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MANUFACTURING OF X-BAND ACCELERATING STRUCTURES: METROLOGY ANALYSIS AND PROCESS CAPABILITY

J. Sauza Bedolla, S. Atieh, N. Catalan Lasheras

CERN, Geneva, Switzerland

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The fabrication tolerances of RF components are essential for CLIC X-band accelerating structures to perform efficiently. On one hand, the capability of high power accelerating structures depends on the shape accuracy and the asperity of the inner surfaces, when microwaves pass through the cavity. On the other hand, surface flatness and dimensional tolerances are necessary to guarantee a correct assembly process. Hence, the discs that build up the structure require sub-micrometre specifications and, in order to meet all the needs, ultra-precision machining using single crystal diamond tools is mandatory. This paper shows the analysis of the metrology results of the fabrication of 118 discs (4 accelerating structures). Dimensional and form tolerances are studied following the production order to find drifts in the production and to predict the impact on the assembly process. Finally, process capability is evaluated.

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The fabrication tolerances of RF components are essential for CLIC X-band accelerating structures to perform efficiently. On one hand, the capability of high power accelerating structures depends on the shape accuracy and the asperity of the inner surfaces, when microwaves pass through the cavity. On the other hand, surface flatness and dimensional tolerances are necessary to guarantee a correct assembly process. Hence, the discs that build up the structure require sub-micrometre specifications and, in order to meet all the needs, ultra-precision machining using single crystal diamond tools is mandatory. This paper shows the analysis of the metrology results of the fabrication of 118 discs (4 accelerating structures). Dimensional and form tolerances are studied following the production order to find drifts in the production and to predict the impact on the assembly process. Finally, process capability is evaluated.

INTRODUCTION

The Compact Linear Collider (CLIC) is an international study for a future high-gradient, multi TeV electron-positron linear collider. In order to test CLIC's main parameters, 72 Accelerating Structures (AS) prototypes, of 22 different designs, have been built during the last ten years. Six principal suppliers of five different countries have participated in the production of CLIC components. This paper evaluates the performance of one of these suppliers in the production of four accelerating structures.

The AS baseline design represents a diffusion bonded stack of cylindrical Oxygen Free Electronic copper discs, which are machined to form a cavity of the RF cells. The discs (or cell) geometry and high order modes damping loads had been extensively optimized in order to maximize the RF-to-beam efficiency, and to meet the beam dynamics and high gradient RF constraints [1]. A regular cell disc is described by about ten different parameters that define its geometry. The internal shape and alignment of the cells are crucial for efficient collider operation. The mechanical tolerances of the cells have been defined according to the RF requirements [2] and they are defined in the CLIC Design Report [3]. Sub-micrometre tolerances are needed to reach the accelerating gradient goal of 100 Mv/m if no tuning is applied and if no temperature correction is allowed to the AS [4].

CLIC TD26R1CC PROTOTYPE

In 2015, there was a re-design of the 3 TeV CLIC main linac AS at 12 GHz [5]. This new prototype is a tapered, damped, 26 regular cells with integrated compact couplers. Main changes include a modification on the "nose" of the waveguide from an elliptical geometry to a 4-th order polynomial function. Moreover, the radius at the bottom of the RF waveguide was increased from 0.5 mm to 1 mm to allow the use of bigger milling cutter, and therefore, to reduce the machining cost. Finally, the disc diameter was increased from 74 mm to 83 mm in order to have a more rigid interface between waveguides and the disc stack. This is the biggest disc diameter design in CLIC production history. The most important tolerances were maintained with respect to the previous design.

