5-axis CNC ultrasonic cutting machine: design and preliminary test

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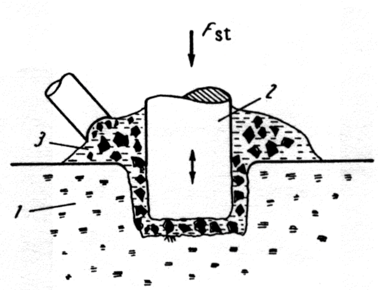
1. Principles of the ultrasonic cutting

The use of ultrasonics for machining processes of hard and brittle materials is known since early 1950s . The technology that has evolved since then, variously termed ultrasonic machining, impact grinding or slurry drilling, relies on the cutting action of an abrasive slurry flowing between the vibrating tip of a transducer and a work piece. All brittle materials – glass, technical ceramics, ferrite, quartz, tungsten carbide, sapphire, ruby and even diamond – can be abraded in this way. The main feature of the process is that the shape of the cavity produced by the tool very precisely emulates the contour of the emitter tip. Other relevant peculiarities of the ultrasonic cutting are the absence of heating and the extremely low stress levels (less than 2 MPa) applied to the work piece, making this process unique for high precision machining of crystals for applications in optics and in semiconductor technology.

Fig. 1. Diagram of ultrasonic cutting process. 1) Workpiece; 2) tool; 3) abrasive suspension.



The abrasive suspension is fed into the space between the work piece and the longitudinally vibrating tool (see Fig.1). As the metal tool tip is brought in the vicinity of the machined surface eventually one of the abrasive grains is squeezed between them. This grain becomes embedded in both surfaces as the tool moves closer. The embedding of the abrasive particle in the tool material merely produces plastic deformation. The embedding of the abrasive particle into the surface of a machined brittle material causes a pocket to be chipped out. The surface of such a material disintegrates at once, whereas a metal surface requires several cycles to disintegrate.
The minute particles of abraded material are removed along the surface perpendicular to the direction of the tool vibrations. As the material is removed, a cavity is formed in the piece, exactly copying the profile of the tool face. During the machining operation the abrasive particles participating in the operation gradually erode, hence a liquid is fed into the machining zone, where it supplies fresh abrasive grains and ensures the removal of the spent grains and material particles. Thus, the ultrasonic machine tool must provide for vibrations of the tool at large amplitude (20 μm_{pp}) and a given frequency (around 20 kHz), and it must supply the required static force (a few kilograms per cm squared) to hold the tool against the work piece and a continuous flow of abrasive suspension into the machining zone. A diagram of an ultrasonic machine tool is shown in Fig.2.

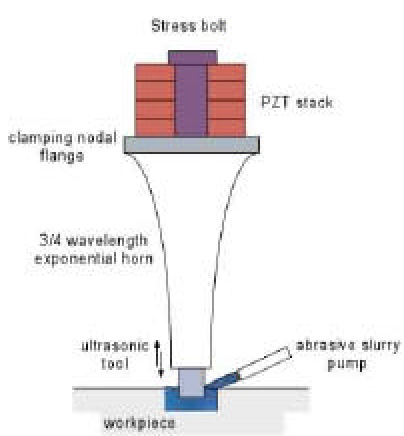


Fig.2 Ultrasonic machine tool schematic

A ceramic stack piezoelectric transducer is the source of mechanical oscillations. It transforms the electrical power received from the power supply (0.5-1.5 kW) into mechanical vibration power with a typical 60-70 % of efficiency. However, the amplitude of the resulting ultrasonic vibration is inadequate for realization of the cutting process and a waveguide focusing device ("exponential horn") is fitted onto the end of the transducer, where it is designed to enhance the vibration amplitude at its output end, with, of course, a corresponding decrease in area. The tool attached to the end of the concentrator makes it possible to form a hole having a desired shape in the work piece. In order to increase the vibration amplitude the vibratory system is designed to be driven at resonance, i.e., its length is equal to an integral number of half-wavelengths at a given frequency. The vibratory system formed by the transducer, concentrator and tool is rigidly clamped to the machine body at a nodal (zero amplitude) point. This solution prevents losses of vibrational energy through dissipation into the body of the machine. A load control mechanism stabilizes the static force between the tool and the work piece, while the abrasive is continuously fed into the cutting zone by a suitable pumping system.

The efficiency of the ultrasonic machining depends first of all on the brittleness of the material. In the machining of a pair consisting of a ductile material and a brittle one, the brittle material will break down more rapidly, regardless of which material is executing vibrations. Thus, besides machinability reasons, in order to limit tool wear the ultrasonic tool is generally made of soft steel or nickel, possibly diamond-impregnated.

Material	Relative machining speed (%)
glass	100
silicon	50
fused silica	50
agate	40
sapphire	9

Table I. Relative machining speed of differente glasses and crystals. The machinability depends on the microhardness of the material.

