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Material Removal Mechanisms in Lapping and Polishing

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Abstract
Polishing processes are critical to high value production processes such as IC manufacturing. The fundamental material removal mechanisms, howeve, are poorly understood. Technological outputs (e.g., surface finish, sub-surface damage, part shape) and throughput of lapping and polishing processes are affected by a large number of variables. Individual processes are well controlled within individual enterprises, yet there appears to be little ability to predict process performance *a priori*. As a first step toward improving process modeling, this paper reviews the fundamental mechanisms of material removal in lapping and polishing processes and identifies key areas where further work is required.

Keywords:
Lapping, polishing, planarization

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1 INTRODUCTION

Lapping and polishing may be among the oldest manufacturing processes, but they seem to be the ones least well supplied with predictive process models. Previous comprehensive CIRP keynote papers (e.g., Komanduri et al. [1], Venkatesh et al. [2], Salje and Paulmann [3]) have provided invaluable technological overviews as have a variety of books and monographs [4]. None, however, provides a structured review of the state of our understanding of the fundamental mechanisms at work in lapping and polishing. The gaps in our knowledge are quite remarkable when contrasted with the economic importance of these processes. How important are the processes that polish diffraction-limited stepper and DVD mastering lenses, planarize ICs in process, and lap hard disk read-heads? This paper will focus on polishing processes, taking insights from the larger scale processes of lapping, loose abrasive grinding, and single point cutting as pointers to the mechanisms involved in polishing. Changes in scale, however, may have dramatic effects on mechanisms.

One central premise of this paper is that a fundamental understanding of mechanisms is key to developing predictive (rather than descriptive) process models [5]. It is common experience that relatively minor changes in polishing process operating parameters can produce dramatic changes in output – or no detectable change at all. We need not only to understand – quantitatively – the mechanisms but also the transitions between them. For the technologist, the key prediction is removal rate; hence this paper has a strong bias towards kinetics.

A second basic premise of this paper is that all lapping and polishing processes can be described as four component systems (Figure 1) and that the mechanisms involved can be grasped by first understanding the interactions among those components. Lapping and polishing are differentiated technologically, but not in this mechanistic view; the relative size of the “grit” and the surface layer removed may change dramatically, but the processes all rely on interactions between these basic elements.

The third basic premise of this paper, therefore, is that our knowledge (and ignorance) of the mechanisms can be catalogued in terms of the interactions between the four basic components, modulated by scaling of the interactions according to the physically relevant external variables. This cataloguing process, we hope, will define critical fundamental questions which need to be answered to enable future improvements in our ability to predict process behavior.

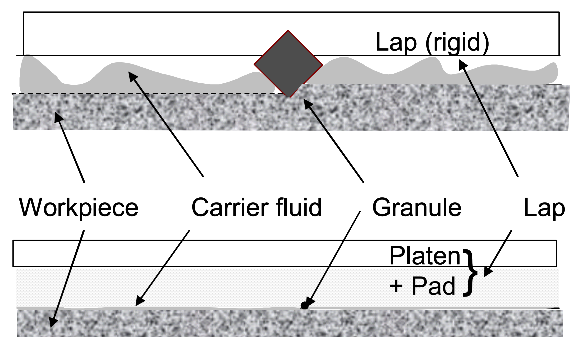


Figure 1: Examples of lapping (top) and polishing processes (lower) which involve a granule, a carrier fluid, a workpiece and a “lap” or platen (see Section 2 for further discussion).

The structure of this paper, therefore, begins with definitions of the individual components. The bulk of the paper addresses the various pairwise interactions between components of the system and important three component interactions. Next we give examples describing complete systems in terms of the component interactions and finally some summary remarks.

Although we discuss a range of important mechanisms, we recognize that this overview is incomplete. Polishing may also be affected by other process related issues, such as the presence of swarf removed from the workpiece or the process kinematics; these issues are not covered here. The economic value of polishing depends not only on removal rate, but on a variety of other process outputs such as finish, figure (shape) accuracy, and sub-surface damage, none of which are explicitly considered here but each of which would be included in a complete mechanistic understanding.

2 THE SCALE OF INTERACTIONS

We indicated above that the purpose of this paper is to describe fundamental mechanisms of material removal. This implies that we are interested in length scales ranging from atomic to, say, the propagation distance of stress or sub-surface damage. Dissolution, for example, takes place on nanometer lateral and vertical scales. By contrast, the ductile cutting using a fine diamond may remove swathes of material microns wide and nanometers deep, while affecting the workpiece material properties to a much greater depth. Polishing is, however, affected by processes at other length scales. Imperfect "fit" between part and lap (at length scales up to the part diameter, depending on the properties of the lap), affects local particle loading, hydrodynamic film formation, temperatures, and hence removal rates. All length scales will be considered.

