Table 11.7 Fatigue characteristics of acoustically active materials [72].

Material	Density ρ, g/cm^3	Young's modulus $E\times10^4$, MPa	Loading frequency f, kHz	Fatigue strength σ_{-1}, MPa
		Magnetostrictive materials		
Nickel	8.9	21.8	19	100
Nickel-cobalt alloy	8.9	20.4	19	106
Iron-cobalt alloy	8.2	22.1	19	112
Iron-cobalt alloy	8.2	22.3	36	145
		Ferrites		
NF	5.14	17.8	36.5	35
NF + 1.5% glass	4.08	16.5	36.5	48
Vibrox	5.48	17.9	36.5	36
		Piezoceramics		
TB	5.43	10.9	27.7	25
TBK	5.53	12.3	27.5	31
PZT19	7.5	7.2	17.5	19
PZT23	7.6	8.2	24.7	23
PZTB3	7.2	7.2	27.0	17
PZTNB	7.3	6.3	18.0	14
PZTUN	7.6–7.9	6.2–8.5	17.8	10–28
PZTZNN	7.8	6.1–7.6	17.3	24–28
UTKSN	7.6–8.0	5–8	18.0	13–21
PZT8	7.55	10.8	28	38.5

to a greater peak alternating stress necessary for the specimen failure.

Ultrasonic loading frequencies were also employed for fatigue testing of tantalum, niobium, and some acoustically active (magnetostrictive, piezoceramic) materials.

V. A. Kuz'menko *et al.* [72] tested fatigue strengths of many acoustically active materials in both excited and nonexcited states under either uniform or non-uniform cyclic compression–dilatation loading. Tests were carried out over the frequency range 17–40 kHz. Magnetostrictive materials were tested as thin (0.1–0.4 mm) laminations, which enabled the strength estimation of their stacks with respect to the methods of lamination production and stacking. Table 11.7 summarizes fatigue strength values obtained for 5×10^8 cycles.

Thus, the reviewed experimental data on the fatigue strength of specimens at various loading frequencies indicate that fatigue strength monotonically increases with frequency. The type of loading does not influence the frequency dependence of fatigue strength.

11.7 Ultrasonic Machining

Current machine building deals with a wide range of novel structural materials possessing special physicochemical properties and updated methods of their machining.

Unusual properties of novel materials, complex shapes of workpieces, and rigid requirements imposed on their accuracy lead to a situation, when conventional methods of machining appear inefficient.

At present, new methods of machining are coming into use. Among them a particular place is occupied by ultrasonic machining methods proposed by Balamuth [89].

The three basic ultrasonic machining processes are

- machining of hard and brittle materials with a vibrated tool and free abrasive particles;

- final surface-hardening treatment;

- machining with vibrating tools.

Some characteristics of these processes will be considered below.

Ultrasonic machining of materials with abrasive particles lies in the feeding of abrasive slurry *3* into a gap between vibrated horn *2* and the workpiece surface (Figure 11.36). Pressing force F_p is applied either to the horn or to the workpiece. Abrasive particles subject to ultrasonic vibrations knock out tiny pieces of material from the workpiece surface, producing a depression which has a profile of the horn end.

Since abrasive particles gradually degrade (wear out); new portions of abrasive slurry should be fed into the process zone, which simultaneously assists in the removal of particles detached from the worked material.

For theoretical description of the process, it is necessary to relate the forces and stresses arising during ultrasonic machining to process parameters, such as the rate of hole growth, v_{ho}, and the process rate Q_V, or the volume of material, V, removed per unit time ($Q_V = V/\tau$).

The processes that develop when abrasive particles are pressed to the workpiece and tool surfaces have been considered by Kazantsev and

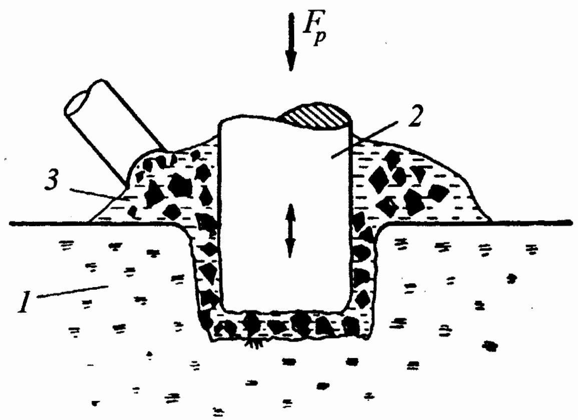

Figure 11.36. Schematic representation of ultrasonic abrasive machining: (*1*) processed material, (*2*) ultrasonic radiator, (*3*) abrasive slurry [52].