- Diameter of the disc Ø83 mm: ±1 µm
- Concentricity of iris with respect to the disc diameter: 2 µm
- Cell iris shape accuracy (zone A): 5 µm
- Cell waveguide shape accuracy: 20 µm
- Flatness accuracy: 1 µm
- Cell iris roughness (zone A) Ra 0.025 µm
- Cell waveguide roughness Ra 0.1 µm

MANUFACTURING

The total fabrication included four structures: 98 standard cells plus 20 compact coupler cells (total 118 discs). This quantity represents the biggest amount of discs ever produced in a single order. The contract was adjudicated to one qualified, CERN's member state company. The production of the whole supply took four months. The parts were produced by a combination of Ultra-Precision diamond fly cutting, milling and turning. All discs were manufactured in batches of four in the milling step, while they were individually machined in the fly cutting and turning steps. The parts were measured at the factory with a customized CMM machine (accuracy better than 0.6 µm) for dimensional control and a white light interferometer (non-contact) for roughness measurements. Results were validated at CERN, where no significant differences were found. Furthermore, visual inspection was also performed before accepting the batch (Figure 1).

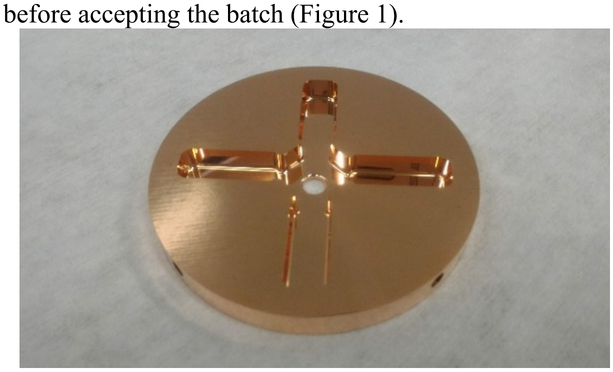

Figure 1: Visual inspection of a standard cell.

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DIMENSIONAL CONTROL

For each disc, a dimensional report, roughness measurements and form measurements were delivered. Two analyses were performed: production order, to find drifts in the production; the assembly order, to predict the impact on the assembly process. The performed analysis has covered all the tolerances; however, for the sake of brevity, only representative graphs are shown in the following.

The discs were identified according to its position on the AS and to the structure number they belong to. G02-1 represents cell number two of the structure number one. The production order started with regular cell disc number G25 (smallest iris) to G02 (biggest iris); compact coupler cells (G01, G26, G00, G27, G28), that have a different geometry with respect to regular cells, were produced last.

Production Order

Given that, this was the first big production series, the production order analysis allow us to look for signs of non-in statistical control process and to learn if significant changes have been applied during the production. Figure 2 shows the control chart order of the diameter Ø83 mm. Normal variability can be observed along with 14 parts out of tolerance. The non-conform parts were accepted since the maximum deviation was 0.5 µm.

Iris diameter is one important feature since it affects the cell to cell coupling and a variation will cause internal reflections and standing wave pattern [6]. Furthermore, the iris cannot be tuned. Figure 3 shows the difference between the measured iris diameters compared to the nominal. Except from five discs, the process systematically created slightly bigger iris diameter (in average 0.5 µm). The discs that did not follow the trend were originally rejected and manufactured, in a second batch, at the end of the production. Even if the parts do not follow the general trend, they are still within the 5 µm tolerance.

Assembly Order

The objective is to identify the variability, in a single graph, of the 29 discs that builds up one structure. Figure 4 shows the structure number one where two discs, cells G00 and G21, are out of the 1 µm tolerance, while G25 is at the upper limit. The G00 disc geometry is different with respect to the normal cells. It presents a non-continuous surface and, for this reason, when discs are unclamped the flatness increases. The G00 is located at the bottom of the structure and it is assumed that the non-perfect surface will be flattened by the weight of the rest of the structure.

In Figure 5, the four structures are arranged in a boxplot. The bigger the box (and the whiskers), the bigger the variability of the measurements. The graph shows that first and third structure have less variability compare to second and fourth structures. Moreover, outliers, measurements distant from the rest of the observations, are present in the four structures. These outliers correspond to the already cited coupler cells (G00) and to regular cells out of tolerance at the beginning of the production. From the first twenty produced discs, there were six parts out of the tolerances. The firm identified the root-cause and introduced a second intermediate fly-cutting operation that greatly improve the flatness of the rest of the discs.

