Ultrasonic Machining (USM)

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خلاصه اصول مربوط به ماشین کاری التراسونیک

- در هر دستگاه آلتراسونیک از یک ژنراتور (برای اینکه فرکانس وتوان برق شهر را بالا ببرد) و ترانسدیوسر (برای تبدیل انرژی الکتریکی به انرژی مکانیکی) و هورن (برای انتقال و تقویت موج) استفاده میشود .
- دستگاه امپدانس آنالایزر به وسیله ای گفته میشود که می توان فرکانس طبیعی یک قطعه را در یک بازه انتخابی برای ما مشخص کند. در این دستگاه زمانی تشدید یا رزونانس اتفاق می افتد که امپدانس صفر شود یعنی مقاومت جسم به حداقل رسیده باشد .

Content & References

- ***Content:***
- ***Definition and component of USM***
- ***Principle of USM (transducer, design of horn & MRR)***
- ***Modeling of MRR in USM***
- ***Discussion***
- ***Ref.:***
- *J. A. McGeough, Advanced Methods of Machining: Chapman & Hall, 1988.*
- *Tool and Manufacturing Engineers Handbook (TMEH), Society of Manufacturing Engineers, 1998*

Definition Of USM

Material Removing Process:

- USM is used to erode holes and cavities in hard or brittle workpieces by using shaped tools high-frequency mechanical motion and an abrasive slurry.

- USM is able to effectively machine all hard materials whether they are electrically conductive or not.

USM System

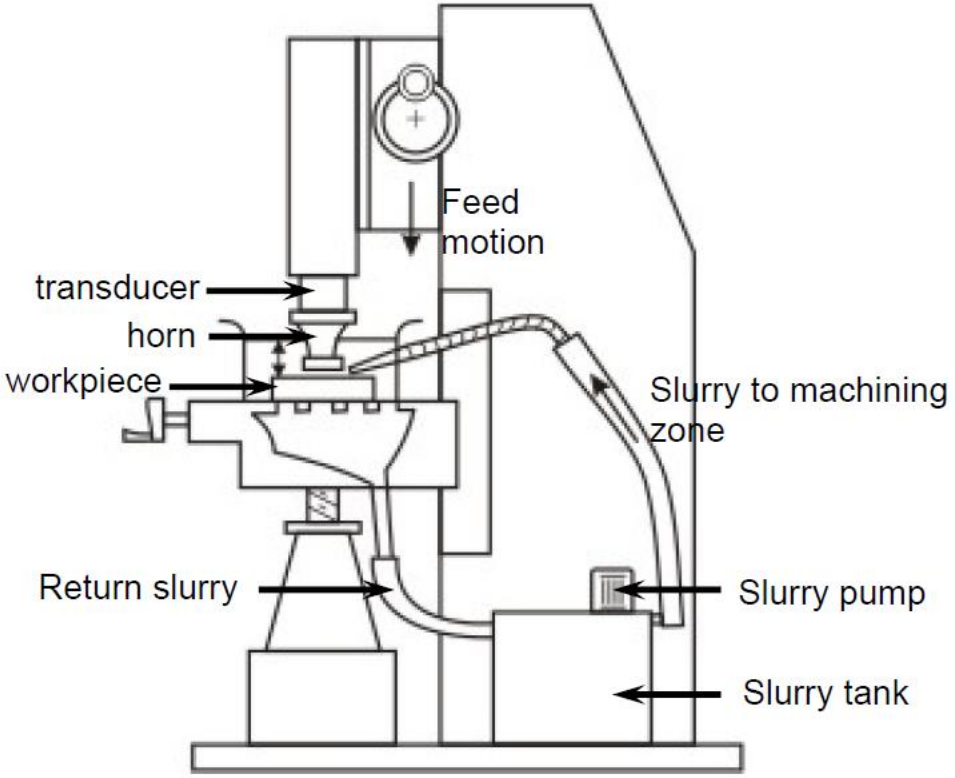

Fig1.Schematic view of an Ultrasonic Machine

- Slurry delivery and return system .
- Feed mechanism to provide a downward feed force on the tool during machining.
- The transducer, which generates the ultrasonic vibration.
- The horn or concentrator, which mechanically amplifies the vibration to the required amplitude of 25 – 100 µm and accommodates the tool at its tip.

Principle Of USM

- **Abrasives:** B_4C; SiC; Al_2O_3; diamond (15 µm – 60 µm)
- **Tool material**: soft material such as :soft steel , Al 7075, Ti
- **Workpiece Material:** metals and alloys (particularly hard and brittle), semiconductors, nonmetals, e.g., glass and ceramics
- **Example:**
- Vibration Frequency.: 20-30 KHz
- Amplitude: 25-100 µm

Advantages	Disadvantages
Machining of any material regardless of conductivity	Low material removal rate
Precision machining of brittle hard materials	Tool wears fast
Does not produce electric, thermal or chemical defects at the surface	Machining area and depth are quite restricted
Can drill circular or non-circular holes in very hard materials	
Less stress because of its non-thermal nature	

Principle Of USM

Transducer:

Magnetostrictive effect:

Magnetostriction is a property of ferromagnetic materials that causes them to change their shape or dimensions due to the applied magnetic field.

Materials: a laminated stack of nickel or nickel alloy sheets.

Piezoelectric effect :

Piezoelectric effect generates a small electric current when compressed. Conversely, when an electric current is applied, the material increases minutely in size. When the current is removed, the material instantly returns to its original shape.

Materials: quartz, zirconate, titanate

Principle Of USM

Effects:

- Agglomeration(توده ای شدن)
- Emulsification(امولسیون سازی)
- Dispersion of colloid(پراکنده کردن کلوییدها)
- Atomization(اتمیزه کردن)
- Fragmentation(خرد کردن) is the idea behind USM- g=16000 g

در اولتراسونیک ابزار، ابزار ساده ای است که در سطح انتهای ان بتوان شکم ارتعاشی ایجاد کرد.

