

Particulate Dynamic Action of a Polishing Lap

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1. Lap Action: Micro and Macro Particulate Mechanics

Earlier studies (Gee 1996, Gee & Williams 1999) considered mechanical ablative actions of abrasive grains, modelled as kinematic micromechanical processes both at the particulate level and as macroscopic areal averaging processes. The latter were subdivided according to whether the lap was resilient ('hard') or yielding ('soft') and then either elastic (as used for semiconductor wafers) or viscous (as in pitch used in the optics industry).

Single-point indenter and ruling studies for machining investigations showed sharp scale transition at a depth of about $1\mu\text{m}$ between brittle chipping at the $10\mu\text{m}$ scale and plastic deformation permitting spatial fidelity at the nanometric level and lower (Gee et al 1992). These collated very much with hard and soft lap-actions which have distinct modes in working brittle materials.

Hard lap 'hogging' involves the disordered generation of brittle-chips whose geometry is determined by brittle-fracture. The action is dominated by chip size, which, together with surface damage and roughness were all of the order of $10\mu\text{m}$. Grains dig in and roll or slide to ablate material at high rates so that the workpiece form converges towards that of the lap.

Changing to a soft yielding lap (elastic polymer material or viscous pitch), a major action is to permit abrasive particles to autonomously self-align whilst sheared *en-masse* over certain geometrical forms (planar, spherical and cylindrical). By this action, they microscopically ablate the surface to improve finish readily to the order of 1nm R_a , as much as four orders below the rough-hogging level. Such action is compatible with observations made relating to single point machining and in turn to the grinding of brittle materials. A plastic regime, existing at scales below some critical depth for fracture, would permit material removal without the divergent unstable crack growth downward into the material which leads to classical conchoidal fracture observed in glassy materials. Shearing action observed in single point experiments using tools with high negative rake-angles would model closely the actions of a sliding grit particle made up of facets embracing large included angles (Gee 1996, Puttick et al 1989).

2. Likelihood of Abrasive Grain Rolling During Polishing

It has been observed that abrasive grains of mean diameter well in excess of $1\mu\text{m}$ can generate surfaces whose finishes have roughness $R_a \sim 1\text{nm}$ (Gee and Williams 1999). Such fine finish is achieved in the plastic ablative mode as brittle chips are orders larger (Gee et al 1992). This being so, were rolling of any particle a putative action, it would be expected to emboss spatial features plastically into the surface; these are likely to be of a scale to $\sim 0.3x$ the mean particle diameter i.e. $>300\text{nm}$, more than two orders greater than the 1nm finish typically measured. Rolling action is therefore extremely unlikely to contribute to such finish.

Having eliminated rolling, the ablative action is constrained to fixed grain orientation in roll and (by symmetry) angular pitch but with lateral freedom in yaw plus in-plane sliding. It may therefore be envisaged that fine surface finish is achieved by grain facets aligned with the surface acting to ablate asperities by 'scrape-planing' action, as suggested by Strong (1938).

3. Response of Elastic Lap

The action of an abrasive particle carried by elastic lap material is related to force applied and thence to the amplitude of height variations imposed as the particle passes over asperities. Linear elastic lap forcing action on the rising side of asperities may therefore be expected to be independent of frequency and solely a function of roughness amplitude. On the ‘falling’ side, depending on the relaxation characteristics and response time, the grain may or may not follow the slope depending on its steepness with respect to the response of the particle/lap material. Since the input shearing action is essentially random and omnidirectional the rising effect may be expected to dominate.

4. Response of Viscous Lap

In the case of abrasive action using a pitch-lap, the force on a grain moving near-normally into the lap is a linear function of its velocity through the viscous pitch medium, i.e. to the grain sink-velocity normal to the surface, deriving from its endeavours to follow surface deviations. Assuming the input forcing function (surface roughness) to be spatially/temporally sinusoidal, (for the purposes of illustration) the sink-rate is a linear function of frequency and amplitude. In-going the depth of a grain in the pitch H is given by:

$$H = A \sin \omega t \quad (\text{eq.1})$$

where A is the zero-peak amplitude and ω is the temporal radial frequency. A lap/surface shearing velocity S m/s will ‘scan’ the roughness spatial frequency of f cycles/m to yield $\omega = 2\pi fS$ rad/s.

