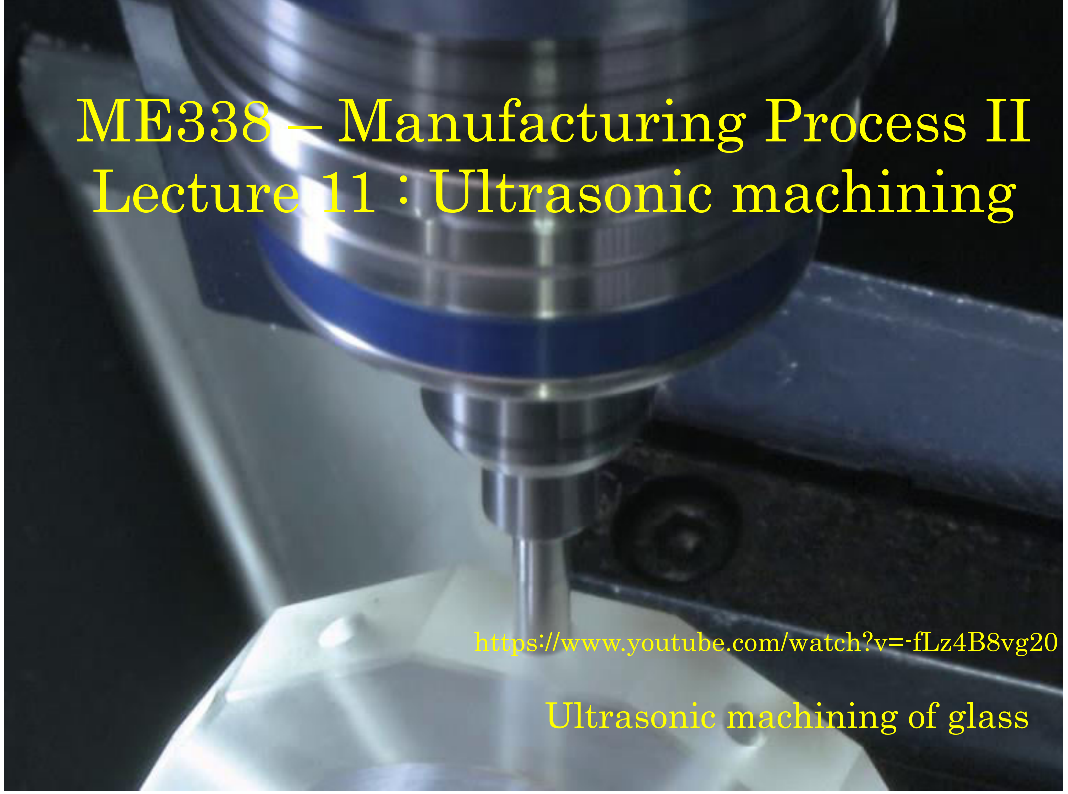
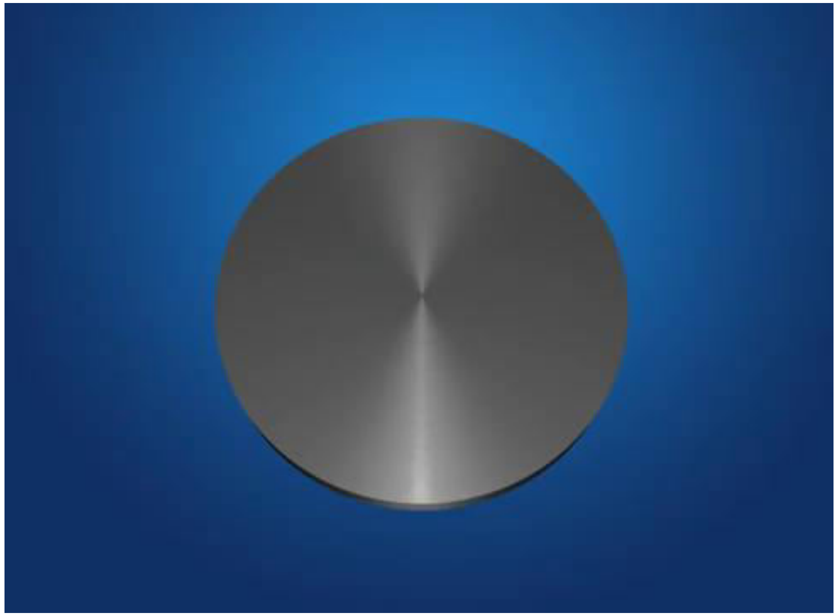
ME338 – Manufacturing Process II
Lecture 11 : Ultrasonic machining