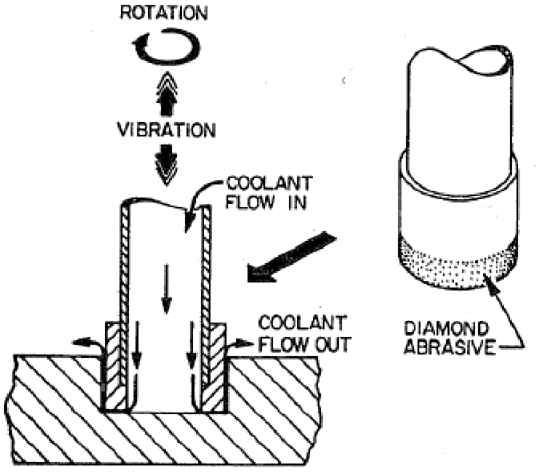

Fig2. Illustration of RUM process (Diamond impregnated tool)

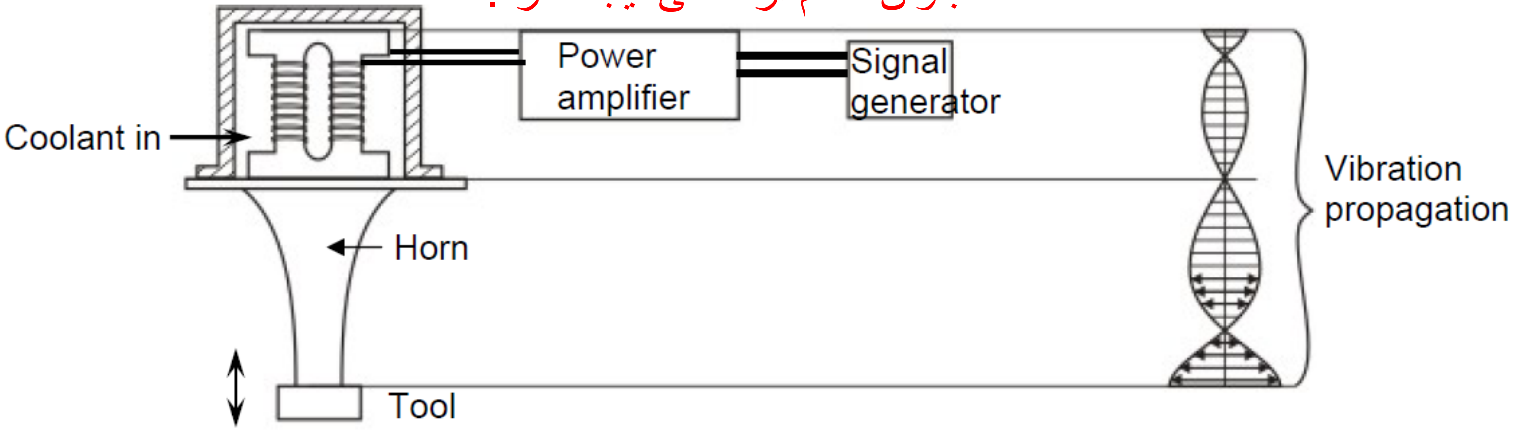

Fig3. Working of horn as mechanical amplifier of amplitude of vibration

Principle Of USM

Design of horn:

Uniform Bar Horn:

$$\left(\frac{\partial^2 u}{\partial t^2}\right) = C^2\left(\frac{\partial^2 u}{\partial x^2}\right) \qquad \frac{E}{\rho} = C^2 \qquad \textbf{(1)}$$

$$\omega = \frac{n.\pi.C}{l} = \frac{n.\pi.\sqrt{\frac{E}{\rho}}}{l} \qquad n = 1,2,3, \ldots. \qquad \textbf{(2)}$$

$$\lambda = C.T = \frac{C}{f} \qquad \lambda = \frac{\sqrt{\frac{E}{\rho}}}{f} \qquad \textbf{(3)}$$

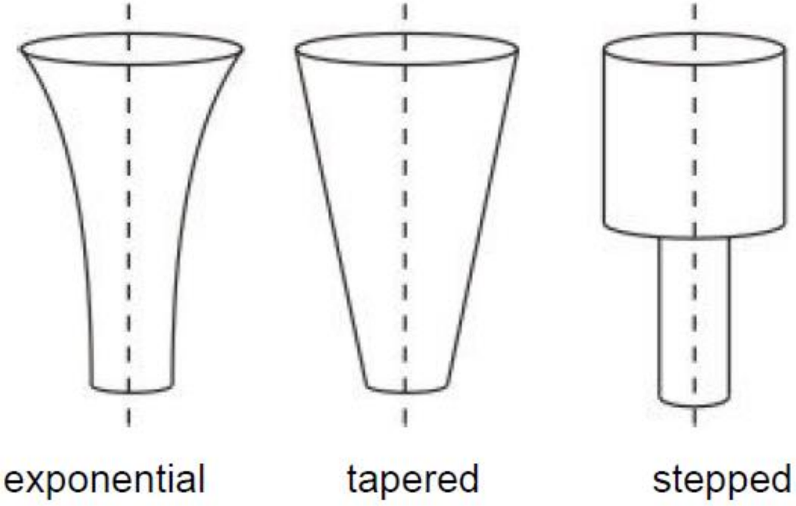

Fig4. Different Horns used in USM

Exponentially Tapered Horn:

$$\left(\frac{d^2 u}{dt^2}\right) - 2\beta\left(.\frac{du}{dx}\right) + K^2 u = 0$$

$$k = \frac{\omega}{c} \qquad A = A_0 e^{-2\beta x} \qquad \textbf{(4)}$$

$$\lambda = \frac{\frac{c}{\sqrt{(1-\frac{\beta^2}{K^2})}}}{f} = \frac{\frac{c}{\sqrt{(1-\frac{\beta^2 c^2}{\omega^2})}}}{f} \qquad \textbf{(5)}$$

Principle Of USM

Material removal:

- Occurs when the abrasive particles, suspended in the slurry between the tool and workpiece, are struck by the down stroke of the vibration tool.
- The impact propels the particles across the cutting gap, hammering them into the surface of both tool and workpiece. Collapse of the cavitation bubbles in the abrasive suspension results in very high local pressures.
- Under the action of the associated shock waves on the abrasive particles, micro cracks are generated at the interface of the workpiece.
- The effects of successive shock waves lead to chipping of particles from the workpiece.