Markov [83–84], who established that the rate of hole growth $v_{ho} = Q_V/S$ (S is the area of hole) is given by

$$v_{ho} = Ac(\bar{\xi})\left(\xi_m^2 F_p\right)^a f, \tag{11.6}$$

where A, varying from 0.5 to 1, depends on the hardness of worked material and abrasive particles; $c(\bar{\xi})$ is the mean abrasive particle size function; f is the of frequency of vibrations. The relations are illustrated in Figure 11.37.

The physicochemical properties of the workpiece material can greatly affect the process rate: higher brittleness criterion Br corresponds to a better ultrasonic machinability of the material. According to their ultrasonic machinability, all materials can be divided into three categories:

(1) Br > 2. Materials of this group, such as glass, quartz, diamond, and ceramics, have the best ultrasonic machinability.

(2) 1 < Br < 2. This intermediate group involves quenched steels and hard metals.

(3) Br < 1. Ultrasonic machining of this group of materials (annealed steels, copper, lead, etc.) is ineffective.

Let us consider in more detail the relationship between the rate of ultrasonic machining, hole depth, and the contribution from the fresh abrasive slurry feeding.

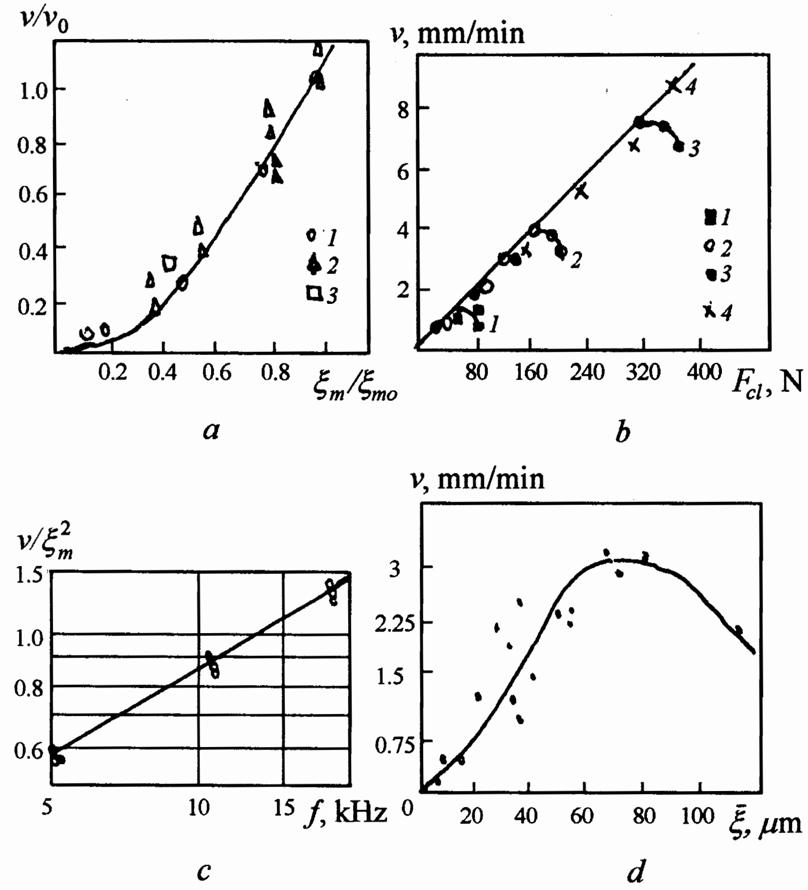

Figure 11.37. Dependence of the machining rate on (*a*) vibration amplitude, (*b*) pressing force at various rates of abrasive slurry feeding [83], (*c*) vibration frequency [85], and (*d*) mean abrasive particle size [83]. Panel a: (*1*) data from [85], (*2*) data from [86], (*3*) data from [87]. Panel b: (*1*) unforced abrasive slurry change, (*2*) suction at 0.1 MPa, (*3*) suction at 0.2 MPa, (*4*) suction at 0.3 MPa.

The rate of ultrasonic machining with abrasive slurry drops with increasing hole depth by the exponential law

$$v_h = v_{ho}\exp(-\alpha h), \tag{11.7}$$

where α is the parameter that depends on pressing force and the method of abrasive slurry feeding.

