

The roughing machining configuration is showed in Figure 5 and the detail picture of roughed inner surface of cavity is showed in figure 6. The machining allowance in reference to finished surfaces was 0.6 mm. After the roughing operation, by realising of the internal stresses the piece deformed and the reference planes approached in reference to each other by around 40 µm.

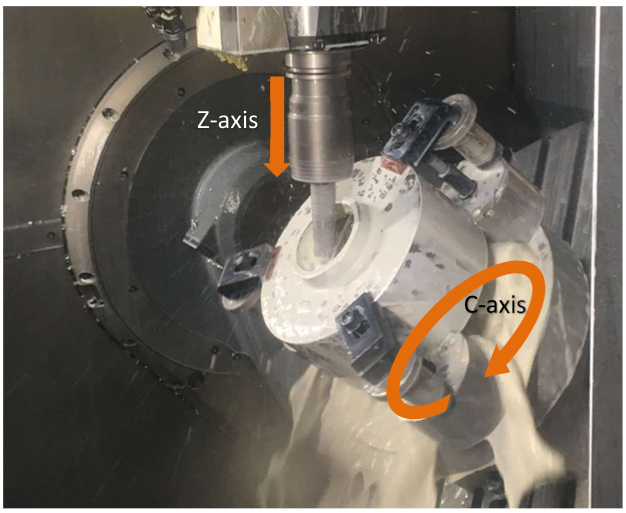

Figure 5. Machining set up during roughing milling with Ø 25 mm toroidal mill.

Figure 6. Inner cavity surface after roughing milling.

3.3. Turning finishing of the inner surfaces

The turning of the inner surfaces of the cavity is performed in two set-ups. For each of them, the piece is clamped in the machine chuck by the massive exterior allowance material. The machining pass goes from the iris to the equator direction, then the tool is off-set from the surface by 0.2 mm and retracts from the workpiece following the profile. Three semi-finishing passes are done, leaving 0.08 mm of the allowance (on the radius) for the finishing pass. The finishing pass is performed by the PCD insert with the constant cutting speed of 350 m/min and the feed rate of 0.01 mm/rotation. Once the half of cavity is finished, the piece is turned, and the process is repeated. The pictures below show the equipped custom tool before (Fig. 7) and during turning operation (Fig. 8).

Figure 7. Final design of the toolholder mounted in the machine.

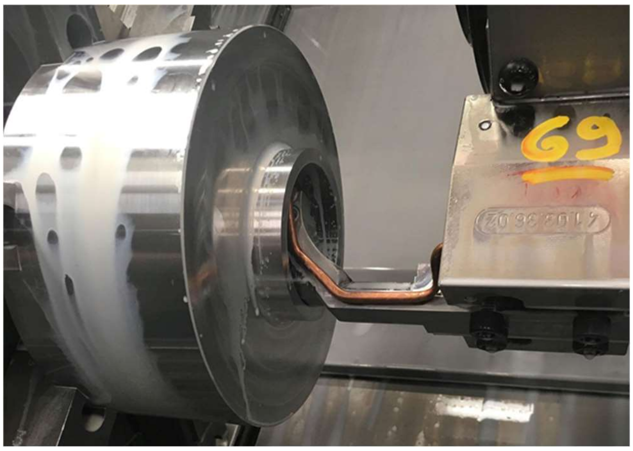

Figure 8. Machining set-up during inner turning finishing.

3.4. Turning finishing of exterior form

During the finishing of the first half of the external cavity form, the workpiece is clamped in the machine chuck by the remaining material. The material is taken up to the allowance of 0.08 mm on the radius and then finished with MCD inserts applied with the same cutting parameters as in case of the internal machining. For the second side, the main difficulty is to hold the cavity by the thin walls of 2.8 mm and at the same time avoid the resonance and chatter. For this purpose, the aluminium mandrel and the small cover plate adjusted to the internal diameter were manufactured. From one iris side the workpiece is fastened in 6 soft-jaws chuck. From the second side, a pressure of 2.5 kg (over this pressure, the cavity starts to deform) is applied on the cover by the tailstock sleeve. The picture below illustrates the machine set-up during the last operation (see Fig. 9).

