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High-volume manufacturing of precision structures for high-gradient, normal conducting RF accelerators

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Abstract

Linear RF accelerators are increasingly being applied in non-research applications such as X-ray sources for material characterization and proton accelerators for application in radiation oncology.

For both scientific and industrial accelerators, ultra-precision machining and –metrology of critical parts need to be executed in a high-volume context. In normal conducting RF accelerators, the accelerating structure consists typically a brazed stack of precision machined plates with very precise features. The features machined into these plates form internal cavities after brazing the plates. In these cavities, applied RF power introduces an electromagnetic resonance which generates alternating electric fields that accelerate the particles. Form accuracy is in the 0.1 µm – 10.0 µm ranges, while surface finish is in the order of 5 nm – 50 nm Ra roughness.

By increasing the accuracy and cleanliness levels of the accelerator parts, the voltage gradients in the accelerator structure can be further increased, leading to higher particle energy and/or smaller accelerator dimensions. Especially the industrial and medical applications benefit from smaller dimensions, enabling e.g. proton accelerators to be used in regular clinical facilities.

Until recently, these accelerator parts were made in a prototype production environment. This paper will discuss our state of the art approach for manufacturing and metrology of accelerator structures on an industrial scale. The focus will be on developments to enable reliable and scalable volume production.

Accuracy, manufacturing, surface, ultra-precision

1. Introduction

Broadly speaking there are two types of radio frequency (RF) powered linear accelerators; those based on superconducting accelerator cavities and those based on normal conducting room temperature cavities. The big advantage of normal conducting room temperature accelerators is the lack of cryogenic cooling and the high electric field gradient that can be generated. Hence the total size of the accelerator itself and its peripheral supplying structures can be reduced.

The high field gradient and high frequency of the micro wave energy ask for accelerator parts with a very accurate shape and low surface roughness. For the CERN CLIC accelerator for example, parts have typical shape accuracy in the order of a few micrometres and a surface roughness below 25 nanometres.

In this paper we address the Ultra Precision Technology (UPT) manufacturing, cleaning and measuring techniques that have been developed for the production of state-of-the-art copper parts for high gradient normal conducting accelerators.

2. Main challenges for accelerating structures [1]

The development of smaller accelerators with equal beam energy demands for high accelerating gradients of the electric field. Furthermore the frequency of the RF field has to be increased. Both factors, getting a high gradient and operation at high RF frequency, require micrometer precise machining and assembly [*figure 2*].

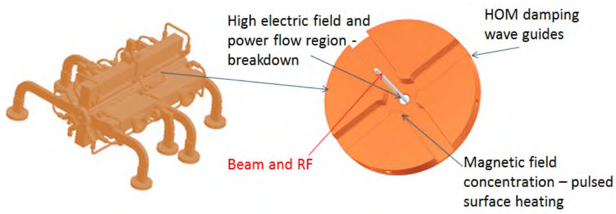

Figure 1. CERN CLIC structure with indication of the functional features that demand surfaces to be machined by Ultra Precision Technology techniques.

There are many more such interrelations between function and manufacturing, so an integrated manufacturing procedure has been developed based upon ultra-precision machining.

3. Ultra-Precision Technology (UPT) techniques

Typically the production sequence of a part consists of alternating machining and measurement steps, in order to assure product quality. Furthermore, the cleanliness of the parts is of high importance as contamination of the parts will lead to contamination of the vacuum-system they are used in.

3.1. Single point diamond machining

Where normal machine tools are made of tungsten carbide, the cutting edge of the tools used for machining the high purity (> 99.99%) oxygen free copper are based on natural diamond. These so-called single point diamond tools allow to machine the soft copper with a high accuracy combined with a mirror finished surface.

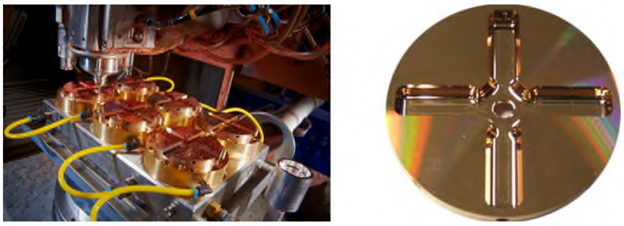

Figure 2. Diamond milling of an Ultra High Precision machined copper cavity for high gradient normal conducting accelerator of CERN CLIC. Diameter of the disk is 80 mm and the shape of the entire product is within 2 um, with a surface roughness of 5 nm Ra in the zone around the central iris and 25 nm Ra elsewhere in the cross-shape. Rotational symmetric surfaces are machined by turning, while non-rotational symmetric surfaces are milled.

