# IMPROVEMENTS IN CAVITY CONSTRUCTION TECHNIQUES

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**Abstract**
Two machining techniques relevant to the construction of accelerator RF cavities, optical-quality diamond turning and Electrical Discharge Machining (EDM), have undergone extensive evolution in recent years. The techniques are described and examples of their use in RF structures are presented.

## 1 INTRODUCTION

A comprehensive review of fabrication techniques relevant to the construction of RF cavities has already been published [1] and this report represents an appendix to it. Because the majority of the techniques described in the original publication have not changed much in recent years, they are not repeated here. This report rather concentrates on two machining techniques, optical-quality diamond turning and electrical discharge machining, where both the techniques and their application to the construction of accelerator RF cavities have evolved substantially over the last decade.

## 2 OPTICAL-QUALITY DIAMOND TURNING

Diamond tools have been used for some time in the fabrication of accelerator RF cavities. An example is the 3 GHz travelling wave accelerating structures of the LEP injector linac at CERN [2]. Using a standard lathe and very careful tool adjustment, 0.01 mm precision and an N3 (Ra $< 0.1$ $\mu$m) surface finish can be obtained in OFHC copper. The primary objective of such diamond turning has usually been to obtain as high an RF quality factor, $Q$, as possible.

Taking advantage of a relatively new and rapidly developing technology, RF cavities can now be fabricated to much tighter tolerances and with a greatly improved surface finish (see Figs. 1 and 2). This is possible on specialized sub-micron precision lathes using single point cutting with natural- diamond tools. The combination gives an improvement over ‘classical’ diamond turning of a soft material like copper of an order of magnitude in tolerance, to $\pm$ 1 $\mu$m, and over an order of magnitude in surface finish, to better than N1 ($R_a < 25$ nm). These advantages are particularly important for high-frequency accelerator applications, where the tolerances are critical for transverse beam stability and a high $Q$ is difficult to achieve because of the high frequency and where precision assembly requires diffusion bonding techniques.

The original motivation for the development of the precision lathes that give such a performance was the direct turning of aspherical optical components and an important early application was germanium infrared lenses for military applications. The range of materials that can be diamond turned has increased and includes non-ferrous metals, crystals and polymers. Servo-controlled tool movement linked to the rotation of the lathe spindle now also allow for the creation of ‘free-form’ optics—simultaneously aspheric and acylindrical forms.

Application of the technology is now rapidly spreading and includes pick-up lenses for DVD and CD players, lenses for fax machines and photocopiers, infrared lenses and mirrors, vision systems for defense applications, semiconductor lithographic equipment, fibre optics and data transmission systems and switches, scanner mirrors, X-ray telescope mirrors, hard disk drives, automotive fuel delivery systems, contact lenses, lens moulds and intraocular lenses.

A number of these applications now even require sub-micron tolerances, albeit for harder materials than copper. For the machining of copper, the ubiquitous RF material, these developments at least provide some margin in the capability of the machines themselves.