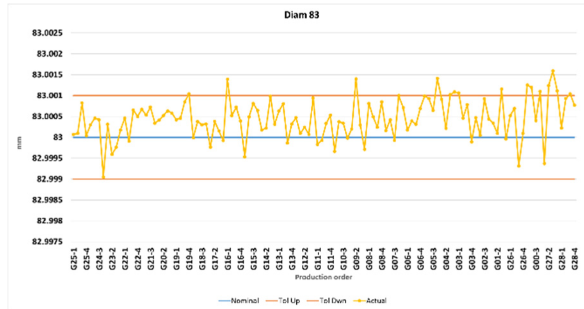

Figure 2: Control chart of Ø83 mm.

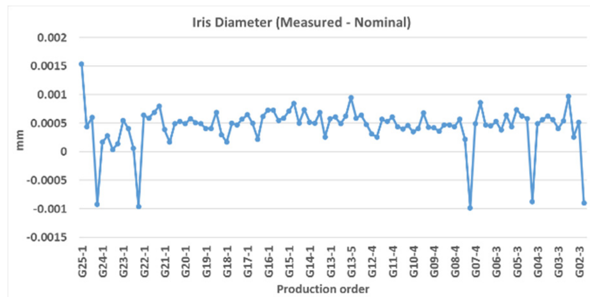

Figure 3: Control chart Iris diameter.

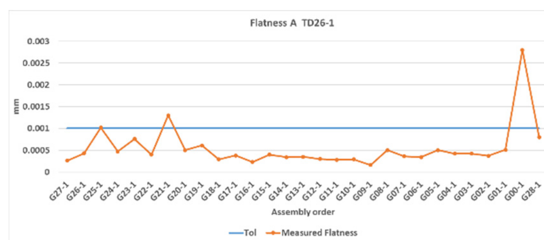

Figure 4: Control chart flatness A structure TD26-1.

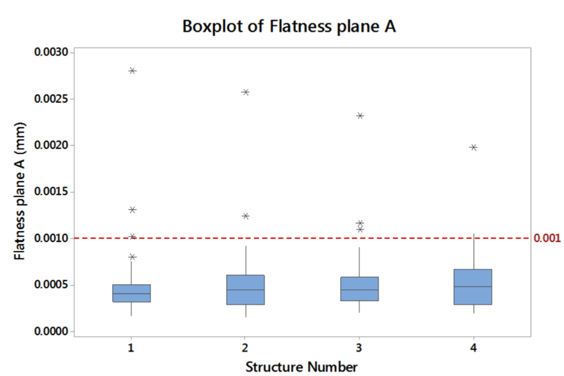

Figure 5: Box plot of flatness plane A.

Roughness and Shape Accuracy.

Scratches, machining marks or sharp features on the cavity surface of the AS can greatly affect its performance. For this reason, roughness was evaluated at six different positions: bottom of the waveguide, turning milling step (two zones), reference plane A, iris (two zones). The roughness measurements were largely conform to the specification. Figure 6 shows the most delicate step for the turning milling zone. In this transition zone, a step of 1 µm is allowed.

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Moreover, shape tolerances of the iris and waveguides were also controlled. Figure 7 presents two different shape measurements on one cell: one section of the iris and the nose of the waveguide. All discs were largely in tolerance.

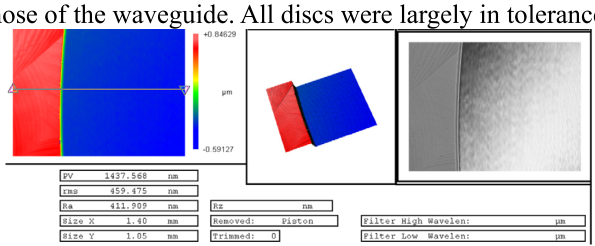

Figure 6: Roughness measurement.