From SPM scans of a pitch-lap we obtained the size and distribution of particles. Typically four particles of $10\mu\text{m}$ are found in a square of side $40\mu\text{m}$ leading to an estimate of the sustained force on each particle of $60\mu\text{g}$ (Gee & Williams 1999).

If we approximate the grain to a sphere of radius r moving at sink-rate v m/s in a medium of viscosity η , Stokes’ Law applies in respect of the sustaining/reacting force F :

$$F = 6\pi\eta rv$$

If, as a start-point, we consider a sphere of radius $0.5\mu\text{m}$ travelling with velocity $1\mu\text{m/s}$ in the medium of viscosity 10^8 Pas (Ns/m^2) or 10^9 Poise, (see section 6), the force on it will be:

$$F = 6\pi 10^8 (0.5 \cdot 10^{-6})10^{-6} \sim 1\text{mN} \sim 100\text{mg}. \quad (\text{eq.2})$$

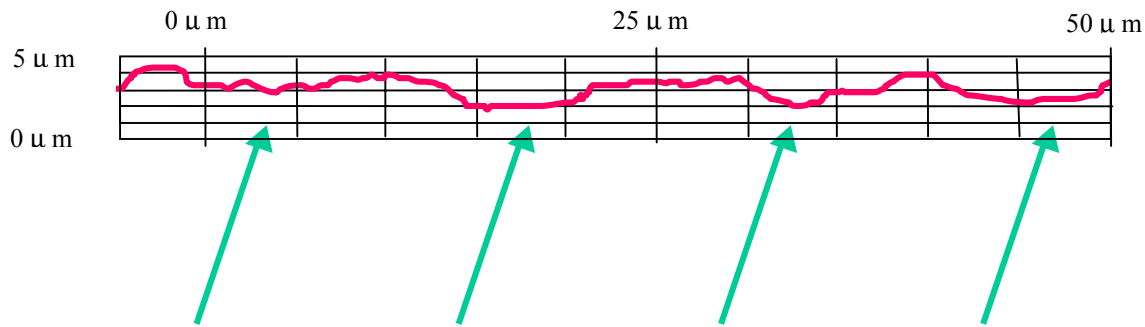
Consider now the sink-rate pertaining from endeavouring to follow, at lap-shear velocity S m/s, a surface of spatial frequency f cycles/m and amplitude A m. From eq.1 above, the sink motion is given by:

$$H = A \sin \omega t = A \sin 2\pi fSt \quad (\text{in m}) \quad \text{where } \omega = 2\pi fS \text{ rad/s.}$$

The instantaneous sink-rate of the grain into the pitch is $v = \omega A \cos \omega t$ (in m/s) $= 2\pi fSA \cos 2\pi fSt$ whose maximum (sink-rate) value is: $v_{\text{max}} = 2\pi fSA$ m/s.

SPM scans of hard-lapped surfaces generated using grits progressing down to 1200 (Fig.1) show a typical spatial period of $15\mu\text{m}$ ($f \sim 7.5 \times 10^4$ cycles/m) and semi-pk-pk amplitude (A) of $1\mu\text{m}$. If the lap is shearing over the work-piece at $S = 0.2\text{m/s}$, and the typical deviating ‘input’ to any one grit particle is perhaps 1/10 of the roughness amplitude ($0.1\mu\text{m}$), we have:

$$v_{\text{max}} = 2\pi fSA = 2\pi 7.5 \times 10^4 \times 0.2 \times 0.1\mu\text{m/s} = \sim 10\text{mm/s.}$$



4 depressions are seen at about 15μm wavelength;
 each is about 2 μ m deep x about 10 μ m long; they are generally convex depressions
 having steeper sides near the highest areas between the depressions.

Fig. 1 SPM scan of typical roughed glass

We can now scale the above starting point equation (eq.2) to measurement-derived scales of velocity, from 1μm/s to 10mm/s (i.e by 10^4), and grain diameter, from 1 to 10μm (i.e. by 10). The force applying to each particle scales from 100mg by a factor of 10^5 to 10kg. This remarkably high value is close to the typical loading on a lap.

In the plastic regime where single-point loads of the order of grams cause ductile deformation (Gee et al 1992), plainly, at much lower forces before such hypothetical kg order forces are invoked, the asperity or roughness peak capable of generating such a velocity component will have yielded and been plastically deformed by the highly raked typical grit facet presenting as discussed previously (Gee 1996).