The machining steps can be separated in two distinct groups i.e. milling and turning. In a milling operation, the machine tool rotates and removes material in an intermitting behaviour i.e. each revolution of the tool a small chip of material is removed. In a turning operation, the part rotates and the machine tool remains in contact with the part and a continuous ribbon-like stream of material is removed. Due to this difference in nature, a turning operation results in a surface roughness that is about five to ten times lower compared to a milled surface. Hence, it is preferred to machine as little as possible by milling [*figure 2*].

3.2. Measuring

During and after machining, parts need to be measured on the CMM [*figure 3*]. Form and position tolerances on the part are in range of 1 to 2 µm and need to be measured with a touch probe. Measuring forces need to be much lower than normally can be expected on the CMM as no metrology marks can be left on the surface. Hence, the parts are measured on a Zeiss UPMC 850 CMM with a dedicated probe that has a measuring force of only 5 grams.

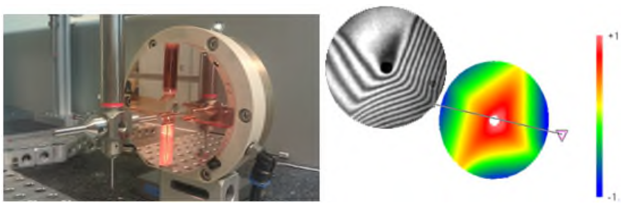

Figure 3. Cern CLIC disk on the CMM and flatness measurements on a white light interferometer.

Parts need to be as flat as possible (below 1-2 µm). Interferometer measurements are used to measure the flatness of parts [*figure 3*]. Surface finish needs to be in the region of a 5 to 25 nanometres and needs to be measured with a white light interferometer (Zygo New View 5032).

3.3. Cleaning

As the parts have to be ultra clean this has to be kept in mind during the whole manufacturing process. To avoid all possible scratches on the parts, gloves need to be worn during pre- and end-machining. Cutting fluids need to be free of chlorine or sulphur as this can contaminate the RF function of the parts. Cutting fluids used in the process need to be removed so an ultrasonic cleaning method, combined with special holding tools, was developed to clean the parts.

3.4 Joining techniques

Individual machined parts need to be joined using a bonding or a brazing technology or a combination of both. Brazing can be done at different temperatures to have several assembly stages. As the RF components need to be used in a vacuum environment, down to 10^{-10} mbar, leak testing [*figure 4*] is one of the last testing stages.

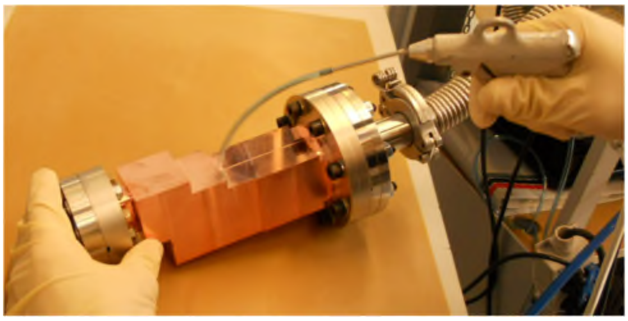

Figure 4. Leak testing of a RF component

3.5. Packaging

Given the fragile nature of the parts i.e. especially the center zone with the high RF power, packaging is a crucial step in shipping the parts to the end customer. Packaging is mostly done in membrane boxes [*Figure 5*].

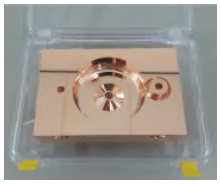

Figure 5 End packaging

4. Results of the industrialization process

VDL ETG has brought the manufacturing of these high tech parts to a reproducible and industrial scale of > 4000 parts/year with a manufacturing capability that is flexible to cope with fluctuating growth of demanded products.

This industrialization opens new opportunities as novel compact accelerator technology, like that of CERN CLIC, has the potential to be used for many other applications beyond the particle physics research: material, biological and medical research with very bright light sources: so-called X-ray free electron lasers and cancer tumor treatment with particle beams (so-called hadron therapy). [2]

First result of this industrialization is the delivery by VDL ETG of all high power RF parts for the SwissFEL, the new X-ray free-electron laser facility at the Paul Scherrer Institute (PSI). For Advanced Oncotherapy, a specialist developer and provider of the next generation of particle therapy systems, the series manufacturing of the CCL and SCDTL Structures, including brazing of the assemblies, is ongoing. Together with the Technical University of Eindhoven VDL ETG has entered a development program Smart*Light that will build a new X-ray light source based on Inversed Compton scattering.

References

[1] W. Wuensch, MeChanICs Kick Off Meeting, 2010
[2] Kenneth Österberg, HIP, MeChanICs Meeting, 2011