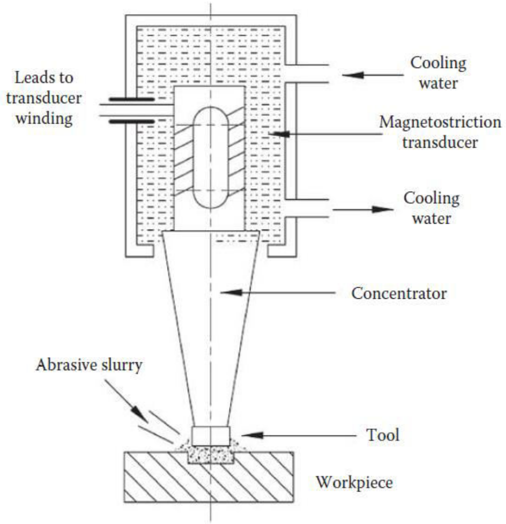
https://www.youtube.com/watch?v=-fLz4B8vg20

Ultrasonic machining of glass

Ultrasonic machining



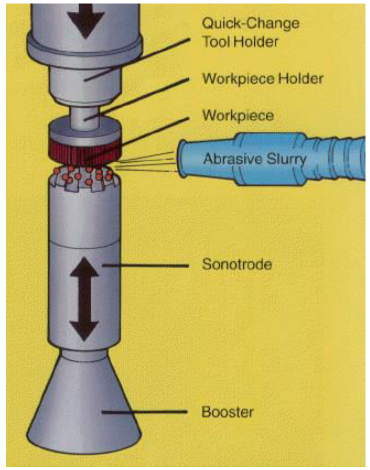
Ultrasonic machining (USM)



- Mechanical abrasion by localized direct hammering of the abrasive grains stuck between the vibrating tool and adjacent work surface
- The microchipping by free impacts of particles that fly across the machining gap and strike the workpiece at random locations
- The work surface erosion by cavitation in the slurry stream

Ultrasonic machining (USM)

- The basic USM process involves a tool (made of a ductile and tough material) vibrating with a very high frequency
- A continuous flow of an abrasive slurry in the small gap between the tool and the work piece.
  - Low amplitude (0.013 to 0.08 mm)
  - high frequency (about 20 kHz)
- The tool is gradually fed with a uniform force.
- Local micro-fracture of brittle work surface caused by the impact of the hard abrasive grains
- The slurry also carries away the debris from the cutting area.
- The tool material being tough and ductile wears out at a much slower rate.



Process characteristics of USM

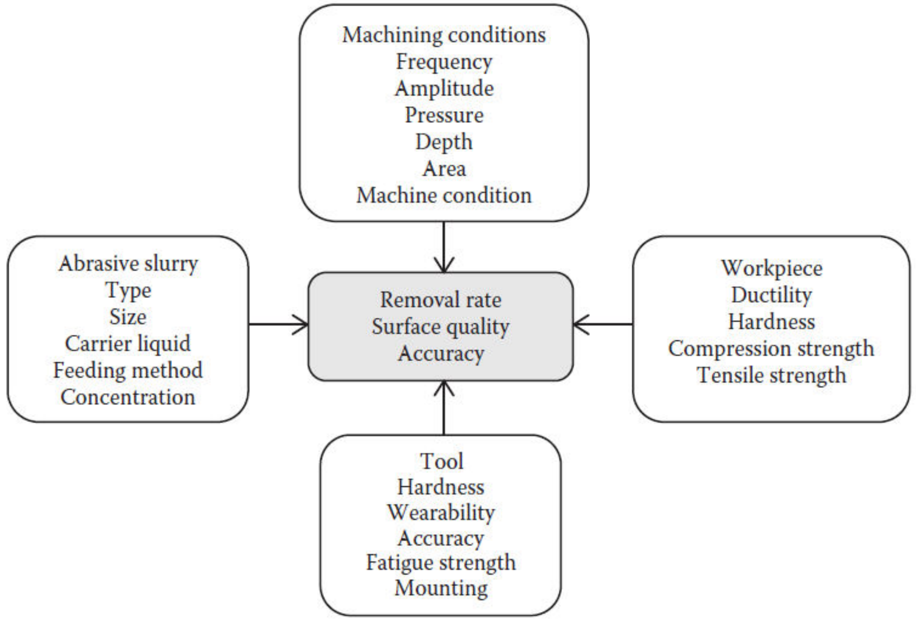
Typical Process Characteristics of USM (Tool, Low-Carbon Steel; Slurry, 30%–40% of 180–240 Grit B_4C; Amplitude, 0.025–0.035 mm; Frequency, 25 kHz)

