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Framework for Assessing Key Variable Dependencies in Loose-Abrasive Grinding and Polishing

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Framework for Assessing Key Variable Dependencies in Loose-Abrasive Grinding and Polishing*

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Summary

This memo describes a framework for identifying all key variables that determine the figuring performance of loose-abrasive lapping and polishing machines. This framework is intended as a tool for prioritizing R&D issues, assessing the completeness of process models and experimental data, and for providing a mechanism to identify any assumptions in analytical models or experimental procedures. Future plans for preparing analytical models or performing experiments can refer to this framework in establishing the context of the work.

Motivation

Precision lapping and polishing processes are likely to be used in manufacturing optics for the National Ignition Facility (NIF). For example, pitch polishing on planetary laps is the key operation that enabled the production of highly flat windows and amplifier slabs for DOE's past and present solid-state ICF lasers: Nova, Omega, Shiva, etc. There are several proposals for developing new high-speed polishing techniques and machinery for reducing the cost of NIF optics. Most of these proposals require significant technical developments before they can lead to cost-effective production processes. It is critical to assess the technical issues associated with these developments.

This paper focuses on the variables that influence the ability of a lapping or polishing operation to meet the figure specification for a workpiece. As an example, a goal for a final polishing operation on a transmissive flat optic might be to attain a final transmitted wavefront of about λ/6 PV, where λ is the inspection wavelength of 632 nm. For a typical optical glass, this corresponds to a surface flatness requirement of approximately λ/3 PV, which is about 210 nm. The criterion for determining if a variable has a significant influence on the polishing process is based on whether or not variations in its value lead to significant changes in workpiece flatness.

Approach

Our approach is to employ a well-known tribological model (Preston's Equation) that predicts the local material removal rate in loose-abrasive lapping. We consider how physical variables influence each of the terms in this equation and how part shape is determined by the integration of the local removal rate over the duration of the operation.

Preston's Wear Equation

The model we are using for the material removal rate for loose abrasive lapping operations is the Preston Wear Equation:[1,2,3,4]

$$\left.\frac{dh(x,t)}{dt}\right|_B = C_B(x,t)\, P_B(x,t)\, U_B(x,t) \qquad (1)$$

$$\text{removal rate} \propto \text{pressure} \times \text{speed}$$

where h is the height of the surface layer that is worn away, P is the apparent contact pressure between the lap and the workpiece and is equal to the contact load divided by the apparent area of contact, and U is the relative sliding speed between the lap and the workpiece. This relative sliding speed is calculated from the magnitude of the difference in vector velocities of the lap and the part at point B on the workpiece. C is a proportionality constant referred to as Preston's coefficient. Although the equation is written here as a function of position and time, the crux of the statement is simply that *removal rate is proportional to contact pressure and speed.*

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If the frictional force exerted by the workpiece along the lap surface is proportional to the contact pressure, then Preston's equation can be interpreted as stating that the rate of material removal $\frac{dh}{dt}$ is proportional to the sliding energy, i.e., $\textit{frictional force} \times \textit{sliding velocity}$. The constant of proportionality is Preston's coefficient C. For many lapping and polishing operations, C is known, and as long as the conditions remain constant, Eqn. 1 results in a simple and convenient way to estimate removal rates.[5]

Variable dependencies

The influence of all variables on the evolution of surface figure during loose-abrasive processing is determined by the Preston equation. For the cases of relative velocity and pressure, this influence is directly stated by Eqn. 1. For variables such as temperature and material properties, their influence is determined by their effect upon C, P, and U. In this paper, the functional dependence of the local material removal rate will be discussed, with the goal of covering all important variables.

Time

All of the variables involved in lapping can, in general, vary with time. This variation can be repeatable and predictable, such as in periodic variations in the sliding velocity, or they may depend on the evolution of the process, such as pressure variations due to part and lap wear and changes in the properties of the slurry due to aging.

The Framework

Figure 1 shows a diagram that depicts the key functional dependencies for the Preston Equation. Each of the three factors on the right hand side of Preston's Equation has a tree leading to different variables and physical processes that influence it. In order to determine what effect a particular variable has on removal rate, one must first identify where on the chart that variable influences C, P, and U. If that variable is not on the chart, then it is unlikely to influence removal rate. This chart is not intended to be a rigorous description of mathematical dependencies, but to indicate the hierarchy of how physical variables influence the material removal process.

Relative Speed, *U*

The relative speed between the part and the lap is determined by the magnitude of the vector difference between the lap velocity and the part velocity. In general, the relative speed varies across the part and in time. Geometry is listed here because the influence of velocity on the distribution of velocities depends on parameters, such as where the part is located in the carrier and the style of lap, e.g., overarm or planetary. The influence of kinematic variables in planetary lapping and polishing is discussed elsewhere[3], and is not repeated here.

Pressure, *P*

Pressure is generally not uniform over the surface of the part and will vary as the part moves over the lap. A "non-uniform pressure distribution" refers to different levels of contact force between the part and the lap at different points on the part. Three main categories influence the pressure distribution: 1) part-to-lap interference; 2) method of loading; and, 3) hydrodynamic effects.

