

Single Point Contributions to Free Abrasive Polishing

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1. INTRODUCTION

Long experience (refs 1,2) has shown free abrasive hard and soft lapping to be capable of generating spherical and planar surfaces of high quality to sub-micrometre form specifications (an order or more better with effort) and nanometre finishes. 'Hogging' with an iron lap leaves surface damage of the order of tens of micrometres, much of which can be removed by finishing with a lap of pitch or elastic polymer. We observed that the geometrical values closely coincided with those obtained for respectively brittle and plastic material removal actions in single-point machining experiments, notably ruling on glass (with the diamond tool located by force, as pertains under a lap) and the paper correlates observations.

2. HARD LAP/WORKPIECE KINEMATICS

Empirically (ref 3, p50), it has been found that, for rapid form convergence through even material ablation over the work area, a lap is required to closely 'nest' with the workpiece over perhaps 70% or more of the surface. Interface shearing, required in at least two tangential motions, restricts the process intrinsically to planar, spherical and cylindrical surfaces. Radius differences in aspherics require smaller and/or flexible laps, sacrificing intrinsic form-averaging and requiring external measurement-based control; stressed blanks and adaptively controlled laps are possible approaches.

In minimal form, an abrasive grit particle might be a regular tetrahedron with 4 facets, 6 edges and 4 vertices, all at acute included angles. If breakage symmetrically truncates one vertex to another facet, this will generate 3 extra edges and 3 vertices (in place of the one removed) at obtuse angles. If it is envisaged that working abrasion removes 'sharp' vertices, the resulting polyhedra will be of mostly obtuse included angles, with perhaps the occasional acute or reflex angle.

Kinematic considerations (ref 4 pp585-590) applied to two rigid bodies in stable sliding contact require the number of degrees of freedom of motion of the one body with respect to the other, together with the number of points of contact (i.e. constraints), to sum to six. A rigid nominally spherical or planar lap therefore contacts a work-piece of corresponding form generally at three points, permitting three shearing degrees of freedom (N.B. cylindrical geometry requires four contact points, permitting two motions). With abrasive, 'point' contact will be through locally-proud grits. A single grit contacting one surface at three points can be stable whilst contacting the other surface at just one point. If it contacts one surface at two points and the other at one, it may roll about the axis defined by the first two. If it contacts each surface at only one point, roll will be defined by the shear vector. Roll permits interchange between contact conditions.

Subjected to a point force of 1N through an indenter, glasses crack to form 10 μ m scale conchoidal chips and corresponding surface damage (refs 5-8). If we apply a force of the order of N (due to weight plus preload) through the lap normal to the interface, either the workpiece or grit may yield,

causing the lap to bear down onto the next proudest grit in that region. If the work-piece cracks, the grit will most likely ingress substantially. Applying shear, the grit will experience torque about an axis parallel to the interface and rotate into fresh undamaged surface to extend the cracking/chipping process. If however a grit presents to the workpiece a facet at less than workpiece cracking pressure, then the grit may yield and the resulting smaller grits may settle below adjacent peaks in surface valleys and take little further part in abrasive action. This appears to be self-ordering to a scale of $\sim 10\mu\text{m}$ defined by the geometry of brittle chip size (refs 9,10).

3. SOFT-LAP POLISHING: GRIT ACTIONS

The ($10\mu\text{m}$ scale) roughness incurred with hard-lap hogging to form can be polished to about 1nm finish using a soft 'pitch' lap with a variety of abrasives and grit sizes of the order of $1\mu\text{m}$. If such grits were to roll under the lap, the 10-100nm features of a $1\mu\text{m}$ chip would be likely to be reproduced by impression embossing in the glass in plastic mode. Such a process is not considered to contribute to achieving 1nm finish. Grit shear 'planing' suggested by Strong (ref 4 p32) might be expected to sustain polishing at the 1nm level and a conforming model for stable grit action has been proposed (ref 11).

Types of 'pitch' used in optical laps are variously obtained from tapping varieties of pine tree or as a by-product of oil or coal-tar production. Although relatively hard at room temperature, it is definitively a high viscosity liquid, which softens noticeably at temperatures above 60C. Its response to force in the manner of a viscous 'damper' will show low-pass temporal frequency filtering characteristics, yielding to slow effects such as sustained force on a grit particle but presenting near-rigid reaction to higher frequency effects like individual lap strokes.

When a pitch lap closes with a preformed workpiece, we may expect three proud grits to make initial kinematic contact and to start sinking into the pitch until a fourth grit makes contact and joins the process. This continues with the next proudest grit successively joining in to share the reaction force. Both the sink rate and individual grit loading reduce with increasing number of grits. The initial 'pressing' by optical glass-workers may be expected to align a large number of grits with the workpiece to support a combined lap-weight plus preload of 1kg or more.

Self-alignment can be seen in Figs 1(a) and (b), AFM micrographs of a pitch lap immediately following the finish-polishing of glass using a mixture of rouge and cerium oxide abrasive. The proudest grits have major exposed lateral dimensions of 3-6 μm and peaks of perhaps 2 μm diameter aligned about $1\mu\text{m}$ clear of the lap surface, (much in excess of the 1nm surface roughness obtained from the grit polishing action). The lap, of 50mm radius (r), had a matrix of facets separated by grooves (of perhaps 20% facet-pitch) so maximum contact area was approximately $A = \pi(0.8r)^2 = 0.64\pi(50 \times 10^{-3})^2 \sim 5 \times 10^{-3} \text{ m}^2$ to sustain a load of 1kg. In all such measurements, over a $40\mu\text{m}$ square the number of aligned proud grits was 5 ± 1 . Taking 5 grits as typically sustaining the load over area $a = (40\mu\text{m})^2 = 1.6 \times 10^{-9} \text{ m}^2$, this grit/area density applied to the full lap area indicates the likely maximum total number of 'working' grits to be $5(A/a) \sim 5[5 \times 10^{-3} / 1.6 \times 10^{-9}] \sim 1.6 \times 10^7$. With a load of 1kg, the force devolving to each grit is therefore $\sim 60\mu\text{g}$, well below the gram order critical values of brittle transition obtained using sub-micrometre radius tools (refs 9,10).