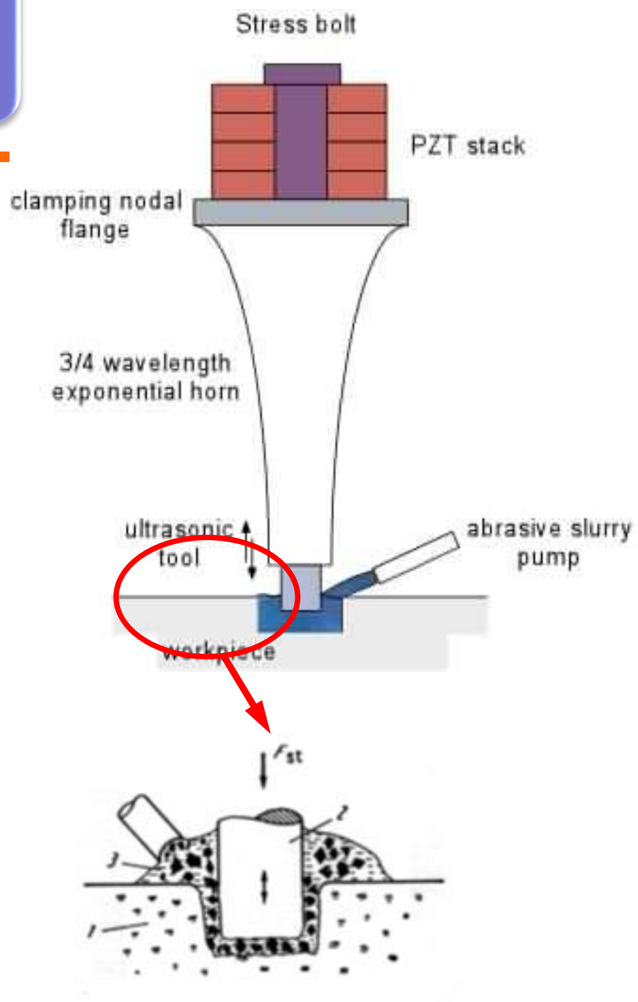

Diagram of ultrasonic cutting process. 1) Workpiece; 2) tool; 3) abrasive suspension.

Fig5. Ultrasonic machine tool schematic

Principle Of USM

The basic components of the cutting action in USM :

1. The direct hammering of the abrasive into the work by the tool (major factor)- particle removes by chipping کوبش
2. The direct impact of the abrasive on the work ضربه یا پرش
3. Cavitation and presence of air bubble induced erosion -کاویتاسیون
4. Chemical erosion caused by slurry خردگی شیمیایی

Modeling Of MRR in USM by Hammering

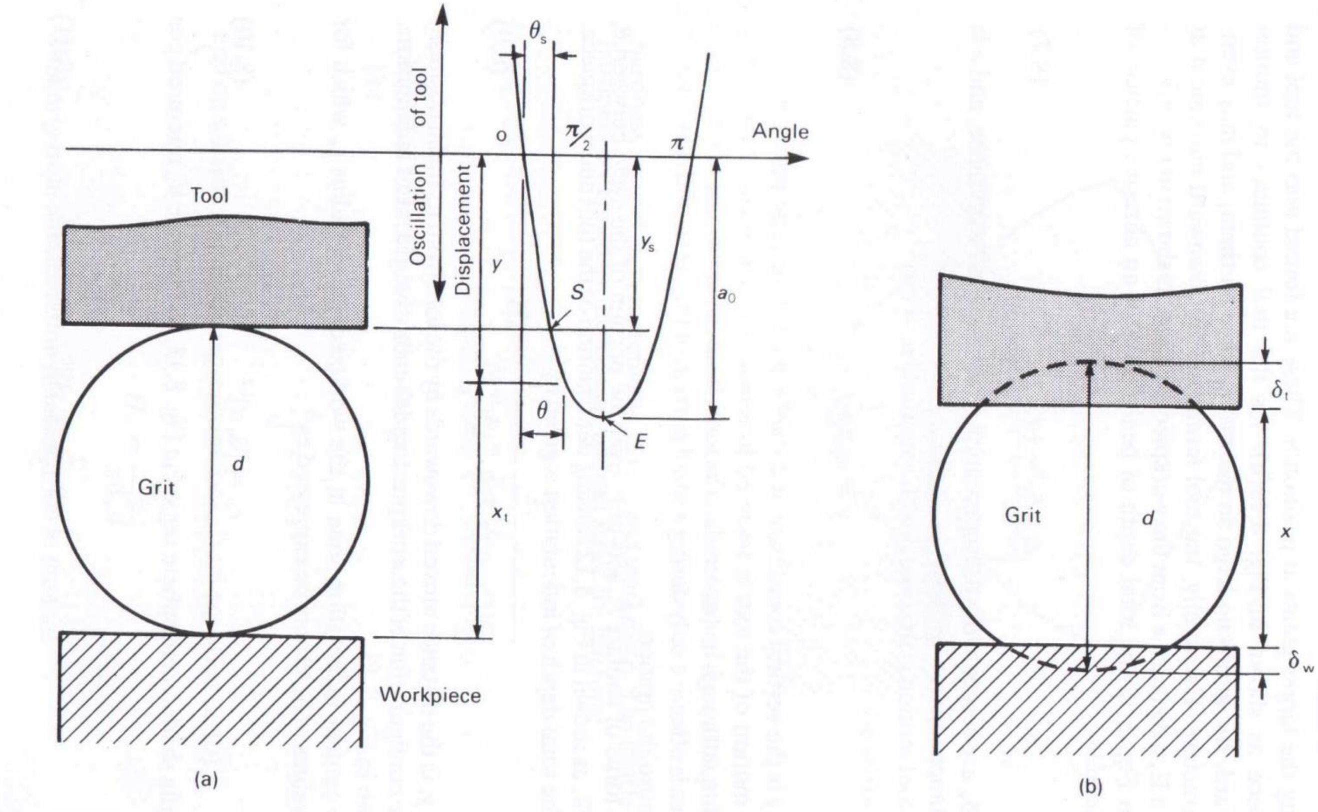

Fig6. Effect of tool and workpiece on impact with grain. (After Kainth *et al.*, 1979.)