It is likely that material will be plastically deformed into the corresponding 'valley' component of the surface roughness and that the total lap system will autonomously settle on a net level corresponding to some material loss in the form of chips washed/swept away. Such action appears to allow for volumetric redistribution with a proportion of the material regressed into the surface in the form of a 'worked' layer as discussed by Twyman (1952 p56).

5. Amplitude/Frequency Variation

The dynamic force applying to a polishing grain in a pitch-lap is a linear function of the forced sink-rate i.e. to both amplitude and frequency of any cyclic forcing function (the surface roughness). Progressive reduction of amplitude during polishing by selective peak 'flattening' will generate two cross-sectional inflections where there was one before. This will be accompanied by a corresponding increase in frequency as the spatial components get smaller. To a first approximation it might be expected that the correspondence is linear and that the forced sink-rate remains approximately constant as frequency increases and amplitude reduces. In turn, this would be expected to cause little variation in the lap drive force/frictional characteristics as polishing progresses.

6. The Issue of Pitch Viscosity

Although pitch in its various forms remains a highly viscous fluid, it approaches an apparently solid state at low temperatures. Its softening point temperature is used to indicate the relative 'hardness' of the pitch and for glass polishing purposes this is usually between about 40 and 90 C. The softening temperature is

defined by a standard test (ring and ball) to determine the temperature at which the pitch viscosity falls to a standard value of 800 Ns/m^2 ($8,000 \text{ Poise}$). The actual viscosity-temperature function is highly non-linear but appears of similar form for most pitches (Kirk-Othmer 1997). The viscosity rises very rapidly below the softening point temperature (Fig 2) but it appears that the material remains essentially viscous.

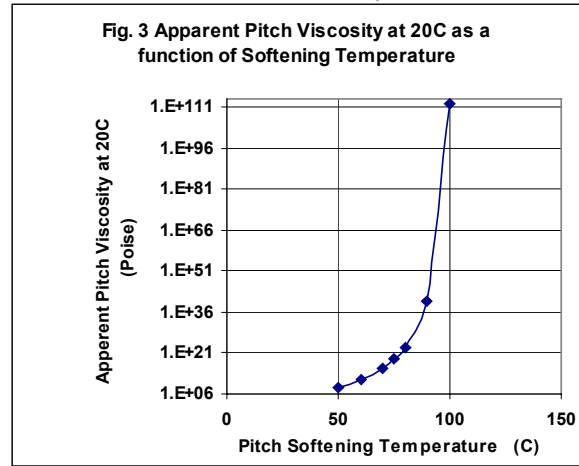
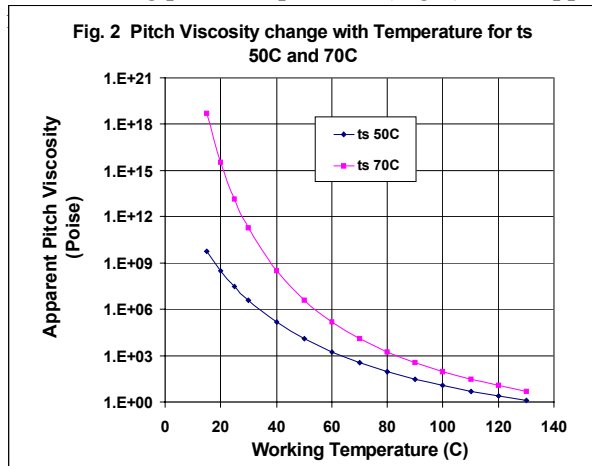


Fig 3. shows apparent viscosity at a working temperature of 20C for a range of softening temperatures. values of 10^9 to 10^{11} Poise being typical. For the 'soft' pitch grades used in polishing (softening temperature about 50C) the working temperature viscosity would be about 10^9 to 10^{10} Poise, yielding to long impress. Pitch also has a very low coefficient of thermal conductivity so that any heat generated locally due to frictional effects is likely to remain local for appreciable time thus causing potentially large local reductions of viscosity compared with the surrounding material (Briggs and Popper 1954). It has been suggested (Gee 1996) that this autonomously compensates for inconsistency in pitch mixtures.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

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