Ultrasonic Machining (USM)

ULTRASONIC MACHINING (USM) is the removal of material by particles of abrasive that vibrate in a water slurry circulating through a narrow gap between the workpiece and a tool that oscillates at about 20,000 cycles per second. The tool reproduces its shape in the workpiece, generally to an accuracy of ±0.001 in., and sometimes to a tolerance of 0.0005 in. or less, without burrs. Accuracy depends on the size of the tool, rigidity of the machine and the tool, temperature of the slurry, grit size, and the procedure for roughing and finishing.

Ultrasonic machining is used chiefly on hard, brittle materials that do not conduct electricity; however, it is used on both metals and nonmetals, and on ductile as well as brittle materials. It is particularly well suited to the production of relatively shallow, irregular cavities, and is one of the few processes suitable for machining extremely fragile material, such as honeycomb. The main disadvantages of the process are low metal removal rate and high cost.

Equipment and Procedure. Ultrasonic machining is done in a machine that can feed the tool down into the workpiece, and that has a worktable capable of moving in three directions. A typical setup is shown in Fig. 1. A magnetostrictive stack makes the tool vibrate up and down 0.0005 to 0.0025 in. at 19,000 to 25,000 cycles per second, driving the abrasive grains across a gap of about 0.001 to 0.004 in. against the workpiece. The stack produces the vibration by changing slightly in length with the rapidly alternating magnetic field. The magnetostrictive material is brazed to a connecting body of Monel that transmits and amplifies the changes in length. A removable tool holder, fastened to the connecting body, also amplifies the vibration. The tool holder is made of Monel or of stainless steel. The tool, usually made of low-carbon or stainless steel to the shape of the desired cavity and a few thousandths of an inch smaller, is brazed or soldered to the tool holder. All these parts, including the tool, act as one long elastic body, carrying and amplifying the vibration (by resonance) to the tip of the tool.

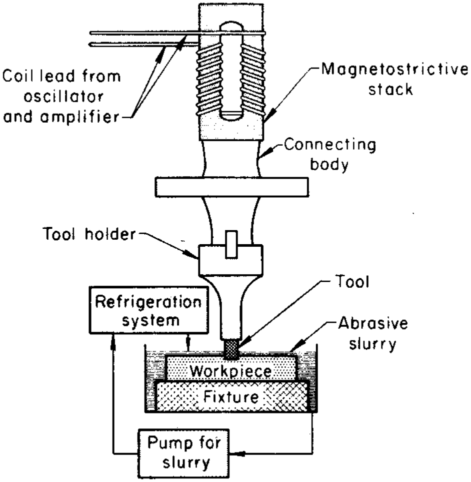


Fig. 1. Schematic of typical setup for ultrasonic machining

Table 1. Effect of Work Material on Performance in "Roughing" by USM

Work material	Removal rate: Cu in. per min	Removal rate: In. per min(a)	Max area, sq in. (b)	Wear ratio(c)
Glass	0.236	0.150	4.0	100
Ferrite	0.196	0.125	3.5	100
Mica(d)	0.196	0.125	3.5	100
Germanium	0.133	0.085	3.5	100
Graphite	0.125	0.080	3.0	100
Quartz	0.102	0.065	3.0	50
Ceramic(e)	0.094	0.060	3.0	75
Boron carbide	0.024	0.015	0.9	2.5
Tungsten carbide	0.022	0.014	1.2	1.5
Tool steel(f)	0.016	0.010	1.2	1

NOTE. Tool material was low-carbon steel; slurry was 30 to 40% of 180 to 240-grit boron carbide; amplitude of vibration was 0.001 to 0.0015 in. at a frequency of 25,000 cps.

(a) Linear penetration rate for a solid cylindrical tool ½ in. in diameter. (b) Maximum practical machining area. (c) Volume of work material removed divided by volume wear of tool. (d) Glass-bonded. (e) Average; results vary with hardness, brittleness and density. (f) Hardened. (SOURCE: M. C. Shaw, Ultrasonic Grinding, *Microtechnic*, June 1956, p 257-265)

The abrasive slurry is circulated by pumping and is cooled to 35 to 40 F to remove the heat that develops in USM. Much of the work is cemented onto glass plates, and cooling is required to keep the cement from softening. In addition, cooling is needed to prevent boiling in the cutting gap and to avoid undesirable temperature-dependent cavitation effects.