$$\delta_t + \delta_w = (d - x) \qquad \textbf{(6)}$$

$$y = a_0 \sin\theta \qquad \textbf{(7)}$$

$$\delta_w + \delta_t = a_0 - y_s \qquad \textbf{(8)}$$

Modeling Of MRR in USM by Hammering

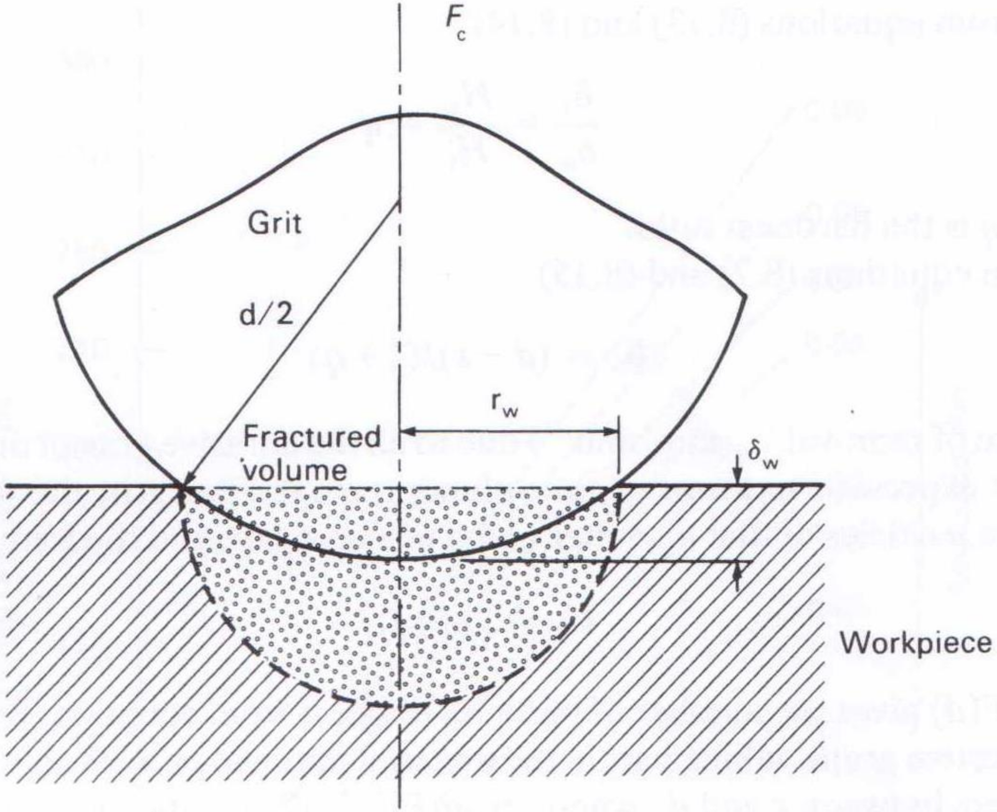

Fig7. Configuration of grit and workpiece. (After Kainth *et al.*, 1979.)

$$r_w = [\delta_w d]^{1/2} \qquad (9)$$

$$V_0 = \frac{2}{3}\pi(\delta_w d)^{3/2} \qquad (10)$$

Modeling Of MRR in USM by Hammering

From Equ. 6 & $\frac{\delta_t}{\delta_w} = \frac{H_w}{H_t} = q \quad \Longrightarrow \quad \delta_w = (d-x)/(1+q)$ **(11)**

The rate of removal Vd (mm^3/min) due to all the abrasive grits of diameter d, may be expressed in terms of the volume removed per grit, the number of abrasive particles of that diameter in the workpiece gap and the frequency f as follow:

$$V_d = V_0 F(d) f$$

(12)

(Rozenberg Statistical distribution for the abrasive grain size d)

$$F(d) = 1.095 \frac{N}{\bar{d}} \left\{ 1 - \left(\frac{d}{\bar{d}} - 1 \right)^2 \right\}^3$$

(13)

d(bar) is the mean diameter of particles in the gap

$$\dot{v} = \int_x^{d_m} \frac{2}{3} \pi (\delta_w d)^{3/2} \left[1.095 \frac{N}{\bar{d}} \left\{ 1 - \left(\frac{d}{\bar{d}} - 1 \right)^2 \right\}^3 \right] f\, dd$$

(14)

$$\frac{2.29 N f}{(1+q)^{3/2} \bar{d}} \int_x^{d_m} [(d-x)d] \left[1 - \left(\frac{d}{\bar{d}} - 1 \right)^2 \right]^3 dd$$

dm is max dia. Of abrasive and x is the distance b/w tool and w/p

Modeling Of MRR in USM by direct impact

$$\dot{v} \propto [dh]^{3/2} Nf \quad \textbf{(15)}$$

$$h = \left[\frac{8F_s y_0 d}{\pi KHC(1+q)} \right]^{1/2} \quad \textbf{(16)}$$

d is the mean diameter of the grains.

F_s is the static force

K is a constant of proportionality.

C is the concentration

h is the depth of indentation

y_0 is the amplitude

H is the hardness of the workpiece

N is the total number of particles making impact per cycle

Discussion

MRR:

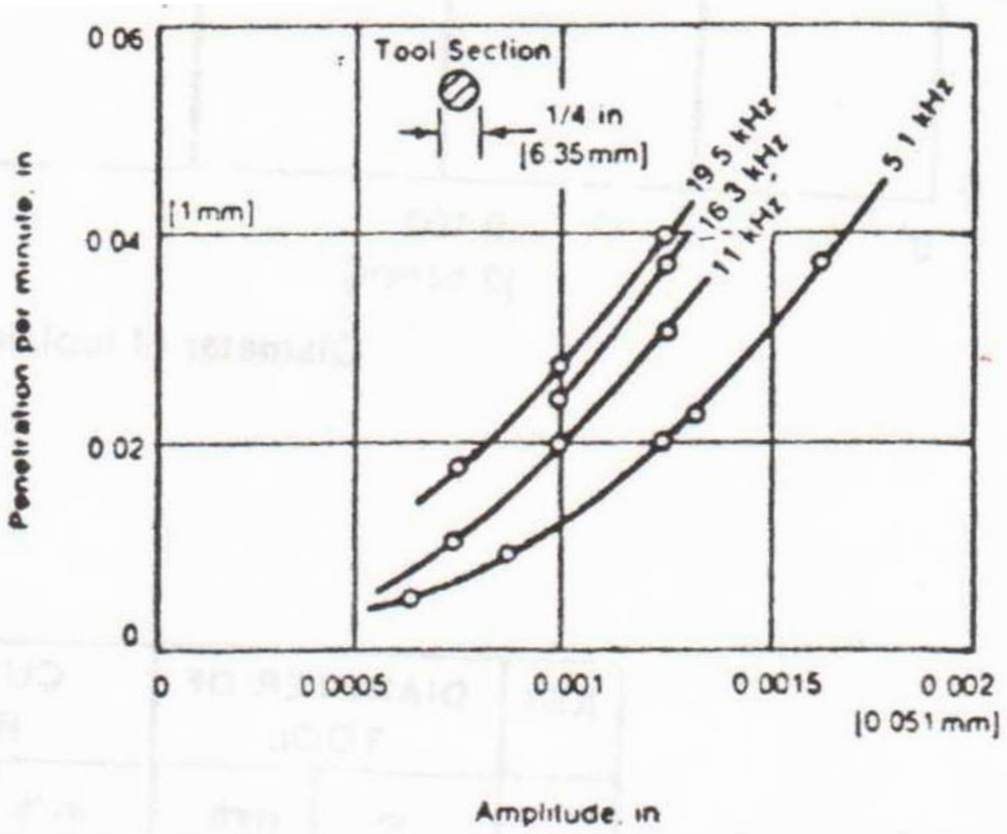

Fig8. 7 Penetration rates in glass as a function of amplitude, for four operating frequencies and constant static load. (E. A. Neppiras and R. D. Foskett. p. 369)

Discussion

MRR:

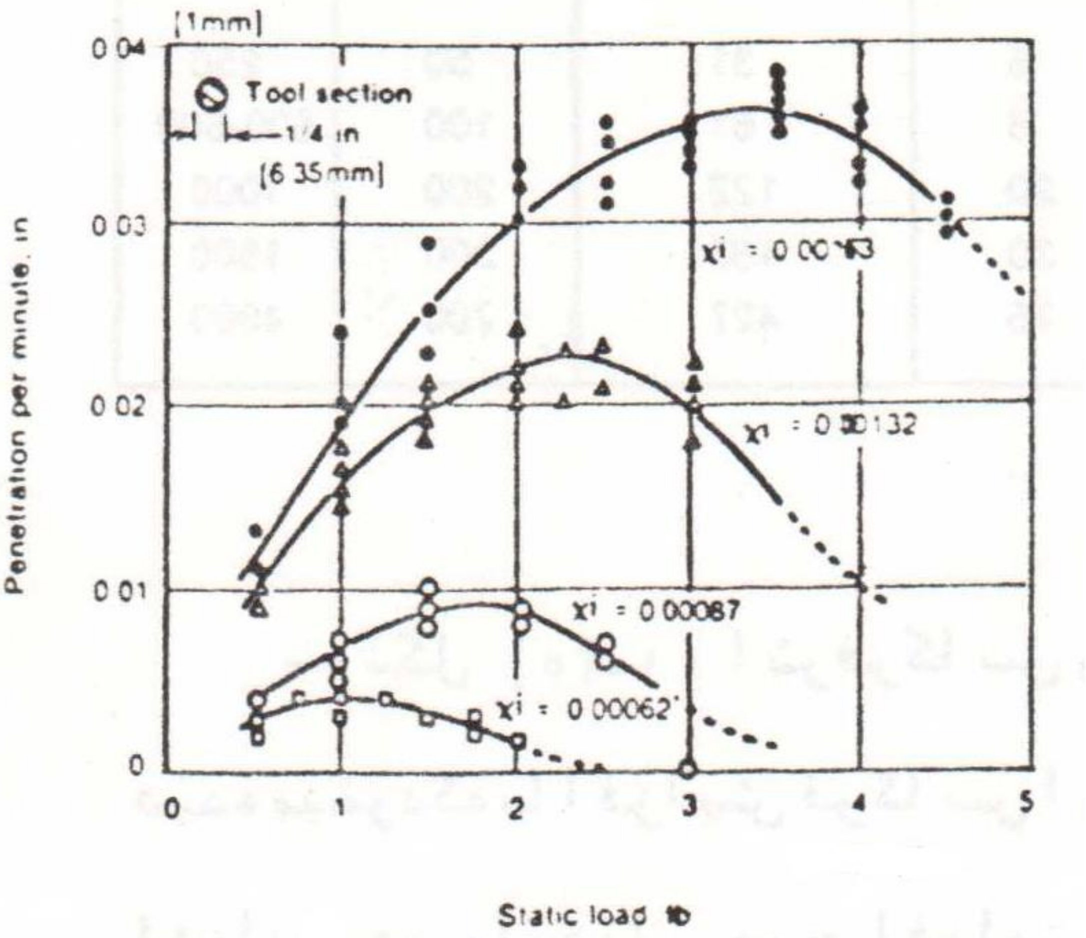

Figure Fig9. ration rate as a function of static load for various amplitudes (E. A. Neppiras and R. D. Foskett, p. 369)

Discussion

Tool wear

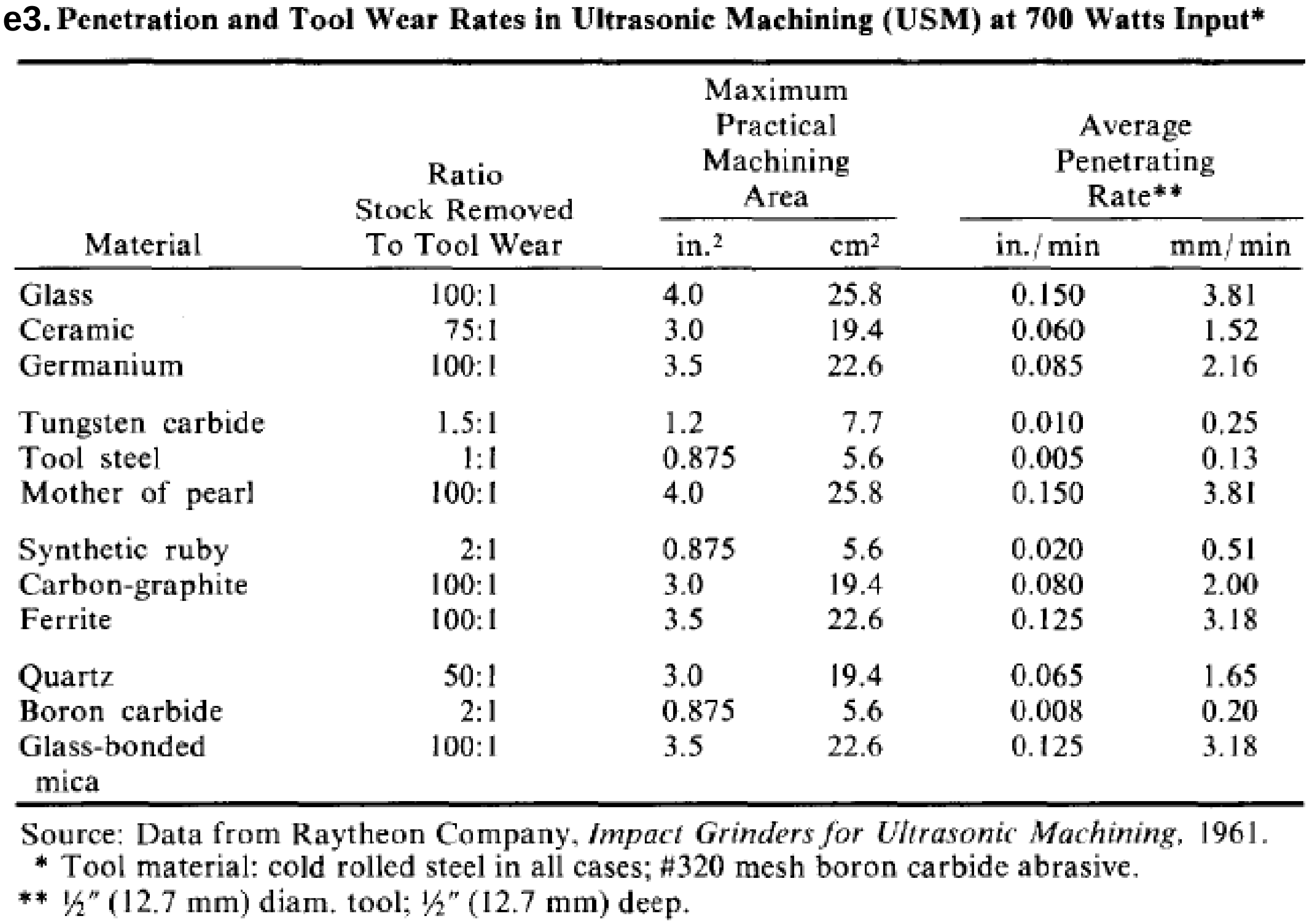

Table3. **Penetration and Tool Wear Rates in Ultrasonic Machining (USM) at 700 Watts Input***