In Table I are reported relative machinability of glass and crystals having different machining speed. Besides the performance, ultrasonic machining is characterized by the purity of the surface and machining precision; these latter are determined mainly by the hardness of the machined material and the grit size of the abrasive suspension. The precision is interpreted as the stability of the clearance between the contours of the hole and the tool. Experience has shown that the lateral clearance is about 1.5 times the mean abrasive grain diameter.

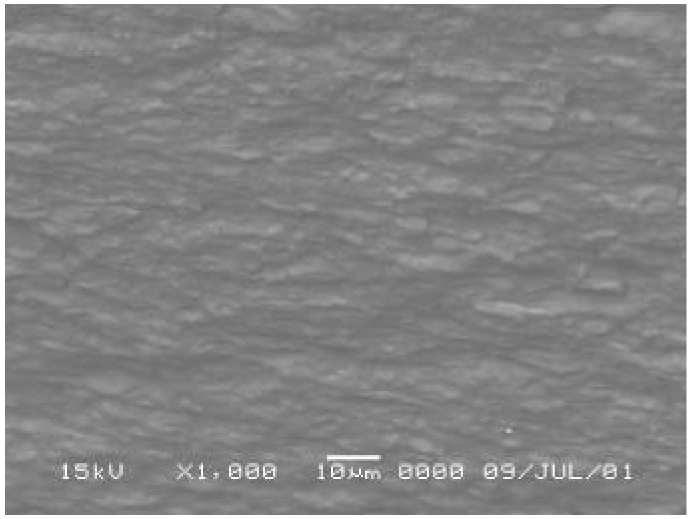


Fig.3 SEM micrograph of a single crystal sapphire surface machined in our laboratory with boron carbide 220 mesh. Irregularities of 1-5 μm can be observed.

The ultimate fluctuations of this clearance create a certain tolerance, which controls the machining accuracy. This means that a machining accuracy of a few microns is achievable with 220-mesh abrasive (see Fig.3 example); a better finishing can be obtained with a higher mesh. The surface purity, which is determined by the mean micro-roughness height, also improves with increasing hardness of the material inversely as the abrasive grain diameter. The performance of ultrasonic machining of a given material depends on the vibration amplitude, frequency, and static force.

The machining speed **v**, defined as the volume of material chipped away in unit time, empirically depends on above parameters as $\mathbf{v} \sim \xi\,(F_{st}\,f)^{1/2}$. Where ξ is the tool vibration amplitude, F_{st} is the static load and f is the frequency of operation. In experiments it has been found that the abrasion rate is often proportional to the frequency, while non-linear frequency dependence of the machining speed comes from changes in the abrasive concentration and in removal rate from the working clearance. The machining speed is also determined by the hardness and grit size of the abrasive, which has to be considerably harder than the work piece or at least of equal hardness. Most used ones are silicon carbide and boron carbide. High-speed motion picture camera observations show that the disintegration of the work piece material is caused by the impact of the tool directly against the abrasive particles immediately close to the machined surface. The machining speed is diminished by the use of more viscous fluids; this happens because the higher the streaming velocity the more rapidly the spent comminuted abrasive can be replaced by fresh abrasive and, consequently, the greater will be the machining speed. Cavitation also affects the machining process. On the one hand, the action of cavitation bubbles on the abrasive particles tends to produce a uniform distribution of bubbles under the tool, while, on the other hand, cavitation reduces the machining speed by the ejection of abrasive particle, so that the abrasive concentration in the working gap is decreased.

The nature of the stresses at the boundary between the tool tip and abrasive suspension depends on the elastic properties of the load (abrasive suspension and machined surface), the power delivered to the transducer and the static force. The vibrations have a harmonic steady-state character while the stress is impulsive. The mean force per period is equal to the static force. A fairly accurate mathematical model of the single impact dynamics shows, in good agreement with the experiments, that the peak force (in Kg) developed by the tool is given by $F_{max} \sim 1.7\ F_{st}\ \xi^{1/2}$, with ξ in microns. Typically, from experimental values of machining speed, the corresponding stress does not overcome 20 Kg/cm^2, well below the yield strength of every material of interest.