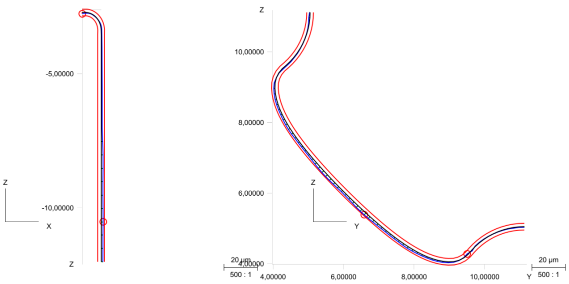

Figure 7: Shape analysis.

PROCESS CAPABILITY

Process evaluation is important for a successful industrialisation. Among several techniques, process capability is considered the most effective method in selecting quality products or parts [7]. Process capability compares the output of an in-control process to the specification limits by using capability indices [8]. Cpk is an index (a unitless number) which measures how close a process is running to its specification limits. The greater the Cpk index, the lesser is the process natural variation.

Figure 8 shows the process capability of Ø83 mm fabrication tolerance. The process has a Cpk = 0.42 which can be translated into 106244 defectives Parts Per Million (PPM). However, at the beginning of the fabrication the tolerance was relaxed from ±1 µm to ±2 µm. Considering this enlarged specification, the production reaches a Cpk = 1.1 thus 14 PPM. The tolerance relaxation was agreed after a technical discussion, capability analysis and commercial settlement. A similar analysis was performed on the concentricity of the iris and external diameter. The Cpk shows an impressive 2.24 hence 0 PPM (Figure 9).

CONCLUSIONS

The production analysis allowed us to identify changes in the manufacturing of the parts: a second fly cutting operation was added in order to improve the flatness. Moreover, the assembly analysis allow us to identify variability among the different structures. Besides some specific problems (i.e. flatness at the beginning of the production), the processes are under statistical control with few parts out of the specifications. The concentricity of the iris w.r.t. external diameter has even a large Cpk. Shape accuracy and roughness of the different features are largely conform. Considering the tight tolerances and the large production, results are positive. An important benefit for CLIC is the correct evaluation of supplier performance by identifying the technically and economically correct tolerances.

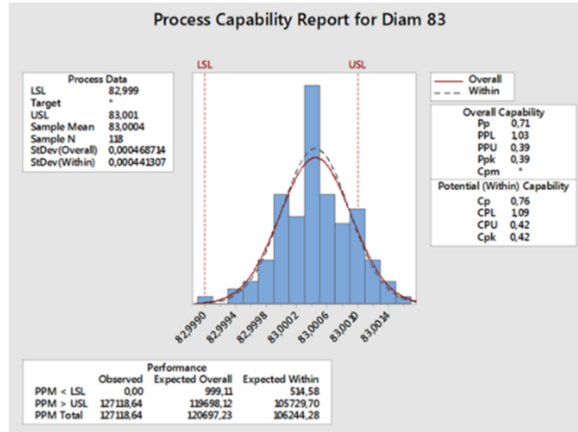

Figure 8: Process capability of Ø83mm.

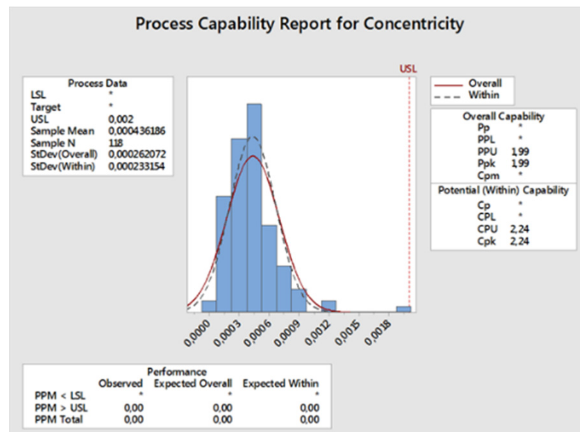

Figure 9: Process Capability of concentricity.

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