Material	Ratio Stock Removed To Tool Wear	Maximum Practical Machining Area in.²	Maximum Practical Machining Area cm²	Average Penetrating Rate** in./min	Average Penetrating Rate** mm/min
Glass	100:1	4.0	25.8	0.150	3.81
Ceramic	75:1	3.0	19.4	0.060	1.52
Germanium	100:1	3.5	22.6	0.085	2.16
Tungsten carbide	1.5:1	1.2	7.7	0.010	0.25
Tool steel	1:1	0.875	5.6	0.005	0.13
Mother of pearl	100:1	4.0	25.8	0.150	3.81
Synthetic ruby	2:1	0.875	5.6	0.020	0.51
Carbon-graphite	100:1	3.0	19.4	0.080	2.00
Ferrite	100:1	3.5	22.6	0.125	3.18
Quartz	50:1	3.0	19.4	0.065	1.65
Boron carbide	2:1	0.875	5.6	0.008	0.20
Glass-bonded mica	100:1	3.5	22.6	0.125	3.18

Source: Data from Raytheon Company, *Impact Grinders for Ultrasonic Machining*, 1961.

* Tool material: cold rolled steel in all cases; #320 mesh boron carbide abrasive.

** ½″ (12.7 mm) diam. tool; ½″ (12.7 mm) deep.

Discussion

TOOL WEAR:

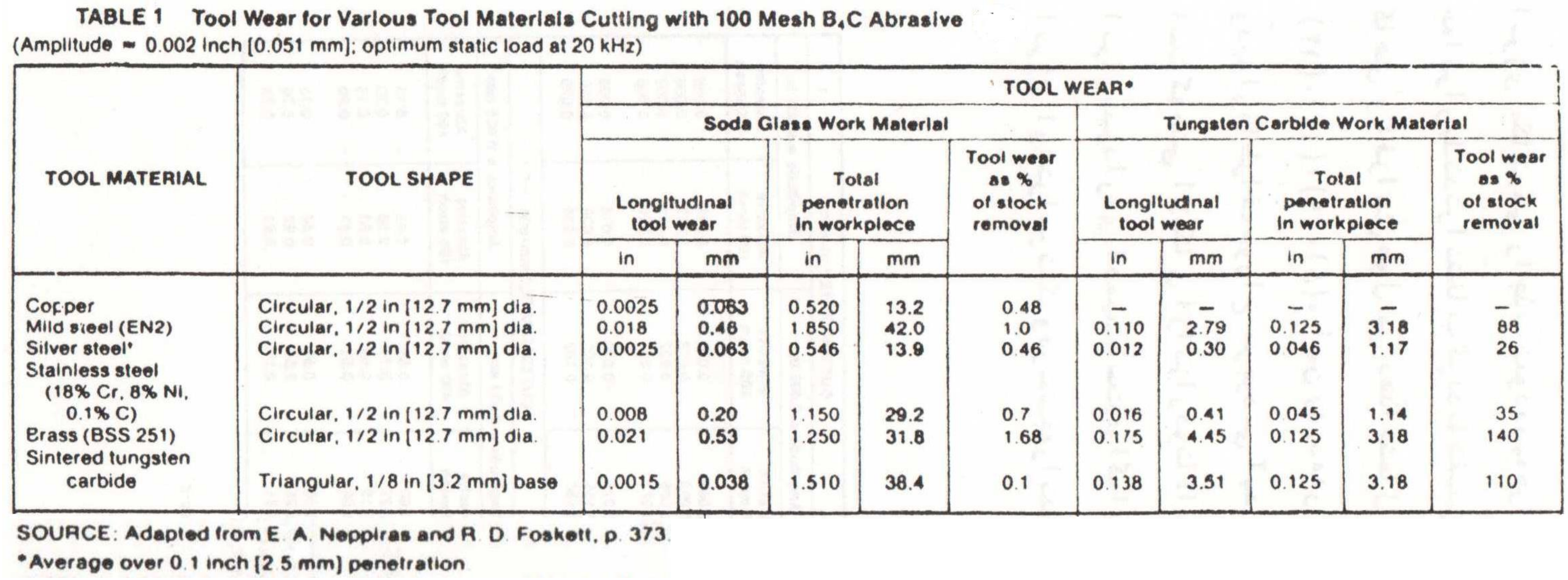

TABLE 1 Tool Wear for Various Tool Materials Cutting with 100 Mesh B_4C Abrasive
(Amplitude ≈ 0.002 inch [0.051 mm]; optimum static load at 20 kHz)

TOOL MATERIAL	TOOL SHAPE	TOOL WEAR*									
		Soda Glass Work Material					Tungsten Carbide Work Material				
		Longitudinal tool wear		Total penetration in workpiece		Tool wear as % of stock removal	Longitudinal tool wear		Total penetration in workpiece		Tool wear as % of stock removal
		in	mm	in	mm		in	mm	in	mm	
Copper	Circular, 1/2 in [12.7 mm] dia.	0.0025	0.063	0.520	13.2	0.48	—	—	—	—	—
Mild steel (EN2)	Circular, 1/2 in [12.7 mm] dia.	0.018	0.46	1.850	42.0	1.0	0.110	2.79	0.125	3.18	88
Silver steel'	Circular, 1/2 in [12.7 mm] dia.	0.0025	0.063	0.546	13.9	0.46	0.012	0.30	0.046	1.17	26
Stainless steel (18% Cr, 8% Ni, 0.1% C)	Circular, 1/2 in [12.7 mm] dia.	0.008	0.20	1.150	29.2	0.7	0.016	0.41	0.045	1.14	35
Brass (BSS 251)	Circular, 1/2 in [12.7 mm] dia.	0.021	0.53	1.250	31.8	1.68	0.175	4.45	0.125	3.18	140
Sintered tungsten carbide	Triangular, 1/8 in [3.2 mm] base	0.0015	0.038	1.510	38.4	0.1	0.138	3.51	0.125	3.18	110

SOURCE: Adapted from E. A. Neppiras and R. D. Foskett, p. 373.