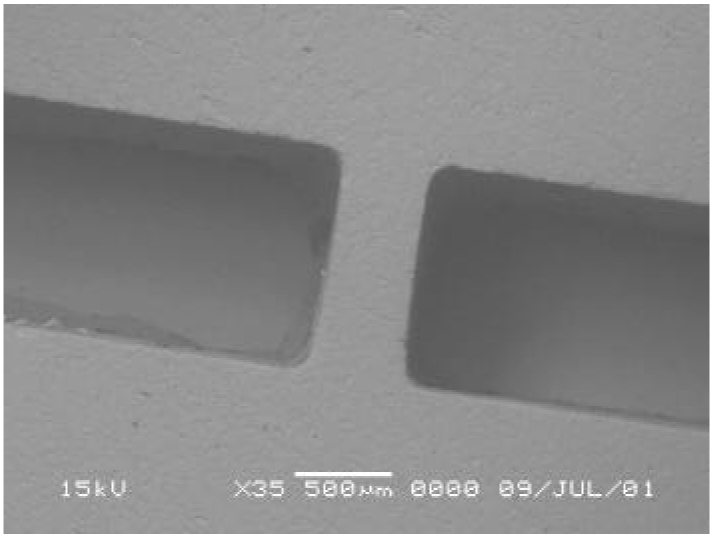


Fig.4 SEM micrograph of a 400 µm thick flex-joint machined from a 3-mm thick sapphire single crystal wafer.

2. Multi-axis CNC ultrasonic cutting

The "classic", moulding-like, ultrasonic cutting process, with single vertical axis feed and shaped tools, had a large diffusion and was development in Soviet Union during the sixties. In the West the cutting has been gradually replaced with a mixed technology, named "twist drilling", where the ultrasonic tool is mounted on a high speed rotating spindle; in this case the diamond tool is in contact with the workpiece and no abrasive slurry is used. In twist drilling the material removal rate is much higher than in classic cutting but the process is not suitable for precision machining of crystals for optics or in semiconductor processing where the minimal stress release is mandatory. For these reasons in the last ten years the slurry cutting is having a new diffusion for high-tech applications. At present only two american companies, Sonex and Sonic-Mill, produce “classic” process ultrasonic cutting machines, with single axis feed, both manual and automatic. Recently the italian company FAIMOND introduced into the market machines of comparable technological level for the jewellery industry. In 2001 FAIMOND R&D division, with the technical support of INFM-Pisa (Italy) and LIGO-Caltech, started to design a new kind of ultrasonic cutting machine.

The machine has CNC feed along X, Y, Z and THETA (rotation) axes; a secondary vertical computer controlled movement, in feedback with a high resolution load cell, stabilizes the tool pressure on the workpiece. Instead of a mould-like tool, the new machine uses properly shaped chisels for lateral feed. With respect to classic vertical slurry cutting, the chisel machining is much more versatile, it allows to obtain more complex shapes and allows an easier load control, being the tool working surface constant. The numerical control also allows a “hovering” machining, eventually with a finer grit, for surface finishing purposes. All the features of classic slurry machining, that is absence of heating and low stress, are preserved.

At present the only similar machine in the world was built twenty years ago by ONERA (Office National d’Etudes et de Recherches Aerospatiales) in France and used for the construction of GRADIO and STEP electrostatic levitation accelerometers. The same machine will be used for LISA inertial sensors. All the potential scientific and technical applications of this unconventional machining process are still almost unexplored. For instance, in interferometric gravitational wave detectors, ultrasonic machining could be used for new mirror suspension mechanics realized in high quality factor materials like fused silica, silicon or sapphire.

The prototype of the new machine has been recently tested at FAIMOND company; the preliminary specs and features of the device are presented in the next section.

3. The prototype

Fig.5 Front view of the 5-axis ultrasonic cutting machine prototype. On the left side is visible the ultrasonic generator, with power and frequency controls. On the right, not visible in the picture, are mounted the PC for the axis control and the 9 inches CRT camera.

The frame of the machine is the same of a conventional 3-axis CNC mill; the table travel is 600 mm along X and 120 mm along Y; the Z-axis slide travel is 150 mm. The slide ways are precision ground and chromium coated; the movement is obtained with precision-ground ball screws and AC servo brushless motors digitally controlled. Micrometer accuracy is achieved with high resolution (0.003 mm) optical position sensors. The ultrasonic head is mounted on a second upper Z-slide powered by a fourth digitally controlled brushless motor; the rotation of the head (up to 1000 rpm around precision ball bearings) is provided by a fifth motor, digitally controlled too.

Th whole head can also operate tilted, in principle up to 180°, for high speed chisel cutting.

The pressure of the tool on the workpiece is monitored by a precision load cell placed under the machining plate; an adjustable counterweight system allows to compensate for the weight of the plate and of the tuning mechanics. The signal from the load cell is processed by the computer and sent to the ultrasonic head motor for the active load stabilization. The static machining load can be set from 0.2 to 10 Kg with a resolution of 0.01 Kg, as well as the feedback integration time. If necessary, a tool wear compensation routine can be implemented in the control.

A suitable recirculating pumping system provides a continuous abrasive slurry renewal, in order to keep a high cutting speed during machining; two selectable separate tanks with 8 liters of capacity store different mesh grade boron carbide, grit 220 and grit 360 respectively for coarse and fine cutting. In each tank a mixer maintains a constant concentration of the slurry.