A key concept in discussing the pressure distribution on the surface of the part is the "unstressed part shape." Because it is almost always the goal to mount optics in an unstressed state, it is the flatness of the surfaces *in this state* that is important. Thus, if a flat surface is produced on a part in a stressed (and deformed) state, then when it is installed in the system, it will tend to its unstressed shape.

'Part-to-lap interference' refers to all instances where the contact surface between the lap and an *unstressed part* is either not flat or comprises an air gap. When polishing in this mode, the areas with higher pressures will have higher removal rates. The word *interference* is used because it represents the geometric mismatch between the surface of the unstressed part and the lap.[6]

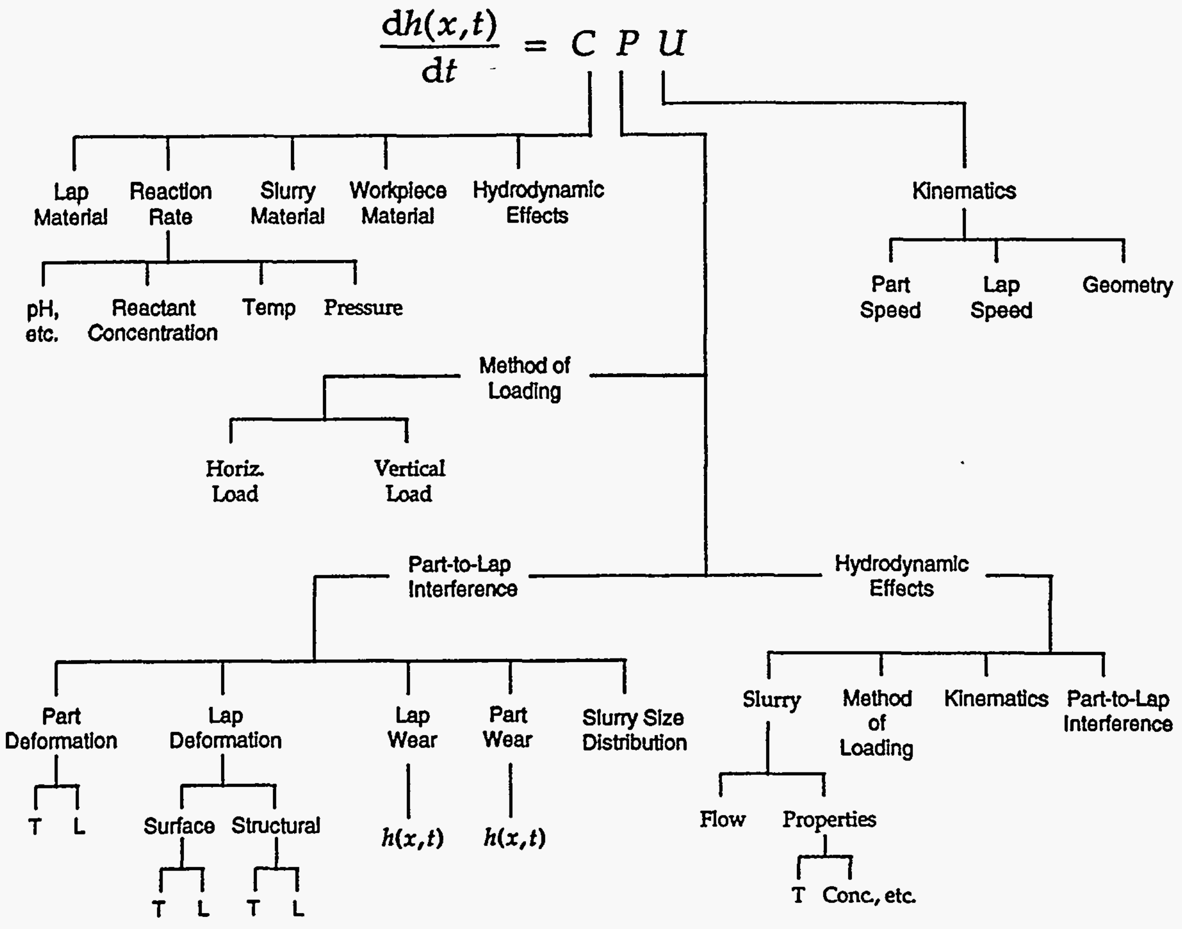

Figure 1. A framework depicting the functional dependencies of the local removal rate in loose abrasive lapping and polishing as described by Preston's Equation. ['T' = Temperature; 'L' = Loading]

Part-to-lap interference may be caused by several factors: part deformation, lap deformation, lap wear, part wear, and the presence of global variations in the sizes of abrasives on the lap.

Two main causes of part deformation and lap deformation are thermal effects and distortion due to applied loads ('T' and 'L' in the figure). For workpieces, thermal deformation will be determined by the heat transfer boundary (and initial) conditions such as slurry temperature and flowrate, slurry evaporation rates, lap temperatures, material properties, frictional work, etc.