	Material Removal Rate			
Work Material	**Volume (mm^3/min)**	**Penetration Rate (mm/min)**	**Maximum Practical Tool Area (mm^2)**	**Wear Ratio[a]**
Glass	425	3.8	2580	100:1
Ceramic	185	1.5	1935	75:1
Ferrite	390	3.2	2260	100:1
Quartz	200	1.7	1935	50:1
Tungsten carbide	40	0.4	775	1.5:1
Tool steel	30	0.3	775	1:1

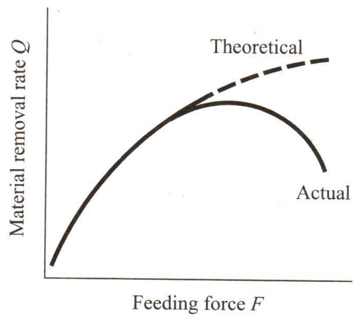
Source: Rao, P.N., *Manufacturing Technology: Metal Cutting and Machine Tools*, 8th edn., Tata McGraw-Hill, New Delhi, 2000.

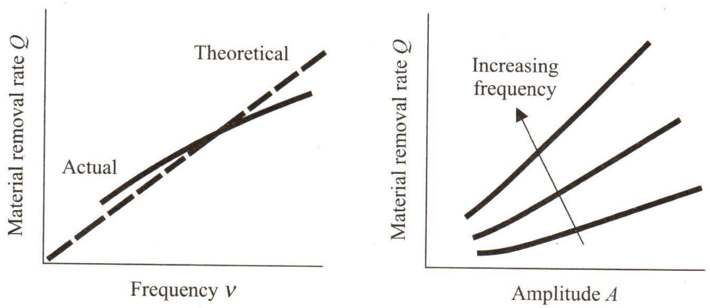
[a] Ratio of material removed from the work to that removed from the tool.

Factors affecting MRR in USM



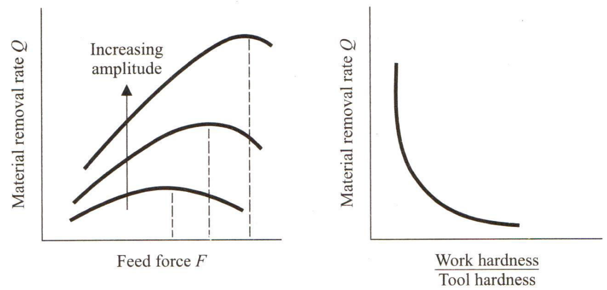
Effect of parameters in USM



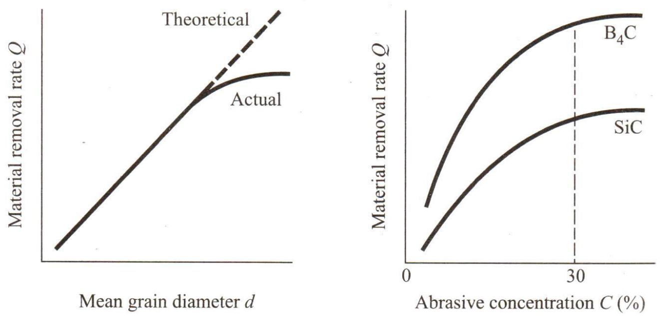


(a) Variation with frequency (b) Variation with amplitude

Effect of parameters in USM



(a) Variation with feed rate (b) Variation with hardness ratio



Abrasive in USM

Grit Number, Grit Size, and Surface Roughness in USM

Grit Number	Grit Size (mm)	Surface Roughness (μm)
180	0.086	0.55
240	0.050	0.51
320	0.040	0.45
400	0.030	0.4
600	0.014	0.28
800	0.009	0.21

Source: ASM International, Machining, in *Metals Handbook*, Vol. 16, ASM International, Materials Park, OH, 1989. Reproduced with permission.