Workpieces. Nearly all materials can be cut effectively by USM, including (contrary to early reports) such ductile materials as soft brass. In general, however, workpiece material for USM is harder than Rockwell C 64, and it is not usually economical to use the process on steel that is softer than Rockwell C 45. In addition to hardened alloy steel, metals machined by USM include tool steel, stainless steel, nickel-base and cobalt-base heat-resisting alloys, and germanium. Other work materials include glass, ceramic, carbide and semiconductors. Table 1 lists average removal rate, maximum practical machining area, and average wear ratio for various work materials, based on the rough cutting of holes ½ in. in diameter and in depth. In this comparison, low-carbon steel tools were used with a 30 to 40% slurry of 180 to 240-grit boron carbide abrasive. Amplitude of vibration of tool tip was 0.001 to 0.0015 in. at a frequency of 25,000 cps. (Removal rates in cubic inches per minute would be proportionately lower

This article is based primarily on information in Chapter 2 of "Non-Traditional Machining Processes", R. K. Springborn, editor, ASTME, Dearborn, Mich., 1967.

for smaller cutting areas, but penetration rates in inches per minute would be of the same order of magnitude.)

Vibration of the workpiece must be prevented for the greatest efficiency in penetration. If the workpiece has little mass or rigidity, it should be held or clamped to a massive fixture to reduce or damp the vibration. Fixtures generally are made of stainless steel, brass or aluminum, with small areas that locate the work.

The workpiece may chip at the breakthrough of a hole unless the work material is cemented to a backing. Thin workpieces are almost always cemented to a backing.

Cored or predrilled holes in the workpiece help the flow of abrasive slurry to the cutting zone. A smaller through hole in the bottom of the workpiece allows the slurry to be pumped directly to the center of the cutting zone.

Workpieces are rotated during USM to increase the penetration rate and to improve uniformity in machining counterbores and other round holes and centered work. For certain operations, such as slicing, it is useful to move the work back and forth. Indexing devices and angle plates are used for some work, and lead screws are used for threading.

Tool holders for USM must transfer vibration, and must provide resonance without failure by fatigue. A tool holder must be fitted to the application; with proper design for resonance, a tool holder can give the tool edge an amplitude gain of six over the stack. Generally, the tool holder is in the shape of a cylinder, a cone, or a modified cone, with the center of mass of the tool on the centerline of the tool holder. The upper portion of the tool is identical to or slightly smaller than the adjacent portion of the tool holder, as illustrated in Fig. 1.

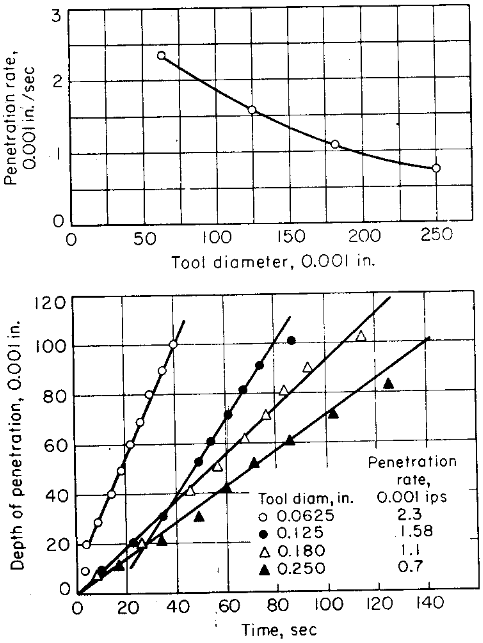
Standard tool holders are stocked, and the suppliers specify limits of tool area and length for each tool holder, so that it can resonate most usefully. The specified range of use avoids failure of the tool or of the brazed joint by overstress. The lowest resonant frequency is specified, permitting maximum reduction of tool length by wear before the tool must be replaced.

Fatigue is the primary cause of failure for tool holders, which are subjected to high-frequency reversals of stress between tension and compression. As in all highly stressed members, surface damage (such as nicks, scratches and tool marks) and excessive grain growth from repeated brazing can cause early failure. Tool holders should be polished, and handled with care. Surface damage such as nicks and scratches must be repaired to restore the polished surface. After 50 cycles of brazing, a tool holder should be heated to 1100 F for 2 hr, to reduce possible grain growth.