Lap deformation can be divided into localized deformation at the surface and large-scale structural deformation. The structural components are similar to those for the workpiece, but would also include thermal effects that account for any internal cooling (or heating) mechanisms and heat sources such as motors, cooling coils, and bearing friction. Furthermore, the surface of a polishing pad will exhibit localized deformation due to indentation by the "high" spots on part, which might be addressed using a Hertzian analysis.[7] Also, the properties and geometry of the pad may be temperature dependent.

'Hydrodynamic Effects' refers to a non-uniform bearing-like fluid pressure distribution that develops due to the sliding motion of the part. This can lead to a tilting motion of the workpiece (if it acts as rigid body slider), or cause a net suction (e.g., for concave parts) or lift of the workpiece with respect to the lap. These influences might be observed as variations in the Preston coefficient. Variables that influence the hydrodynamic effects include the slurry flowrate and its properties, the method of applying traction loads to the workpiece, kinematics, and the part-to-lap interference.

The '**Method of Loading**' directly influences the pressure distribution. If the vertical load is applied in a non-uniform distribution, e.g., a small number of discrete loads, then the pressure distribution will tend to a linear (planar) distribution for a rigid-body workpiece, and may lead to a complex distribution if the workpiece deforms. The judicious placement of small weights on the surface of workpieces has long been a key tool used by opticians to correct various flatness errors on workpieces. Workpieces might also be loaded from above by a pneumatically-loaded plate, which can be rotationally-driven. If the motion of this plate or its flatness causes deformation of the workpiece, then the pressure distribution under the workpiece will be affected. In addition, if this plate prevents the workpiece from tilting to follow the lap, such as due to stiction in the gimballing motion of the plate, then a non-uniform pressure distribution will be created. The method of applying the horizontal load on the part will, in general, cause a moment (or force couple) to form with the inertial forces and the frictional forces, contributing to a non-uniform pressure distribution under the part.

Influences on the Preston Coefficient, *C*

The Preston coefficient accounts for the efficiency in converting frictional energy into material removal. It depends upon the material properties of the lap, the slurry distribution and its properties, and the workpiece properties, including thermal, mechanical, and chemical properties. Because polishing might be viewed as stress-induced chemistry, the properties of the reactants are important. Similarly, any variable that influences the reaction rate can influence the Preston coefficient. Furthermore, Cook[8] and Brown[9] point out that a significant amount of the material removed during the polishing of silica glasses is redeposited on the surface, which clearly affects the apparent rate of material removal, and thus *C*. Variables that might influence the reaction rate include the reactant concentration, the pH of the fluid, the temperature (Arrhenius dependency) and the local pressure.

Coupling of effects

It is clear that there can be substantial coupling among the physical influences upon the material removal rate. Thus, changing a variable such as temperature in lapping and polishing can cause several effects. In comparing different experiments or calculations that investigate the influence of particular variables, we should use the framework of Figure 1 to determine if the link to the local material removal rate is the same. Ensuring a common link to *C*, *P*, and *U* will provide an "apples-to-apples" comparison among different experiments.

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[1] Preston, F., "The theory and design of plate glass polishing machines," **J. Soc. Glass Tech.**, vol. 11, pp. 214-257 (1927).

[2] Brown, N. J., **Optical Fabrication**, UCRL-MISC- 4476 Rev. 1, September 1990.

[3] Taylor, J. S., et. al., "High-speed lapping," **1994 Engineering Thrust Area Report**, LLNL, *in press*.

[4] Cumbo, M. J., **Chemo-Mechanical Interactions in Optical Polishing**, Ph.D. Thesis, University of Rochester (1993).

[5] For example, for pitch polishing of BK7, C is about $8(10)^{-14}$ cm^2/dyne (see ref. 2). Therefore, to calculate the removal rate for a pressure of 25 gm/cm^2 and a speed of 10 cm/s:

$$\frac{dh(x)}{dt} \cong 8(10)^{-14}\frac{\text{cm}^2}{\text{dyne}} \times 25\frac{\text{gm}}{\text{cm}^2} \times 10\frac{\text{cm}}{\text{s}} \times 981\frac{\text{dynes}}{\text{gm}} \times 10{,}000\frac{\mu\text{m}}{\text{cm}} \times 3{,}600\frac{\text{s}}{\text{hr}} = 0.7\frac{\mu\text{m}}{\text{hr}}$$

[6] There is an analogy here with the concept of interfering asperities in tribology, see N. P. Suh, **Tribophysics**, Prentice Hall, 1986, chapter 3 "Generation and transmission of force at the interface: the genesis of friction."

[7] see Suh, N. P. *op cit.*, chapter 4, "Response of materials to surface traction."

[8] Cook, L. M., "Chemical processes in glass processing,"**J. Non-Crys. Solids**, 120 (1990) pp. 152-171.

[9] Brown, N. J., "Some speculations on the mechanisms of abrasive grinding and polishing,"**Precision Engineering**, 9(3), July, 1987, pp. 129-138.

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