*Average over 0.1 inch [2.5 mm] penetration

Discussion

Abrasive:

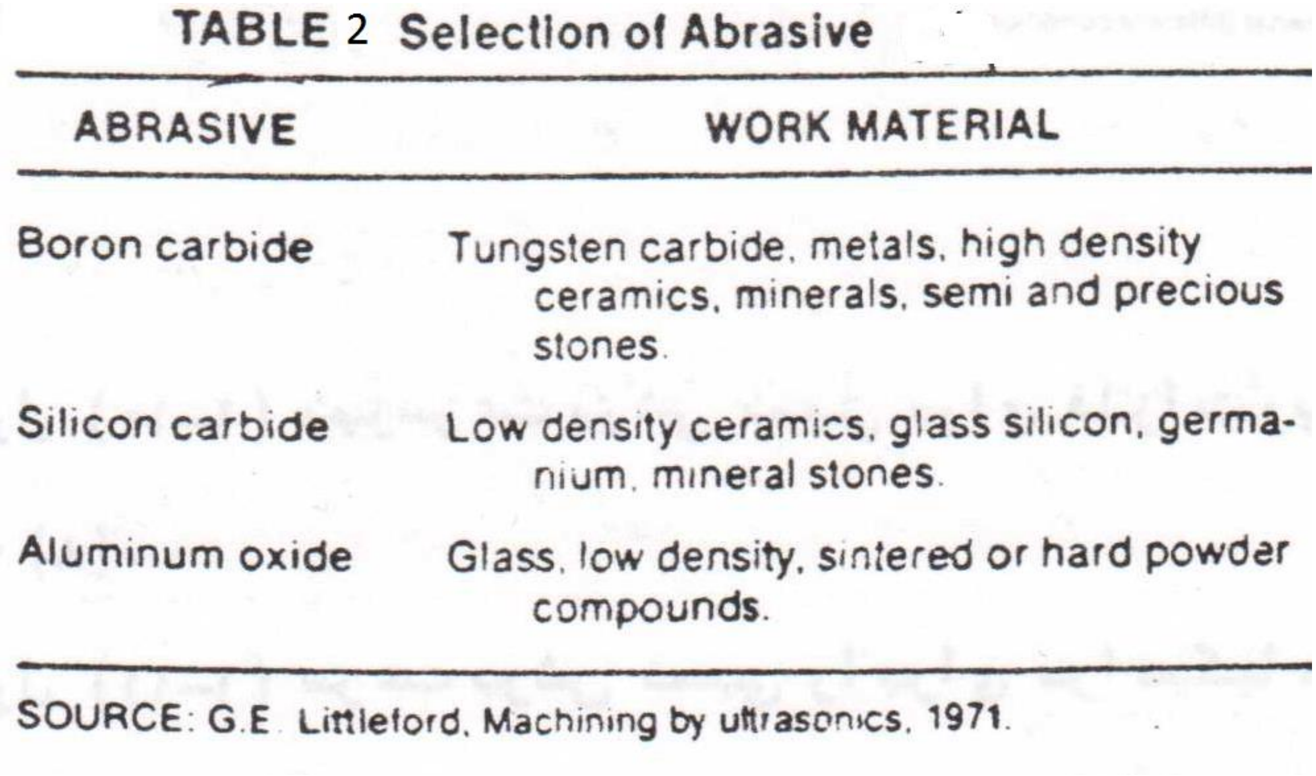

TABLE 2 Selection of Abrasive

ABRASIVE	WORK MATERIAL
Boron carbide	Tungsten carbide, metals, high density ceramics, minerals, semi and precious stones.
Silicon carbide	Low density ceramics, glass silicon, germanium, mineral stones.
Aluminum oxide	Glass, low density, sintered or hard powder compounds.

SOURCE: G.E. Littleford, Machining by ultrasonics, 1971.

Discussion

Surface roughness:

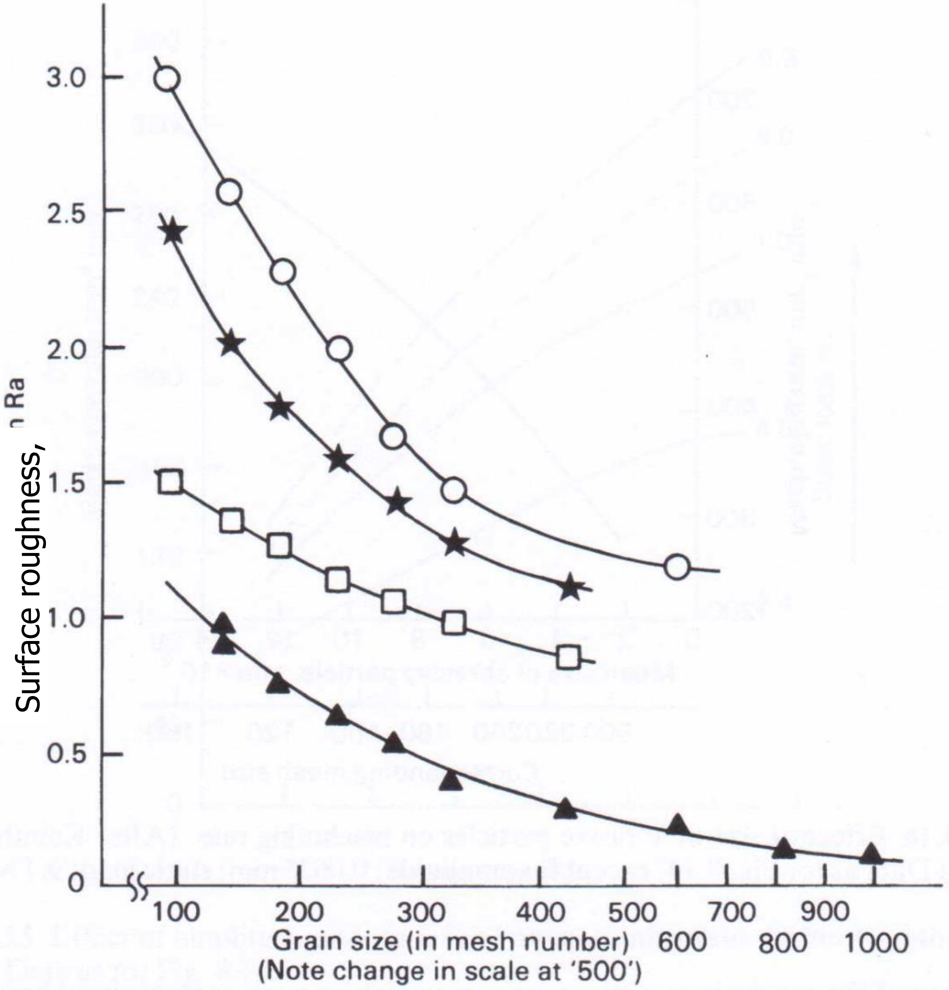

Fig10. increase n surface roughness with increase in grain size. (After Kennedy and Grieve, 1975.) Workpiece materials: ○glass, ★silicon semiconductor, ☐ceramic, ▲ hard alloy steel.