Tools for USM must be ductile and tough, rather than hard; but metals that are extremely ductile, such as copper, brass and aluminum, give a short tool life. Low-carbon steel is a good tool material; and 52100 steel, stainless steel, and molybdenum give superior performance. Many commercial forms of material can be used as tools without additional machining — for instance, music wire, gage wire, drill rod, stainless steel tubing, and hypodermic tubing.

The mass and the length of the tool are important. Too great a mass absorbs much of the ultrasonic energy, reducing the efficiency of machining. Too long a tool causes overstress of the tool and of the brazed joint, resulting in failure. Most tools for USM are less than 1 in. long, but some tools as long as 1½ in. are used; tools as long as 6 in. are rare.

Long, thin tools with too great a "slenderness ratio" will whip. (Slenderness ratio is the ratio of length of a structural column to its least radius of gyration.) Slenderness ratio of a tool should not exceed 20. For instance, if the tool is a solid cylinder with a diameter of 0.060 in. (radius of gyration = 0.015 in.), its length should be no greater than 20 × 0.015 = 0.30 in. A hollow cylinder of 0.060-in. OD and 0.047-in. ID (radius of gyration = 0.019 in.) may have a length no greater than 20 × 0.019 = 0.38 in.



SOURCE: John Krawczyk, Ultrasonic Grinding Techniques in Microminiaturization, Diamond Ordnance Fuze Laboratories, TR-950, 1961.

Fig. 2. Effect of tool diameter on penetration rate in ultrasonic machining of ceramic with solid stainless steel tools

Cutting efficiency is at its best when the tool vibrates at a specified optimum amplitude or stroke for the machine tool and for the size of grit. Reasonable combinations are:

800-grit	Stroke, 0.0005 in.
400	0.0015
240	0.0025

For efficient operation, the assembly must be resonant at the designed frequency of the system, when vibrating at the optimum stroke. This condition of resonance will give these proofs:

1 Cavitation of water in the slurry will cause the loudest sound.
2 The feed indicator of the machine will show the greatest rate of feed.
3 The ends of the tool holder give the greatest sensation at a light touch.

The stroke of the tool can be observed in a microscope. Such viewing is important when experimenting with USM, because some tools and workpieces are too delicate or too brittle for a long stroke. It may be necessary to use a stroke as short as 0.0005 in. to prevent damage.

Rate of penetration in USM is limited chiefly by the degree to which the required circulation of slurry can be maintained on all parts of the area being machined. Thus, penetration is slower in machining large areas or cavities with a high ratio of depth to smallest lateral dimension. The normal maximum hole depth for USM is 1 to 2 in.; holes are sometimes made to a depth of 6 in., with special provision for circulation of the abrasive slurry.

A hollow "trepanning" tool has a faster rate of penetration than a solid tool of equal outer size, because of the smaller cutting area. A hollow tool of ½-in. OD by 7/16-in. ID can penetrate the work at more than four times the speed of a solid tool to make a hole of equal diameter, because the hollow tool has a cutting area that is only 23% as great as that of the solid tool.

Figure 2 shows penetration rates used by one manufacturer in ultrasonic machining of ceramic with solid stainless steel tools and a 33% slurry of 320-grit boron carbide abrasive. The penetration rate was slower for larger tools; for the 0.250-in.-diam tool, penetration rate was about a third of that for the 0.0625-in.-diam tool.

A volume removal rate 16 times as great would be required to maintain the same penetration rate as for the 0.0625-in. tool. But because slurry circulation could not be kept at the same level for the larger cutting area as for the smaller area, the volume removal rate for the larger tool had to be restricted to five times that for the smaller one.

Removal rate, or volume of work material removed per unit of time, is approximately proportional to the cutting area of the tool, provided slurry circulation and other operating conditions are held constant. However, in most production applications, conditions are not changed to correspond to the requirements of larger cutting areas, and therefore removal rate usually cannot be increased in proportion to the increase in cutting area (as shown above).

Tool vibration also affects removal rate. Although the relations are complex, removal rate is roughly proportional to the frequency and to the amplitude of tool oscillation.

The wide variation in removal rate for different types of work material is shown in Table 1. Early information on USM indicated that hard or brittle materials can be cut more readily than soft or ductile materials, but the contrary has sometimes been observed.

In one series of tests done under typical USM conditions, 4140 steel in the annealed condition (Rockwell B 95) machined 15 to 30% faster than after being oil quenched (Rockwell C 50), but normalized material (Rockwell C 34) machined almost as rapidly as annealed 4140. Copper alloy 260 (cartridge brass, 70%) machined twice as fast as annealed 4140 steel.

