MACHINING AND CHARACTERIZING X-BAND RF-STRUCTURES FOR CLIC

S. Atieh, M. Aicheler, G. Arnau-Izquierdo, A. Cherif, L. Deparis, D. Glaude, L. Remandet, G. Riddone, M. Scheubel (CERN, Geneva)
D. Gudkov, A. Samoshkin, A. Solodko (JINR, Dubna, Moscow Region)

Abstract

The Compact Linear Collider (CLIC) is currently under study at CERN as a potential multi-TeV e+e– collider. The manufacturing and assembling tolerances for making the required RF components are essential for CLIC to perform efficiently. Machining techniques are relevant to the construction of ultra-high-precision parts for the Accelerating Structures (AS). Optical-quality turning and ultra-precision milling using diamond tools are the main manufacturing techniques identified to produce ultra-high shape accuracy parts. A shape error of less than 5 µm and roughness of Ra 0.025 are achieved. Scanning Electron Microscopy (SEM) observation as well as sub-micron precision Coordinate Measuring Machines (CMM), roughness measurements and their crucial environment were implemented at CERN for quality assurance and further development. This paper focuses on the enhancements of precision machining and characterizing the fabrication of AS parts.

INTRODUCTION

There will be over 141’000 AS at 3 TeV for CLIC [1]. Each AS contains about 30 cells (discs), which form the accelerating cavity. The building cells of the test structures are single discs. Fig. 1 shows the waveguide side of a disc. This is a heavily damped cell with four damping waveguides. Since recent studies focus on the high gradient performance of the structures, mutual cell alignment is achieved thanks to the self-fitting feature of nesting geometries [2]. The AS is one of the ultra-high-precision components of linear accelerators to fulfil high-energy beam requirements [3]. The capability of high power AS depends on the asperity of the inner face, when electrons and microwaves pass through the cavity.

The surface qualities of the disc and cavity faces have great influence on arc generation. The surface roughness of the inner face also affects the surface contact area and the inner vacuum level. A strict shape accuracy of ± 2.5 µm and surface roughness of Ra 0.025 is required. The development of ultra-precision diamond machining technology is highly demanded for ultra-high added-value parts and products. In addition, this technology allows ultra-high-precision components with a surface roughness of a few nanometres to be manufactured without needing any subsequent polishing.

MACHINING

In order to meet all the needs and specifications of the AS, ultra-precision machining lathes using single crystal diamond tools are mandatory.

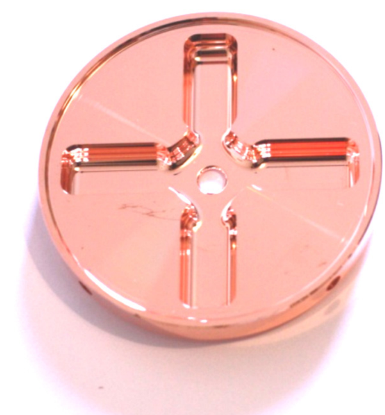

Figure 1: Typical damped cell of TD18 structure.

Such lathes are characterized by high thermal stability, hydrostatic-dampening, smallest movements of the axes, high stiffness, wear-free guideways and drives. Strict adherence to the specified precision also involves the use of controlled waviness diamond tools, where the waviness is defined by the amount of deviation from a true circle and is measured from peak to valley (typical range of waviness values is between 0.1 µm and 0.05 µm).

In precision machining using mono-crystalline diamond tools, the uncut chip thickness typically ranges from several micrometres to a few tenths of a micrometre. At such scales, surface finish and chip formation are more intimately affected by the microstructure of the work-piece [4]. In particular, while cutting poly-crystalline materials at the precision level, the material removal mechanism is highly influenced by individual grain size and orientation (as shown in Fig. 2). Therefore, unlike conventional metal cutting, the cutting mechanism in precision machining is significantly influenced by the material properties and microstructure of the work-piece material, such as ductile/brittle behaviour and micro-topographical features such as voids, secondary phases, and interstitial particulates.

Other significant advantages of ultra-precision milling are the absence of considerable residual stress after machining, and low cutting forces (do not exceed a few newtons). These factors facilitate the subsequent final diamond turning to form the flat surfaces with a required flatness ≤ 1 µm and free from burrs.

Among the various factors that affect surface roughness and shape accuracy of a work-part, a dominant factor is careful raw material choice. In this study phase of CLIC the discs have been machined from high quality multidirectional forged OFE copper (99.99 % min Cu) in half-hard temper having a fine (max. 90 µm) and homogeneous grain size, low oxygen content (5 ppm), and specific limits in ppm for sixteen additional named elements. The principal benefits are improved weldability and brazability, better mechanical stability, and increased yield strength enabled by the half-hard temper with limited risk of voids during machining. The raw material complies with ASTM F68 and the stringent requirements of CERN specifications [5] in terms of composition, microstructure, tensile properties, hardness, and ultrasonic examination criteria. The homogeneity of the material is 100% ultrasonically inspected to detect any potential continuity faults.