Abrasive slurry

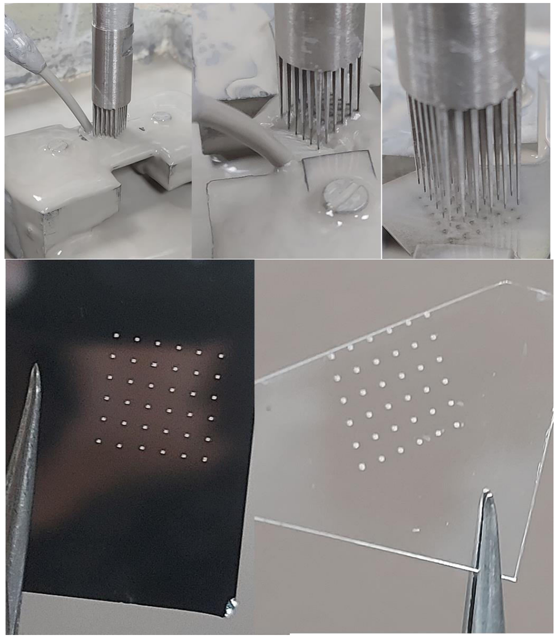
- The most common abrasives are Boron Carbide (B4C), Silicon Carbide (SiC), Corrundum (Al2O3), Diamond.
  - Size: 10 μm – 50 μm
  - B4C is the best and most efficient among the rest but it is expensive.
  - SiC is used on glass, germanium and most ceramics.
  - Cutting time with SiC is about 20-40% more than that with B4C.
- Diamond dust is used only for cutting diamond and other hard materials.
- Water is the most commonly used fluid although other liquids such as benzene, glycerol and oils are also used.

Ultrasonic machining (USM): Applications

- USM is best suited for hard, brittle materials, such as ceramics, carbides, glass, precious stones, and hardened steels. (Why?)
- Capability
  - With fine abrasives, tolerance of 0.0125 mm or better can be held.
  - Ra varies between 0.2 – 1.6 μm.
- Pros & Cons:
  - *Pros*: precise machining of brittle materials; makes tiny holes (0.3 mm); does not produce electric, thermal, chemical damage because it removes material mechanically.
  - *Cons*: low material removal rate (typically 0.8 cm^3/min); tool wears rapidly; machining area and depth are limited.

Ultrasonic machining at IIT B

USM operation



Mechanics of USM

- Main reasons for material removal in an USM :
  - The hammering of the abrasive particles on the work surface by the tool.
  - The impact of free abrasive particles on the work surface.
  - The chemical action associated with the fluid used.
- M.C. Shaw's earlier model of Material Removal:
  - $Q \; \alpha \; v\, Z\, f$
    - Q = Volumetric material removal rate
    - v = volume of the material dislodged in single impact
    - Z = number of particles making impact per cycle
    - f = frequency of vibration; number of impact tool is hitting the grains

$$Q \; \alpha \; \frac{d^{1/4} F^{3/4} A^{3/4} C^{1/4}}{{H_w}^{3/4}} f$$

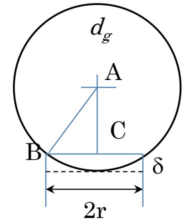
- Assumptions: Rate of work material removal is proportional to:
  - The volume of work material per impact, number of particles making impact per cycle, and frequency (number of cycles per unit time)
  - All impacts are identical and all abrasive grains are identical and spherical in nature

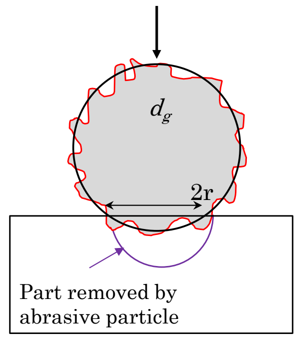
Modelling of Ultrasonic machining process

- Abrasive particles move under high frequency vibrating tool.
- USM is a form of abrasion and material removal in the form of small grains by three mechanisms
  - Throwing of abrasive grains (size of abrasive < tool-workpiece gap)
  - Hammering of abrasive grains (size of abrasive > tool-workpiece gap)
  - Chemical erosion due to micro –agitation
- Assumptions:
  - Abrasive are spherical in shape and rigid (exact sharp edges are difficult to predict)
  - No loss of kinetic energy of abrasive particles, i.e., complete transfer of Kinetic energy of abrasive particles into material removal
  - Brittle material are failed due to brittle fracture and Fracture of volume is considered to be hemispherical with diameter equal to chordal length of indentation