Nature of abrasive, particle size, and concentration of slurry also directly affect removal rate. Boron carbide is the hardest and fastest-cutting abrasive used in ultrasonic machining. Removal rate is roughly proportional to abrasive particle size up to a size approximately equal to the tool amplitude; for sizes substantially larger than tool amplitude, the relation is reversed. Removal rate increases with increasing slurry concentration up to about 30 to 40% (by volume) of abrasive; at very high concentrations, removal rate drops off rapidly.

Metal removal in USM appears to proceed by a complex mechanism involving both fracture and plastic deformation to varying degrees, depending in a given instance on work material and other process variables.

Wear Ratio. The effect of work material on wear ratio (volume of material removed from the workpiece divided by volume worn from the tool) is given in Table 1 for typical USM applications. Large differences in wear ratio for low-carbon steel tools are shown, depending on the hardness of the work material.

Table 2 illustrates the effect of tool material on wear ratio in the machining of glass and steatite, using stainless steel, carbon steel and brass tools.

All of the factors that affect removal rate (see preceding section) also influence wear ratio, except under conditions for which they affect tool and workpiece identically.

Size of hole that is produced by a given tool is affected by the size of the abrasive grit that is used with the tool. A circular hole produced by USM has a minimum diameter equal to the tool diameter plus an overcut of twice the size of the abrasive particles. (See table with Fig. 3 for relation between grit-size number and average particle size.) With size 180 grit, a ¼-in. tool makes a hole 0.250 + (2 × 0.0034) = 0.257 in. in diameter. Using No. 240 grit (0.0025 in.), a tool cuts a hole at least 0.005 in. larger than the tool.

Another consideration in hole size is taper — in some materials, taper may exceed 0.005 in. on the diameter per inch of depth. A finishing cut, to enlarge a roughed hole, should remove about 0.004 in. (on the diameter) from the largest portion of the roughed hole. If a through hole with a diameter of 0.502/0.500 in. must be drilled with minimum taper through a 1-in.-thick workpiece, using 240-grit abrasive, the hole should be roughed with a tool 0.487-in. in diameter, and finished with a tool 0.496 in. in diameter. If a finer abrasive were used in finishing, the diameter of the finishing tool would be correspondingly larger, and the roughing tool (still used with the coarser abrasive) also would be larger. These figures would be valid also for blind holes, but a greater number of tool passes would be needed to get a small radius at the bottom corner of the hole, because the tools become rounded as they wear.

Accurate detail at the bottom of a hole must be made by using a greater number of cutters, although they are duplicates except for wear (needing no increase in size). A large number of duplicate tools may be needed for some accurate work. Accuracy also may demand frequent changes of abrasive.

Surface roughness produced in USM depends on size of abrasive particles, work material, tool amplitude, and slurry circulation. Typical effect of grit size (a factor that can readily be adjusted to control roughness) is illustrated in Fig. 3.

Abrasives and Slurry. Silicon carbide, boron carbide and aluminum oxide are the abrasives most used for USM. Boron carbide is harder, faster-cutting and more durable than the other materials, and is the most widely used, although it costs 20 times as much.

The abrasive is carried in a slurry of water with 30 to 60% of abrasive by volume. When using larger tools, concentration of abrasive is usually held in the lower part of the range, to avoid difficulty in maintaining slurry circulation in the less accessible areas of the workpiece.

Just as in conventional grinding, the finer abrasives make the smoother finishes (as shown in Fig. 3), but the finer grit cuts at a slower speed. The finest grit does the most accurate work; 800 grit cuts within 0.00025 in.

Table 2. Wear Ratios of Three Tool Materials in Ultrasonic Machining Glass and Steatite

Tool material	Wear ratio for tools used on: Glass	Steatite
Stainless steel	100	40
Carbon steel, cold rolled	100	35
Brass	40	10

Wear ratio is depth of cut divided by linear wear on tool. Ratios are for tools ¼ in. in diameter on tapered tool holders, with 320-grit boron carbide abrasive supplied at a pressure of 1½ psi. (Source: John Krawczyk, Ultrasonic Grinding Techniques in Microminiaturization, Diamond Ordnance Fuze Laboratories, Report No. TR-950, July 28, 1961)

Grit sizes 200 to 400 are used for roughing, and 800 to 1000 for finishing. Fresh abrasive cuts better, so that grit must be added to the slurry from time to time. At intervals the slurry should be replaced completely. For a dependable, uniform finish, the grit must be uniform; therefore, abrasives should be segregated so that one grade does not contaminate or mix with another.