For ultrasonic machining to be efficient, vibrations should be of a sufficient amplitude and frequency, the horn should be pressed to the

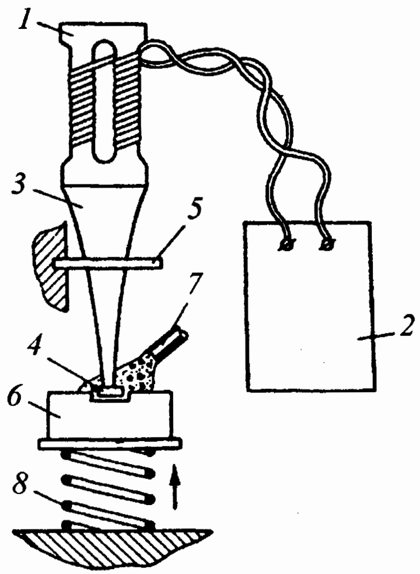

Figure 11.38. Schematic representation of an ultrasonic tool for abrasive machining [88]: (*1*) electroacoustic transducer, (*2*) ultrasonic generator, (*3*) horn, (*4*) instrument, (*5*) vibratory system fixture, (*6*) workpiece, (*7*) abrasive slurry feeder, (*8*) pressing arrangement.

workpiece with a required force, and the abrasive slurry feeding to the process zone should be continuous. Figure 11.38 illustrates an ultrasonic tool for abrasive machining. At present, many types of such tools are available (with a power ranging from 0.03 to 4 kW) for machining brittle materials and drilling holes 0.15–100 mm in diameter.

These machines may be either portable or stationary. The former are small and their ultrasonic assemblies can be handled during operation. They are employed for drilling holes of low depth and diameter, engraving, and marking. The rated power requirement of these tools is 30–50 W.

Stationary ultrasonic machines with a vertical arrangement of their vibratory system are most widespread. They may be low-power (0.03–0.2 kW), medium-power (0.25–1.6 kW), or high-power (1.6–4.0 kW). Besides, they may be designed as multipurpose or specialized tools.

Apart from ultrasonic machining with an abrasive grit, there is an alternative method, in which ultrasonic vibrations are fed directly to a cutting tool. The effect of ultrasound on machining depends on vibration amplitude, velocity, frequency, workpiece peripheral speed,

Table 11.8 Effect of ultrasound on hardness and specific deformation work upon a ball indentation [88].

Material	Vibrational frequency f, kHz	Vibrational amplitude ξ_m, μm	Indenter penetration depth h, mm	HB hardness, kg/mm^2	Specific deformation work A_{sp}, J/mm^3
D16 aluminum	–	0	0.2	14.8	13.8
alloy	7.9	4.5	0.2	2.4	2.9
	–	0	0.4	10.5	10.5
	7.9	4.5	0.4	5.4	4.9
	–	0	0.8	15.6	15.6
	7.9	4.5	0.8	5.3	5.2
Grade M1 copper	–	0	0.4	76.5	66.3
	7.9	4	0.4	31.9	29.6
	–	0	0.1	76.6	77.5
	7.9	5	0.1	35.0	34.8
Grade 45 steel	–	0	0.2	133.6	142.5
	7.9	3	0.2	101.0	66.6
	–	0	0.4	156.0	148.7
	7.9	3	0.4	115.0	81.5
VTi5 titanium	–	0	0.2	127.5	128.5
alloy	7.9	4.5	0.2	55.8	74.0
	–	0	0.05	181.0	162.5
	20.7	15	0.05	67.8	67.9
CrNi55WMoTiCoAl	–	0	0.15	298.0	331
nickel alloy	21.0	5	0.15	77.5	68

thickness of material to be cut, as well on physical properties of the workpiece and tool materials.

Ultrasonic vibrations imposed on the tool influence the speed and direction of effective cutting, the level and, sometimes, the sense of internal stresses. It may also modify friction conditions at the worked surface, and the efficiency of lubricating coolants. All these effects may reduce cutting forces and improve the surface quality and dimensional accuracy.