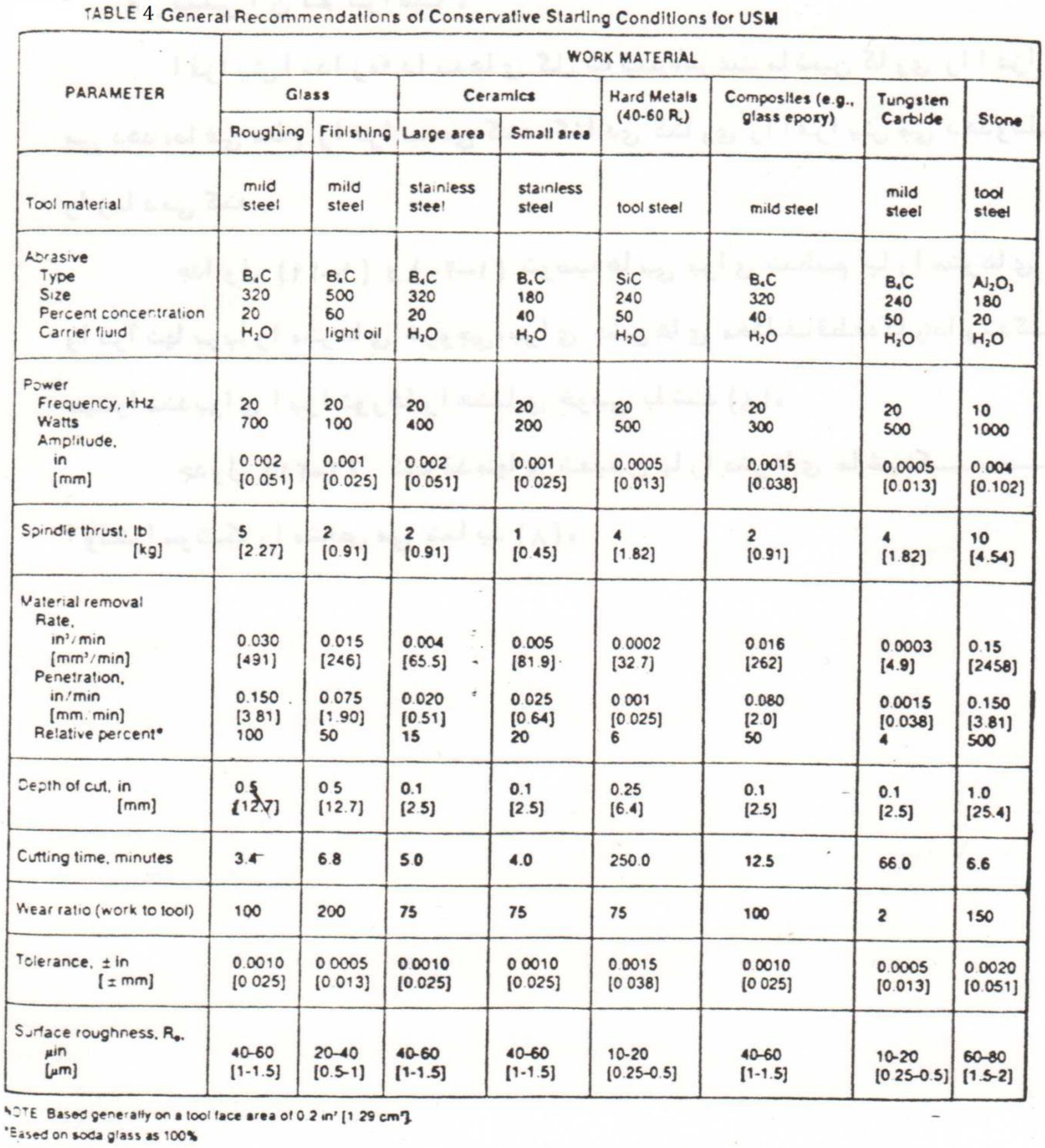

TABLE 4 General Recommendations of Conservative Starting Conditions for USM

PARAMETER	WORK MATERIAL							
	Glass		Ceramics		Hard Metals (40-60 R_c)	Composites (e.g., glass epoxy)	Tungsten Carbide	Stone
	Roughing	Finishing	Large area	Small area				
Tool material	mild steel	mild steel	stainless steel	stainless steel	tool steel	mild steel	mild steel	tool steel
Abrasive								
Type	B_4C	B_4C	B_4C	B_4C	SiC	B_4C	B_4C	Al_2O_3
Size	320	500	320	180	240	320	240	180
Percent concentration	20	60	20	40	50	40	50	20
Carrier fluid	H_2O	light oil	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
Power								
Frequency, kHz	20	20	20	20	20	20	20	10
Watts	700	100	400	200	500	300	500	1000
Amplitude, in [mm]	0.002 [0.051]	0.001 [0.025]	0.002 [0.051]	0.001 [0.025]	0.0005 [0.013]	0.0015 [0.038]	0.0005 [0.013]	0.004 [0.102]
Spindle thrust, lb [kg]	5 [2.27]	2 [0.91]	2 [0.91]	1 [0.45]	4 [1.82]	2 [0.91]	4 [1.82]	10 [4.54]
Material removal								
Rate, in^3/min [mm^3/min]	0.030 [491]	0.015 [246]	0.004 [65.5]	0.005 [81.9]	0.0002 [32.7]	0.016 [262]	0.0003 [4.9]	0.15 [2458]
Penetration, in/min [mm/min]	0.150 [3.81]	0.075 [1.90]	0.020 [0.51]	0.025 [0.64]	0.001 [0.025]	0.080 [2.0]	0.0015 [0.038]	0.150 [3.81]
Relative percent*	100	50	15	20	6	50	4	500
Depth of cut, in [mm]	0.5 [12.7]	0.5 [12.7]	0.1 [2.5]	0.1 [2.5]	0.25 [6.4]	0.1 [2.5]	0.1 [2.5]	1.0 [25.4]
Cutting time, minutes	3.4	6.8	5.0	4.0	250.0	12.5	66.0	6.6
Wear ratio (work to tool)	100	200	75	75	75	100	2	150
Tolerance, ± in [± mm]	0.0010 [0.025]	0.0005 [0.013]	0.0010 [0.025]	0.0010 [0.025]	0.0015 [0.038]	0.0010 [0.025]	0.0005 [0.013]	0.0020 [0.051]
Surface roughness, R_a, μin [μm]	40-60 [1-1.5]	20-40 [0.5-1]	40-60 [1-1.5]	40-60 [1-1.5]	10-20 [0.25-0.5]	40-60 [1-1.5]	10-20 [0.25-0.5]	60-80 [1.5-2]

NOTE Based generally on a tool face area of 0.2 in^2 [1.29 cm^2].

*Based on soda glass as 100%