The action of a sinking grit is analogous to the falling sphere viscometer in which force $F = 6\pi\eta r v$ (where η is viscosity, r radius and v is sink-velocity) so larger dimension grits exert proportionally

larger force on the workpiece. Considering grits of different sizes but single polyhedral form, the area of the typical facet bearing on the surface will be proportional to the *square* of grit dimension and, since force is proportional to grit size, it follows that contact-pressure will be an *inverse* function of grit size. Moreover, should a grit tend to remain proud for any reason, it will bear a higher load and incur higher frictional heating so reducing the viscosity of adjacent pitch until the grit sinks to peer-level. Further, in shear, a grit facet which 'planes' the workpiece may be expected to experience tangential force proportional to its dimension and the viscous shear reaction force to be likewise proportional to dimension so 'working' grits would be dragged tangentially through the pitch at equal rates irrespective of size and so remain in the same relative position. These three autonomous mechanistic effects will tend to regulate even sharing of the lap-work by a large number of grits of not necessarily the same size, as has been observed (ref 12).

In other fields such as semiconductor wafer preparation, polymer elastic and/or fiber soft laps are employed with similar results but, unlike pitch, an elastic lap is not rate-sensitive. It will hold grits against a workpiece with a force determined by local deflection which is proportional to grit-dimension, coincidentally as in the pitch lap and so grits will likewise exert facet contact pressure on the workpiece as an inverse function of dimension. These very different underlying physical actions but coincidence of effect permit a variety of soft lap materials.

4. CONCLUSIONS

Whilst there remain issues of chemistry and fluid action, it is possible to analyse aspects of mechanical constraints on the actions of abrasive grits during polishing. This paper has considered how grits of micrometre dimension and protrusion from a soft pitch lap may yield surfaces in brittle glasses polished to roughness levels of the order of 1nm. It is shown experimentally that, under a pitch lap, abrasive particles maintain self-alignment and distribution so that the pressure exerted by any individual grit remains well below that leading to brittle cracking.

It is reasoned that an elastic polymer lap is mechanistically different but that, with respect to grits of different size, its action coincides with that of the viscous pitch lap.

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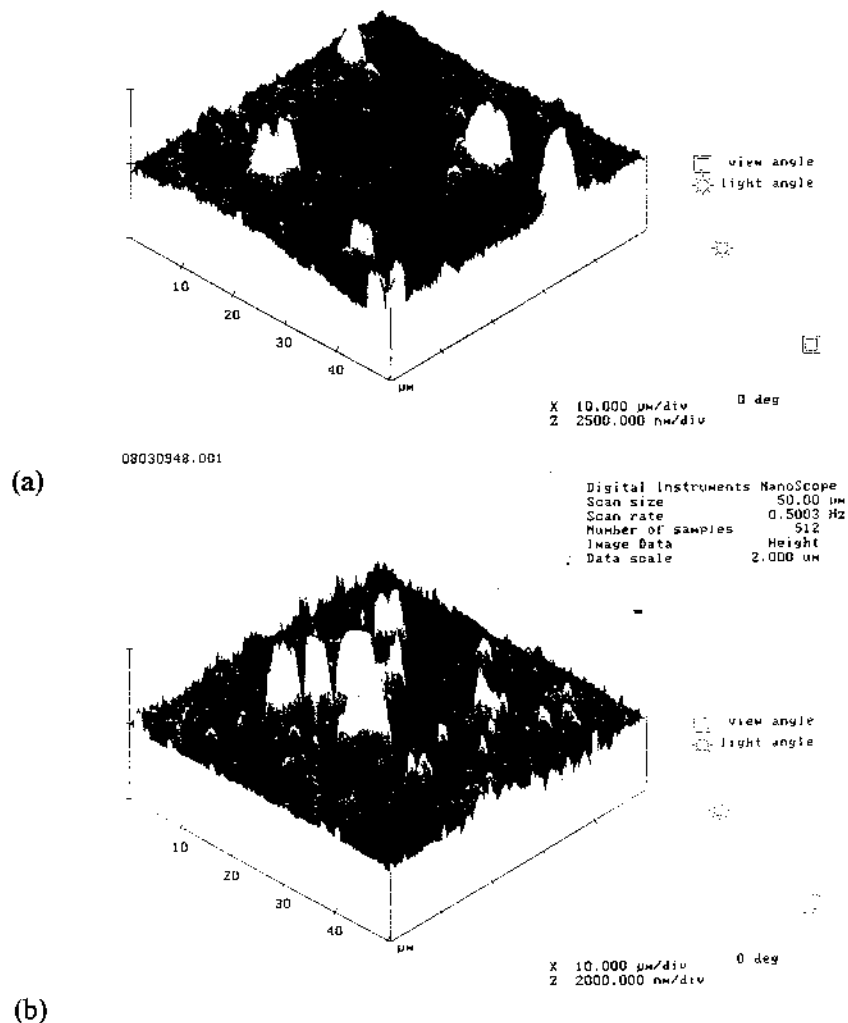


Fig 1 Scanning Force Micrographs of Grits in a Pitch Lap after Polishing Glass