Experiments show that ultrasonic vibrations reduce both material hardness and specific deformation energy (Table 11.8). The actual improvement depends on indenter penetration and vibrational amplitude. Theory predicted a drastic reduction in the friction coefficient during

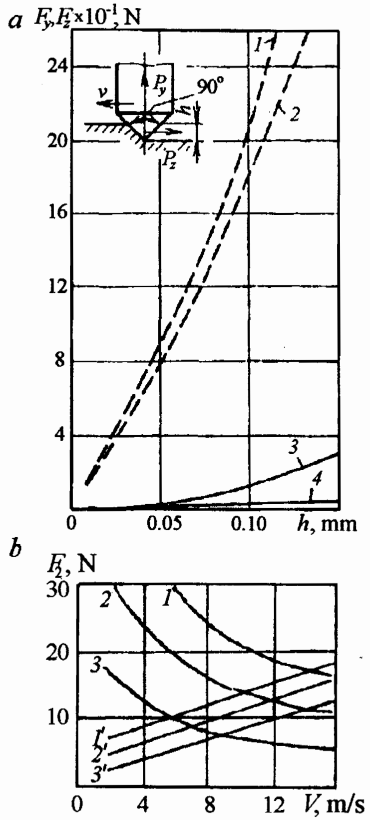

Figure 11.39. Dependence of forces (*1*, *3*) F_y and (*2*, *4*) F_z on (*a*) scratch depth and (*b*) velocity v of grade VTi5 titanium alloy tooling at different depths h (μm): (*1*, *1'*) 20, (*2*, *2'*) 15, (*3*, *3'*) 10 [90]. Figures with apostrophes refer to experiments with ultrasonic treatment (f = 20 kHz, ξ_m = 11 μm). Panel *a*: (*1*, *2*) control experiments, (*3*, *4*) experiments with imposed ultrasonic vibrations.

ultrasonic indentation as compared to respective static process [88]. In addition to pressing the tool to the workpiece, machining also involves their relative motion.

Using an indenter cone, Markov [90] investigated the effect of ultrasound on the scratching of various materials and found that ultrasonic excitation of the cone along its axis reduced the degradation resistance of all the materials studied, viz. Pb, Cu, and grade VTi5 alloy.

Figure 11.39 shows variations in forces F_z and F_y caused by the penetration of grade W18 steel cone (the vertex angle 90°) into VTi5 alloy to depth h. Static testing was carried out at a maximum speed of

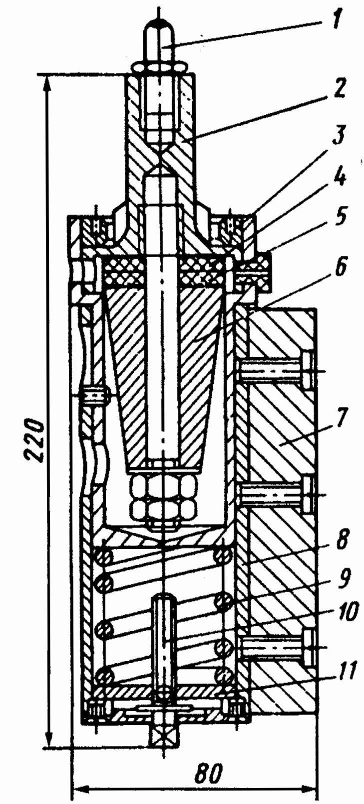

Figure 11.40. Cross-sectional view of a UZP-2 ultrasonic head for diamond smoothing [88]: (*1*) diamond tip, (*2*) radiator, (*3*) removable body, (*4*, *5*) piezoceramic transducer plates, (*6*) sleeve, (*7*) fixture, (*8*) stationary body, (*9*) spring, (*10*) screw, (*11*) nut.

10 mm min^{-1}; in ultrasonic tests, 20-kHz vibrations with an amplitude of 15–20-μm were used. The scratches produced in two test series differed in width, depth, and profile.

At scratching velocity $v > \omega\xi_m$, the efficiency of ultrasonic vibrations decreased. With increasing velocity v, forces F_y and F_z either grew (ultrasonic process) or diminished (conventional process) (Figure 11.39,*b*). The superimposing of ultrasonic vibrations on a cutting tool can be effective in threading, drilling, hole enlarging, hole trueing, reaming of holes of a small diameter, turning and gear shaping of ductile metals, grinding, honing, superfinishing, lapping, and other machining processes.

Special machines and ultrasonic systems have been elaborated for the ultrasonic cutting of brittle materials with the use of rotary diamond tools. The relevant acoustic systems, employing either magnetostrictive or piezoceramic transducers, can be mounted on conventional tools such as drills, mills, and borers. It should be noted that piezoceramic transducers require no water cooling.