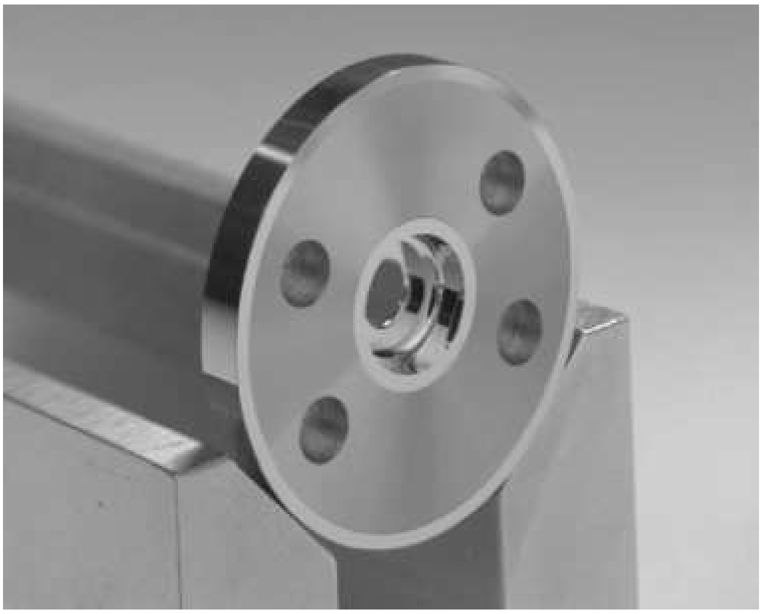

Fig. 1: Prototype diamond-turned disk of a CLIC 30 GHz accelerating structure. The outside diameter is 35 mm. The RF structure is in the 8.7 mm diameter cell and 4 mm diameter loading iris, which are the shiny features at the centre of the disk. The outer features are for bonding the disks together.

Fig. 2: Prototype diamond-turned disk of an NLC X-band accelerating structure. The four holes coupled to the accelerating cells are used for transverse wakefield suppression.

### 2.1 A description of the technology and the machines

There are some common characteristics among the specially designed lathes that are necessary for micron tolerances and optical (Ra values of less than 10 nm) surface finishes. The support structures of such lathes are very stiff, have low coefficients of thermal expansion and are dimensionally stable. Supports are often made from natural or synthetic granite and are vibration isolated from the ground. The individual temperature components of the machine are very tightly controlled—this is accomplished through multiple temperature control loop systems. Hydrostatic bearings, usually either air or oil, are used for the spindle of the lathes. The rotational accuracy is in the nanometer range. Tool motion is controlled using laser interferometer feedback loops. The control loops are designed to give a very high 'stiffness'. Tool positioning resolutions are of the order of 1 nm.

In order to obtain micron tolerances, parts to be machined must be fixed to the lathe's spindle in such a way as to induce little stress. Typically a vacuum chuck is used. During the set-up of the machine the vacuum chuck is turned using a diamond tool to ensure that it is flat and to provide a precise reference surface.

Rough-machined blanks to be diamond turned are typically over-dimensioned by a few hundredths of a millimetre. Care must be taken when machining the blanks to induce a minimum of stress. Blanks are first diamond turned on a face so that the face can be fixed to the vacuum chuck with minimum stress. The process of making a flat reference surface may have to be repeated a few times as induced stresses are released. Diamond cutting forces are of the order of a few grams. Parts which can not be vacuum chucked because the flat surfaces are not large enough to provide enough chucking force, or parts with many holes can be glued to a backing plate. Gluing is not desirable for RF components, but if it is unavoidable, the glue should be cleaned from the piece as soon as possible. Another important issue to consider when designing parts for highest precision is that as many critical features be machined as possible during a single chucking. This is especially important for maintaining concentricity between internal RF features and external mechanical reference surfaces.

### 2.2 Examples of application in accelerator RF systems

One of the primary applications of diamond turning to accelerating RF cavities has been in the linear collider studies at CERN [3], KEK [4] and SLAC [5]. All of the studies require travelling wave accelerating structures with tolerances in the 1–10 $\mu$m range and as a consequence have pursued optical quality diamond machining. Typical parts are 30–100 mm in diameter, with minimum turned inside diameters of 4 mm. In addition to producing prototypes, the studies have shown that for mass production diamond machining can be implemented at a reasonable cost.

## 3 ELECTRICAL DISCHARGE MACHINING

EDM is a process in which material is removed from a workpiece by electrical discharges. The technique works for any material with electrical conductivity and includes metals, alloys, carbides, and graphite—therefore almost all of the materials used in accelerator RF cavities. There are two distinct classes of EDM: die sinking and wire cutting. In die sinking, the form of the machining reproduces the shape of an electrode. In wire cutting a wire electrode cuts a programmed contour in the workpiece. The advantages of EDM over more classical types of machining include:

- Its capacity to make complex shapes, especially those with small internal features. For example, the internal radii of a milled rectangular hole are limited to the radius of the mill. A much smaller radius, 0.1 mm, is possible with wire-cut EDM.
- The absence of cutting forces allows simplified jigging and the possibility to machine very delicate structures.
- The absence of cutting forces gives the potential for very tight tolerances.
- Certain materials such as carbides and titanium are difficult to machine classically but present no difficulty for EDM. Electrodes can be made from a material that is easy to machine.
- Simplified assembly. Since EDM can form complex inside shapes, parts can often be machined from a single block of material. To make the same inside shape with classical machining may require machining into a few blocks of material and then bonding.