MRR by USM – single abrasive particle

- If δ is the indentation depth, d_g is the diameter of the abrasive grain, and r is the radius of indented area
- $r^2 = d_g\delta - \delta^2, \; r^2 \sim d_g\delta$
- Fracture volume is considered to be hemispherical with diameter equal to chordal length of indentation
- Volume of the material removed in brittle material caused by the fracture and microcracks
- $Vol = \frac{2}{3}\pi r^3 = \frac{2}{3}\pi (d_g\delta_w)^{3/2}$
- $Vol \sim K_1 (d_g\delta_w)^{3/2}$
- Number of impacts (N) on the work piece by the abrasive particles in each cycle depends on the number of particles beneath the tool at any time.
- This is inversely proportional to diameter d_g.
- $N = \frac{K_2}{d_g^2}$



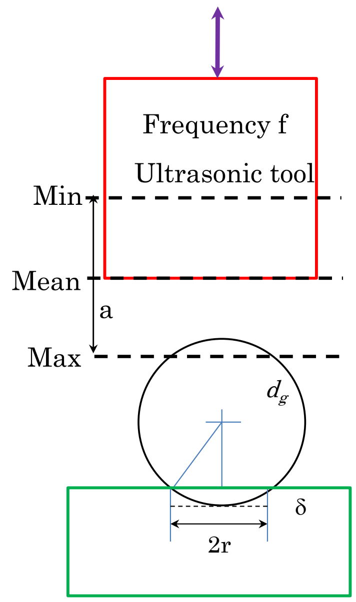


MRR by USM – single abrasive particle

- Material removal rate (MRR) will depend on the following:
  - Volume removed by single abrasive particle per cycle (*Vol*)
  - Number of effective particles below the tool (K_3)
  - Number of impacts per cycle (*N*)
  - Number of cycles per second (*f*) : Vibration frequency
- $Vol \sim K_1(d_g \delta_w)^{3/2}$
- $N = \frac{K_2}{d_g^2}$
- The general material remobal model equation can be written as:
  - $MRR = K_1(d_g \delta_w)^{3/2} * \frac{K_2}{d_g^2} * f * K_3$
  - $MRR = K_1 K_2 K_3 f \sqrt{\frac{{\delta_w}^3}{d_g}}$

Grain Throwing model

- It is assumed that a particle is hit and thrown by the tool on to work surface.
- Assuming that the ultrasonic tool is vibrating as per the sinusodial patten
- If the displacement of the tool (y), time (t) and amplitude (a/2)
- $y = \frac{a}{2} Sin(2\pi f)t$
- $v = \frac{dy}{dt} = \frac{a}{2}(2\pi f)Cos(2\pi f)t$
- $v_{max} = a\pi f$
- Assuming the abrasive particles under the ultrasonic tool are also moving at the same speed v_{max}
- Maximum Kinetic energy of single abrasive particle
- $KE = \frac{1}{2} m {v_{max}}^2 = \frac{1}{2}\left[\left(\frac{\pi}{6} d_g^3 \rho_g\right)(\pi a f)^2\right]$

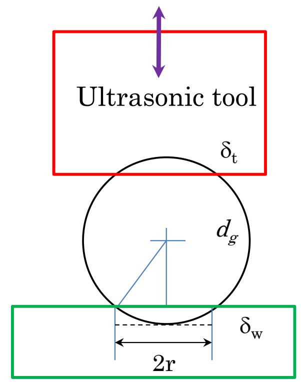


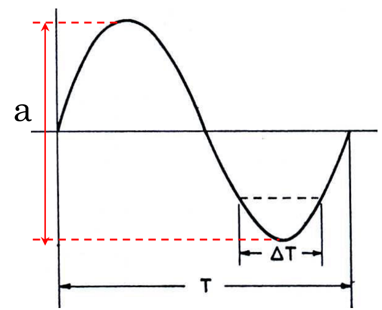
MRR by Single abrasive particle

- Upon impact, work material is subjected to a equivalent force F, which will lead to indentation depth δ
- As the force F will vary as per the indentation depth (from zero to maximum value at δ)
- The work done during the indentation by a single abrasive will be : $\frac{1}{2} F\delta$
- If σ_w is the fracture strength of the work piece material , then Force F would be:
- $F = \sigma_w(\pi r^2), F = \sigma_w \pi(d_g \delta)$
- Work done $W = \frac{1}{2} F\delta = \frac{1}{2}\sigma_w \pi d_g \delta^2$
- As the KE = Work done. $\frac{1}{2}\left[\left(\frac{\pi}{6} d_g^3 \rho_g\right)(\pi a f)^2\right] = \frac{1}{2}\sigma_w \pi d_g \delta^2$
- $\delta^2 = \frac{\rho_g}{6\sigma_w}(\pi a f)^2 {d_g}^2$
- MRR can be found as: $MRR = K_1 K_2 K_3 f \sqrt{\frac{{\delta_w}^3}{d_g}}$