Various ultrasonic heads are available for ultrasonic burnishing (Figure 11.40).

11.8 Ultrasonic Surface Treatment

Surface deformation is a widespread and effective method for hardening metallic materials. With this method, the surface layer of a material is a subject of high compressive stresses, which results in a better product strength, durability, and reliability.

By now, many surface deformation techniques have been elaborated and involve rolling, ball treatment, and shot blasting. Ultrasonic surface hardening, as one of the recent techniques in this series, was pioneered in the USSR in the late 1950s and early 1960s [91–93]. At that time, Soviet researchers evaluated the effect of ultrasonic surface hardening on residual welding stresses and proposed a hardening-finishing process.

Applied ultrasonic vibrations relieve residual stresses and improve surface finish and hardness, thereby providing a better wear resistance of products.

There are three major methods for ultrasonic surface deformation that differ with respect to working tools and bodies (Figure 11.41):

- single-tool process,
- multi-tool process,
- free-body process.

Ultrasonic single-tool process is similar to conventional ball deformation method, in which a ball (or a roll) is pressed with force F_N to the surface of a workpiece moving specifically with respect to the tool. The only difference between ultrasonic and conventional processes is that the tool is vibrated at a frequency and amplitude that are determined by operation conditions and the type of the electroacoustic transducer used. Tool *1* connected to horn *3* moves relative to the workpiece surface during a deformation cycle.

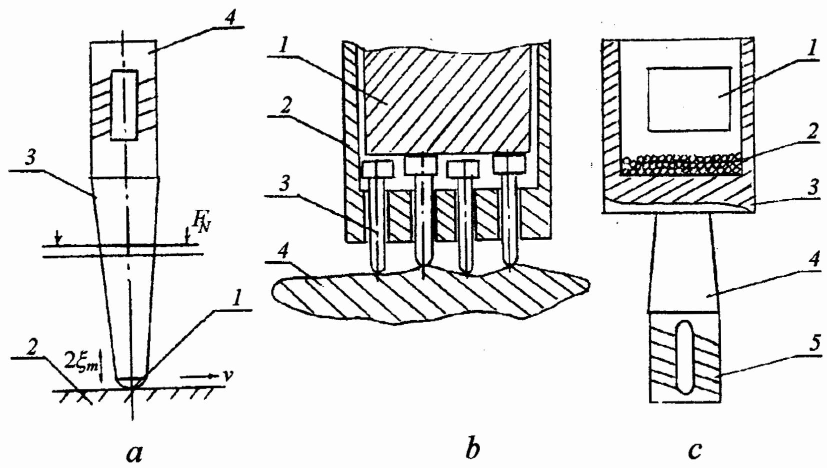

Figure 11.41. Schematic representation of ultrasonic surface treatment methods (*a*) with a single vibrating instrument [92], (*b*) with a multi-tool instrument [92], and (*c*) with free bodies [94]. Panel a: (*1*) tip, (*2*) workpiece, (*3*) ultrasonic horn, (*4*) electroacoustic transducer. Panel b: (*1*) horn, (*2*) cartridge, (*3*) tools, (*4*) workpiece. Panel c: (*1*) workpiece, (*2*) balls, (*3*) vibrated chamber, (*4*) ultrasonic horn, (*5*) electroacoustic transducer.

A multitool arrangement, which is generally similar to those used in conventional embossing, is illustrated in Figure 11.41,*b*. Tools *3*, possessing one degree of freedom along the system axis, are placed in cartridge *2* between workpiece *4* and horn *1*. The horn is pressed to the workpiece with a constant force. The tooling travels with respect to the workpiece during operation.

In many applications, it is convenient to use free bodies rather than fixed tools (Figure 11.41,c). Bodies may represent, for instance, ultrasonically excited balls. Workpiece *1* is placed in vibratory chamber *3* which contains steel balls *2* as working bodies. The vibratory chamber is connected to horn *4* and electroacoustic transducer *5*.

Ultrasonic treatment results in a drastic increase in dislocation density, crystal fragmentation, and variation in the stress–strain state of material's surface. All these effects depend on process conditions, including acoustic parameters, the properties and geometry of material, and stress pattern at its surface.

Ultrasonic hardening was found to raise the mean dislocation density in metals from 10^6–10^8 to 3×10^{11} cm^{-2}. To compare, surface rolling could augment mean dislocation density only to 6×10^{10} cm^{-2} [98].