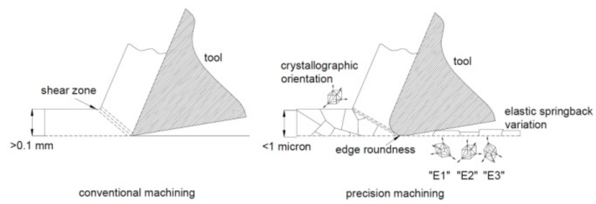

Figure 2: Relative scale comparison of conventional vs. precision cutting processes [4].

STANDARD PROCEDURE FOR SEM OBSERVATION

Milling as seen in Fig. 1 forms most of the inner surface of the discs. The quality of this milling is vital to avoid sharp ridges or burrs. Extensive care must be taken to connect the turning surface of the elliptical iris to the milled flat surface. There are three sites of interest (SOI), on which SEM observations are focused during the quality check applied to each produced structure:

1. Chamfer to top plane;
2. Transition radius between cell wall and iris wall;
3. The iris itself.

These SOI are indicated in Fig. 3 alongside selected examples. Special attention is paid to any deviation from the geometrical shape designed and level of surface finishing. Pictures are taken in two different sample positions: from the top and inclined 40°-50° in defined standard magnifications.

POSTMORTEM OBSERVATIONS

The prototype structures are submitted to high-power tests in order to evaluate their performance in terms of achievable breakdown rate at a given accelerating gradient, e. g. [6]. After these tests (several thousand hours) the structures are cut open according to an examination plan, as seen in Fig. 4. In this way the inner surfaces are accessible and any degradation occurring during the high-power test can be documented. Special focus is drawn to electrical breakdown crater distribution in individual cells or along the structure. Additionally, the characterization of any abnormality helps understand the ongoing processes in the AS exposed to high-fields.

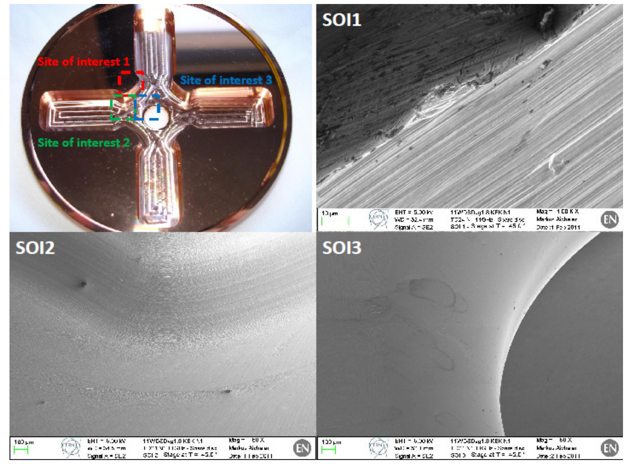

Figure 3: Standard designation of SOI. SOI1: burrs inspection on the top plan; SOI2: radii milling transitions; and SOI3: turning milling transition in the iris.

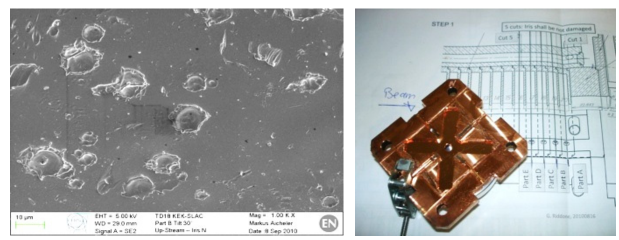

Figure 4: Observation of tested and opened structures, SEM of breakdowns feature.

Dimensional Measurements

Each structure follows a quality control assessment of the geometrical dimensions and the obtained machining precision on its so-called witness discs. The main specified tolerances are the shape accuracy (according to ISO 1101) of 5 µm in a precise reference system, this means ± 2.5 µm on each side of the theoretical dimension, a flatness of 1 µm, while the roughness is Ra 0.025. Until last year the AS were measured by a conventional CMM, the Ferranti® Merlin 750 with a measuring volume of 750 x 500 x 500 mm. The estimated measurement uncertainty is U = ± 3 µm with 2 K. This CMM does not have the capability to measure parts to the required uncertainty. Furthermore, as this machine is equipped with a TP2 sensor from Renishaw®, the probing force is between 0.07 N and 0.15 N, anisotropic depending of the probing direction. This causes damages (indents) on the mirror quality surface up to 4 µm in depth on the soft copper (hardness 40 HV30).