Fig.6 Internal view of the machine. A polycarbonate transparent box (for high voltage safety) hosts the rotating ultrasonic head with the centering slides and the piezoelectric transducer cooling system. The working table is surrounded by the anti-splash container and by the secondary high-flow slurry feeding. Below the table (the protection carter has been removed) is visible the load control system.

The ultrasonic power supply generates up to 800 W with sinusoidal waveform; a stack of four ring piezoelectric transducer converts the electrical power into mechanical vibrations. The piezos are kept at constant temperature by a refrigerated oil (Mobilect-45) flow in a sealed circuit; the cooling system allows stable long time operation and prevents overheating of the transducers. The ultrasonic power is transmitted to the workpiece by means of a 3/4 wavelength horn made of titanium alloy Ti6Al4V; the horn, with an end diameter of 19 mm, is provided with a M6 threaded hole for tool fixing. The ultrasonic head is designed for 20 kHz operation; a suitable feedback system acts on the generated frequency to track changes of the electromechanical impedance of the piezo-horn-tool-slurry-workpiece system; in this way the power transmitted to the tool is dynamically controlled for the maximum available cutting speed.

All the signals for the CNC operation are managed by a PC embedded on the machine; a 32-bit logic programmable controller is used to execute machining routines in standard EIA-ISO language.

A Windows-based interface has been implemented on the PC for the static load and the feed control and monitoring. Preliminary test cycles of the machine have been done to check all the implemented functions; the highlights of the test session are briefly presented below:

- The abrasive slurry pumping-mixing system is able to provide a continuous abrasive renewal without any problem of re-precipitation of the boron-carbide. Care has to be taken only for long time (week) inactivity. The secondary (high-flow) abrasive feed is able to wet all the working table for large size workpiece machining; anyway when the high-flow irrigation is activated we have verified the formation of heaps of boron carbide next to the corners of the container; a set of compressed air nozzles will be implemented. For small size a suitable tooling is preferable to contain the slurry just around the workpiece.
- The ultrasonic power supply and the automatic frequency tracking electronics are operating within the specs. The high voltage sliding contacts of the rotating head showed some fault for speed over 200 rpm; different materials and design has to be used for operation up to 1000 rpm.
- The piezo cooling system is correctly operating keeping stably the transducers and the head temperature at 20 °C.
- The CNC sensors and actuators work correctly; the power of all of the brushless motors is properly dimensioned. Basic ISO cycles have been used for the tests.
- The static load dynamic control works properly. A special numerical ISO routine has been written for this function: every 10 msec the program compares the signal from the load cell with the set static value and changes the height of the ultrasonic head to restore the tool pressure; the increment has been set to 0.01 mm. The load (2-2.5 Kg) is stable within +- 10 grams.
- The chisel machining has been tested on a sapphire disk (Mohs hardness 9). The following routine has been implemented by the CNC:
    - the tool moves along Z at constant static load by 0.03 mm;
    - it moves along X and Y axes at constant height with a speed of 2mm/min;
    - after the first cycle the tool comes back to the initial position and restarts.

  Different tools have been tested: the cycle has been properly executed by using tool sizes ranging from 4 to 300 mmq. Then the cutting speed for this mode of operation is at least 1mm^3/min. Five time faster cut has been obtained replacing the soft steel chisel with a diamond one.

- A classic mould-like machining run has been done on the same sapphire piece. In this case only the constant load feed has been used. A 5 mm in diameter, 2 mm deep, hole has been machined in the sapphire in 1.5 min, for a corrisponding cutting speed, surprisingly high, of 25mm^3/min.

Prototype preliminary specs

- CNC ultrasonic cutting machine, 5-axes controlled X, Y, Z, THETA, LOAD; 0.003 mm resolution optical position sensors.
- Cutting speed: 5 mm^3/min in “chisel” mode, 25 mm^3/min in “mould” mode, on a 9 Mohs hardness material, with 220 mesh boron carbide slurry.

Technical details:

- size: 1280x1550x1950 mm
- weight: 800 Kg
- table size and travel: X=600mm, Y=120mm, Z=150mm
- secondary vertical way: LOAD=150mm
- head rotation THETA up to 1000 rpm
- head tiltable up to 180°
- ground slide ways, chromium coated and precision ground ball screws
- AC servo brushless motors digitally controlled for X, Y, Z, THETA, LOAD axes
- PC embedded with 32-bit logic programmable controller EIA-ISO standard
- Double irrigation and mixing system for grit 220 and grit 360; tank capacity 8 liters.
- Ultrasonic horn in titanium alloy Ti6Al4V
- Power ultrasonic generator 800 W, sinusoidal waveform; automatic frequency tracking in the range 18-22 kHz.
- Piezoelectric stack converter oil cooled.
- Automatic tool pressure control with high resolution load cell selectable from 0.2 to 5 Kg with 0.01 Kg of resolution.