To use two grades of abrasive, one for roughing and one for finishing, it is necessary to use two separate fixtures to hold the work and two separate abrasive systems (pumps, tubes, and other components).

Efficient cutting demands an adequate supply of abrasive at the cutting face. When cutting deep holes or machining large surfaces, special techniques are needed to help supply the abrasive as needed. These include:

1. Feed of the slurry through the tool holder to supplement the external flow
2. Predrilled holes to permit the flow of abrasive up through the workpiece, exiting at the cutting face
3. Flutes on the tool (somewhat like the flutes of a twist drill)
4. Relief of the tool behind the cutting face, to provide clearance for abrasive flow
5. Automatic feeding that provides easier abrasive flow along the sides of the tool.

Flow of the abrasive slurry must also carry away the material that is removed from the workpiece. When rust inhibitors are used in the slurry, they should not cause foaming. Steel workpieces may have to be treated after USM to prevent rusting.

A predrilled through hole in the workpiece permits better circulation of the abrasive, and prevents any kind of compression that would retard the motion of the tool. Other work must be vented, as by holes in the tool. Cross holes (0.030-in.-diam or smaller) can be drilled in the hollow tool a third of the length back from the cutting face. New holes must be made after the tool wears to the old ones.

Typical Applications

Five typical applications of ultrasonic machining are summarized below:

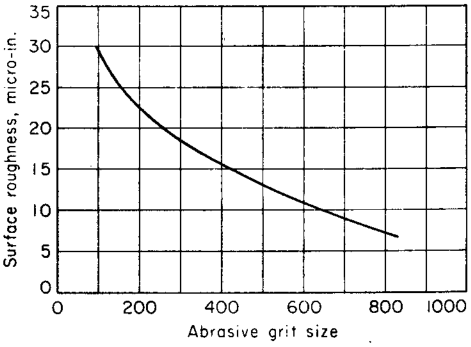
Application 1. Four narrow rectangular holes were cut at the same time in the moving part of a hydraulic servo valve, of 52100 steel at Rockwell C 60 to 62, removing 0.005 to 0.010 in. of stock with a corner radius of 0.0015 in.

Application 2. A carbon flat, 3 by 4 by 0.040 in., was machined by USM, making 2176 holes through it, each 0.031 in. square, in less than 10 min.

Application 3. Dense ceramic, 1/16 in. thick, was machined by USM, making 27 through holes in 3 rows of 9, the centers accurate to ±0.001 in. The holes, about 3/16 in. in diameter, were made simultaneously by a tool that resembled 27 tubes. The tool made 150 parts before it needed sharpening.

Application 4. A bundle of 97 hypodermic needles served as the tool to cut wafers of silicon or germanium in the making of transistors. The wafers, 0.008 to 0.030 in. thick, were cemented to a glass plate before the blanks, 0.030 in. in diameter and larger, were cut and removed from the backing. Each of many such arrangements produced thousands of blanks daily. Each unit was rated at 1000 watts of electric power.

Application 5. A round through-hole having a final diameter of 0.5000 ± 0.0002 in. was trepanned in a 0.187-in.-thick carbide wire-drawing die, using a combination roughing and finishing tool. The abrasive for both cuts was boron carbide, 320-grit for roughing and 600-grit for finishing. Roughing (tool diameter, 0.490 in.) produced a tapered hole with a diameter of 0.493 in. at the top and 0.489 in. at the bottom in 15 min. A 10-min finishing operation (tool diameter, 0.4992 in.) eliminated the taper, for a final hole diameter of 0.5000 ± 0.0002 in. Surface roughness on completing the roughing cut was 22 micro-in.; this was improved to 15 micro-in. by the finishing cut.



Grit size	Average particle size In.	Microns	Grit size	Average particle size In.	Microns
180	0.0034	86	400	0.00090	23
220	0.0026	66	500	0.00065	16
240	0.00248	63	600	0.00033	8
280	0.00175	44	800	0.00028	7
320	0.00128	32	900	0.00024	6

SOURCE: A. L. Roses, Techniques of Ultrasonic Machining, *Tool and Manufacturing Engineer*, Apr 1961, p 71-75.

Fig. 3. Effect of abrasive grit size on surface roughness produced in ultrasonic machining. The minimum overcut is calculated by doubling the average particle size.