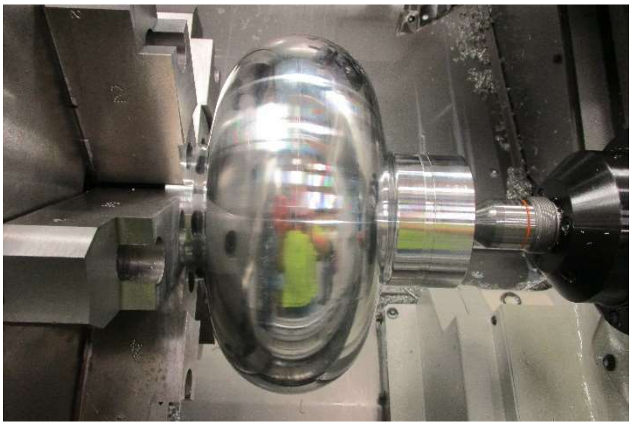

Figure 9. Machining configuration during external finishing.

4. Results

The measurements of the finished prototype are performed by Zeiss Prismo Ultra 12/18/10 Coordinate Measuring Machine (CMM). The maximum deviation from the nominal value in the interior surfaces is equal to 43 μm and 24 μm on the external surfaces. Figure 10 illustrates the shape variations on the external and internal surfaces. The overall thickness deviation of the wall varies in range of ±30 μm (to compare, ±200 μm in case of hydroformed cavities [5]). Those deformations occur probably during the removing of residual stresses in material while exterior machining, and while applying clamping force by the mandrel.

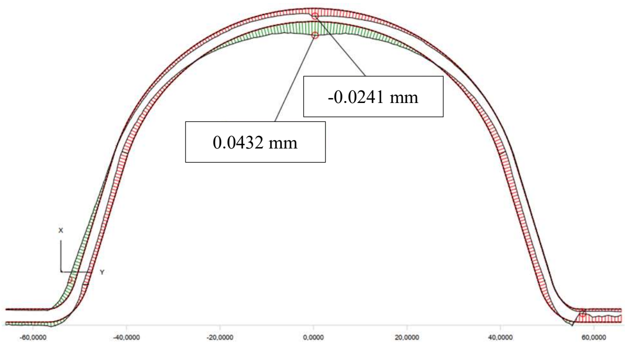

Figure 10. Internal cavity shape.

The surface roughness was controlled using Mitutoyo S-3000 stationary instrument. The measured roughness is equal to Ra 0.16 μm. The cavity weights 740 g, 94.8 % of initial material was removed during machining.

5. Conclusions

As a result of machining and tool development, the first aluminium prototype of bulk 1.3 GHz cavity was successfully manufactured (see Figure 11.).

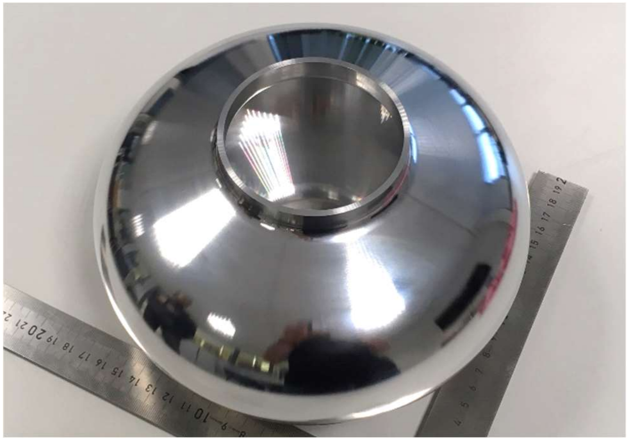

Figure 11. Finished cavity prototype

During the manufacturing process, the custom toolholder for internal finishing was developed, designed and modified to achieve functional and rigid form. The fabrication process from raw material to final product takes around 20 hours of machine time, which makes the process relatively inexpensive in serial production. The main disadvantage is a large volume of material loss, which would increase the cost in case of high-value material as high RRR niobium.

The bulk manufacturing process open the fabrication opportunity to obtain cavities with geometrical tolerances as never achieved before and sound base material free of shaping and welding imperfections. The manufacture of fully functional OFE copper cavity is planned for 2020.

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