CERN recently acquired an ultra-high accuracy CMM, (Leitz® PMM-C Infinity) with a measuring error MPE_E [µm] = 0.3 + L/1000 (L in [mm]), a probing error MPE_P [µm] = 0.4 and a scanning probing error MPE_{THP} [µm] = 1.2 / 59 [s] according to ISO 10360-2 and ISO 10360-4 respectively. The actual 3D probe head LSP S4 enables a homogenous and adjustable probing force of 0.02 N up to 0.16 N depending on the settings needed for the measurement. Touching the part next to the stylus leaves marks on the soft copper. The probe makes these marks during point-by-point or scanning measurements. The depth of these marks is about 50 to 80 nm. The manufacturer of the machine is now developing, with CERN's input, a new head LSP S4 ANF to decrease the depth of the indents with an expected probing force of 0.005 N. Figure 5 shows a recent dimensional control plot of a qualification damped-disc (a disc of so-called TD18 structure).

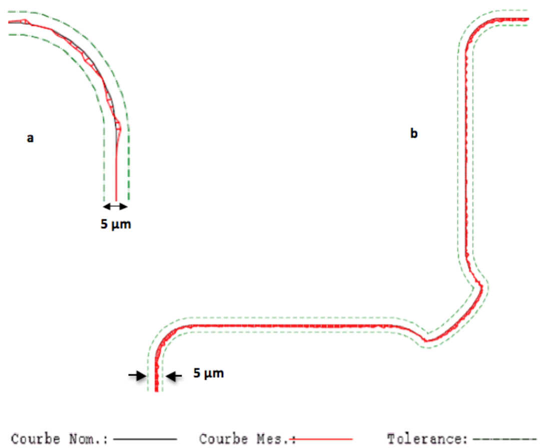

Figure 5: Dimensional plot showing the achieved shape (red) regarding the nominal path (black) and specified tolerances (green): a) iris; b) waveguide.

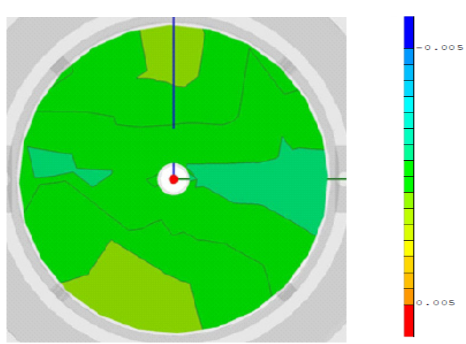

Figure 6: Surface flatness profile of reference face A, scale in mm.

The achieved flatness of 0.9 µm is shown in Fig. 6. To achieve nominal accuracy, the CMM needs a special controlled environment with low temperature gradients. To comply with these extreme conditions a dedicated laboratory was designed and installed: no solar radiation on its roof, no other machine inside the room, an optimized heat load, the light is always turned on and nobody can be inside the zone when measurements are being made so the laboratory has an additional working space in the air lock for programme construction and results analysis. All these measures were taken to comply with the temperature gradients, which are: 0.1 K/metre as a spatial gradient, 0.2 K/hour, and 0.4 K/day.

ROUGHNESS MEASUREMENTS

The roughness specification for the discs is very tight Ra 0.025 and in the iris Pa 0.025 is required. A white light interferometer (Veeco-Wyco NT3300) is used to perform these measurements on the part's accessible areas. Measurement uncertainty is down to the nanometre thanks to the Phase-Shifting Interferometry (PSI) mode. The Vertical Scanning Interferometry (VSI) has a measurement uncertainty of 50 to 60 nm. Fig. 7 shows the roughness in the milled waveguide (Ra = 5 nm), while the achieved roughness of turning is Ra = 2.6 nm for the same part.

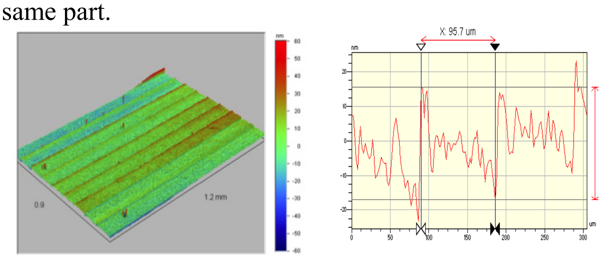

Figure 7: Roughness profile in the milled zone of the waveguide of a damped-disc. Ra 5 nm and Rt 36 nm are measured.

CONCLUSION

Ultra-precision machining technology plays an important role in developing high quality surface and high form accuracy. For the first time since the beginning of the development, the application of this process to AS manufacturing gave excellent results, within the ambitious requested specifications; roughness of Ra ≤ 25 nm (in milling and turning), shape accuracy ≤ 5 µm.

All these quality control techniques lead to characterize the precious and precise parts we get from word-wide collaborators and industry, enabling us to characterize and develop various new ultra-precision machining strategies. This will help us to extend the collaboration between CERN, CLIC, and industry.

As the dimensional control techniques are improving every day, we have to envisage other contactless techniques like pneumatic measurements, inductive measurements as well as optical devices and methods.

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