MRR model : grain hammering

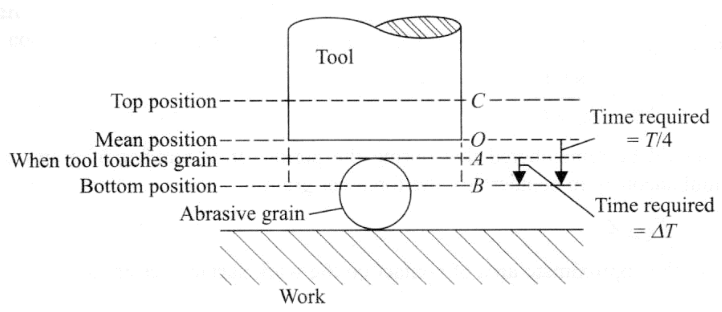
- When the gap between the tool and the work piece is smaller than the abrasive mean diameter, it will result into partial penetration in the tool (δ_t) as well as in the work piece (δ_w).
- The value of δ_t and δ_w will depends upon their hardness
- Total indentation $\delta = \delta_t + \delta_w$
- If the vibration frequency is f, then cycle time T=1/f
- Force applied by the ultrasonic tool on the abrasive grain will be only for a short duration (ΔT)
- Abrasive particle is in contact with the tool and work piece both.





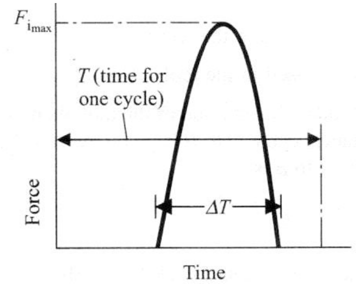
MRR model : grain hammering

- Force applied by the ultrasonic tool on the abrasive grain will be only for a short duration (ΔT)
  - Abrasive particle is in contact with the tool and work piece both.
- Force on the grit by the tool starts increasing as soon as grit gets in contact with both tool and the work piece at the same time. It attains maximum value and then starts decreasing until attains the zero value.



MRR model : grain hammering

- The mean force (F_{avg}) on the grit can be expressed by:
  - $F_{avg} = \frac{1}{T}\int_0^T F(t)dt$
  - $F_{avg} = \frac{1}{2T} F_{max}\Delta T$



- Total indentation $\delta = \delta_t + \delta_w$
- Vibration amplitude a/2
- Mean velocity of the tool during the quarter cycle:
  - $v = \frac{distance}{time} = \frac{(\frac{a}{2})}{(\frac{T}{4})} = 2a/T$
- Time (ΔT) required to travel from A to B (total indentation δ):
  - $\Delta T = \frac{\delta}{v} = \frac{\delta T}{2a}$

MRR model : grain hammering

- Average force applicable on abrasive particle
- $F_{avg} = \frac{1}{2T} F_{max}\Delta T$
- $F_{avg} = \frac{1}{2T} F_{max}\frac{\delta T}{2a}$; $F_{avg} = \frac{F_{max}\delta}{4a}$
- Let N be the number of grains under the tool , Stress acting on the tool (σ_t) and work piece (σ_w) can be found as follows.
- $\sigma_w = \frac{F_{max}}{N(\pi d_g \delta_w)}$; $\sigma_t = \frac{F_{max}}{N(\pi d_g \delta_t)}$
- $\frac{\sigma_w}{\sigma_t} = \frac{\delta_t}{\delta_w} = \lambda$
- $\sigma_w = \frac{4aFavg}{N\delta(\pi d_g \delta_w)}$; $\sigma_w = \frac{4aFavg}{N(\delta_w(1+\lambda)(\pi d_g \delta_w)}$ $\quad N = \frac{K_2}{d_g^2}$
- $\delta_w^2 = \frac{4aF_{avg}}{\pi\sigma_w N d_g(1+\lambda)}$; $\delta_w^2 = \frac{4aF_{avg}d_g}{\pi\sigma_w K_2(1+\lambda)}$ $\quad MRR = K_1K_2K_3 f\sqrt{\frac{\delta_w{}^3}{d_g}}$

MRR model : grain hammering

- $MRR = K_1K_2K_3 f\sqrt{\frac{\delta_w{}^3}{d_g}}$
- $MRR = K_1K_2K_3(d_g)^{1/4} f\left[\frac{4aF_{avg}}{\pi\sigma_w K_2(1+\lambda)}\right]^{3/4}$