The main disadvantages of EDM are that it is relatively slow (and consequently expensive) and that it is not easy to produce a good surface finish (this is even slower). For these reasons EDM is not competitive with turning for producing the main inside RF surfaces of large and/or circularly symmetric cavities. It can, however, prove a very competitive technique for the production of auxiliary features such as power couplers, damping waveguides, cooling channels. It is, for example, ideal for producing rectangular waveguide holes inside solid material. EDM is also interesting for very high frequency (30 GHz and above) accelerating structures which have features smaller than a millimetre. EDM may also be applicable to cavities of very complex geometry such as planar and muffin-tin structures.

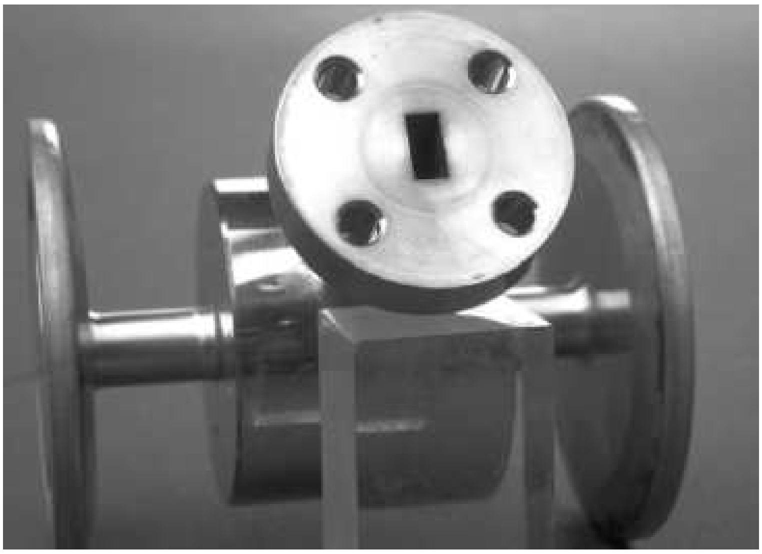

Fig. 3: Close-up view of a 30 GHz test cavity with a wire-cut output waveguide

### 3.1 A description of the technology

EDM removes material by creating a succession of sparks between an electrode and a workpiece via a pulsed DC voltage. Each spark makes a microscopic crater in the workpiece. The electrode and the workpiece are immersed in a dielectric bath, either water or mineral oil. Because of the submersion in a liquid bath, RF parts made with electrical discharge machining require an especially thorough cleaning. With typical bias voltages of X to Y volts and gaps of a few microns to a millimetre, sparks with peak temperatures of 8000–12 000°C are produced. The liquid dielectric is used to flush away the metallic particles produced by the sparks. Lower applied gradients produce a better surface finish but at the expense of a lower machining speed.

Die sinking electrodes are typically made from copper, graphite, or tungsten copper and wire electrodes from copper or brass. Wire electrodes have typical diameters of 0.2 to 0.1 mm. Electrode wires can be shifted longitudinally during machining, renewing the part of the wire doing the cutting, thus eliminating any effects of tool wear. This allows a very high degree of reproducibility over may parts. Die sinking electrodes are eroded somewhat during machining, but the effect is usually much less than the tool wear of mills.

### 3.2 Examples of application in accelerator RF systems

An example of wire cutting used in an RF application is shown in Fig. 3. It shows a 30 GHz high gradient test cavity with its output waveguide and RF and vacuum flange facing the viewer. The dimensions of the WR-28 standard waveguide are $3.56 \times 7.11$ mm. The waveguide and flange have been formed from a single block of stainless steel and the waveguide itself has been formed by wire cutting. The cut was made with a 0.2 mm diameter wire, which gives only 0.1 mm diameter radii in the waveguide corners.

This allows connection with very small impedance mismatch directly to components made from extruded waveguide tube. Because the piece was made from a single block of material, no intermediate brazing steps were required.

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