3 THE FOUR PROCESS COMPONENTS

As indicated in Section 1, the mechanisms of lapping and polishing involve four components: the *workpiece, fluid, granule,* and *lap.* In this paper we will address only processes which involve a solid workpiece moved in some predetermined manner with respect to a counterface (the lap) in the presence of a two phase slurry comprised of the fluid and solid phase granules. Thus we specifically include mechanisms involved in magneto-rheological finishing and elastic emission machining (for example) and specifically exclude ion finishing, plasma assisted chemical etching, etc. The latter "fine finishing" processes which do not involve the four components may, nevertheless, provide some interesting insights which will be briefly noted elsewhere. The scope of this paper is defined not by technical considerations (e.g., finish, function, etc.) but by the mechanisms of material removal involved.

3.1 Workpiece

The object of polishing is to modify the workpiece. Workpieces vary in bulk chemical composition and may have property variations as functions of both lateral dimension and depth.

Chemical compositions of materials to be polished fall into specific categories, based on the types of bonding involved. Metals, as a group, have properties that are distinct from covalent network materials (like silicon nitride or boron carbide) and these differ from ionic network materials (like quartz or silica) and from simple ionic materials (like calcium fluoride). Materials to be polished may be pure or may be mixtures with characteristic component sizes. Lateral or depth dimension variations may be discrete or continuous. The importance of the chemical composition is that characteristically different materials are susceptible to different polishing regimes.

Lateral dimension variations may arise from differences in grain orientations (e.g., in metals), phase changes (e.g., in ceramics such as AlTiC for hard disk read heads) or different materials (e.g., circuit features encountered in chemomechanical planarization). Characteristic length scales for these variations range from nanometers (for nanocrystalline materials) through tens of micrometers (for typical metal grain sizes) to millimeters (for computer chip patterning).

Depth variations may be intrinsic (due to different bonding for surface and bulk species) or may arise during the manufacture of the workpiece (e.g., , CVD or PVD processes allow for density variations of material put onto a surface). They may arise from processing conditions (like plastic work of the near surface, or sub-surface cracking) or may be part of the polishing design process (as in the formation of surface films during CMP).

3.2 Fluid

The fluid phase of the slurry may be characterized by its chemical composition and by its physical properties.

Chemical compositions of fluids include water and non-aqueous fluids like hydrocarbons and alcohols. The pH of the fluid may be controlled by addition of acids or bases, or by the use of a buffer system. In CMP, the fluid also contains a primary chemically active ingredient (like hydrogen peroxide or other oxidizers for metal CMP) and may include secondary chemical ingredients (like BTA or other inhibitors to control chemical interactions), or physically active additives (like surfactants).

Physical properties of the fluids affect both fluid dynamics and material transport in polishing. These properties include viscosity, density and thermal conductivity, all of which are pressure and temperature dependent. These properties can also be varied by changes in the chemical composition of the fluid.

3.3 Solid Granules

There is some advantage to choosing the word *"granule"* deliberately to avoid implications of size or function in more commonly used terms such as "abrasive" or "grit". "Abrasives" may not affect material removal in ways that follow Archard's Abrasive Wear Law or may not be sized according to the various national "grit" ratings.

The function of solid granules in the slurry is to mechanically remove material from the surface of the workpiece. The granules themselves can be distinguished by a number of factors, including chemical composition, size, shape and concentration, while the effect of each of these factors may be important or insignificant.

Chemical compositions of granules vary to include materials like diamond, and CBN (which have network covalent bonds and are relatively inert), or silica, alumina, ceria, etc. (which are ionic network materials whose surface properties change with pH). For a given composition, the materials may be of different phases (in oxides, for example). They may be single crystals or may be polycrystalline (of one or several different phases) and they may be pure materials or mixtures of different abrasives. Chemical effects ("chemical tooth") may be present or absent in a given system, and may be permanent or become activated (by light or other means) *in situ*. Designer abrasives, with hard oxide cores and soft organic shells, or with soft organic cores and hard oxide shells, may also have special mechanical removal properties.

Size parameters involve both average size and size distribution. Granules used in polishing range in size over three orders of magnitude from colloidal silica or alumina

particles which are tens of nanometers in diameter to diamond and silicon carbide abrasives which are tens of microns in size. If weight percent concentrations are used, then particle size affects the number of (active) particles in the slurry. For small diameter particles, a given slurry weight percent contains more particles than for large diameter ones. Under some conditions, agglomeration of smaller particles becomes important, affecting the average size and the size distribution. In some cases, the granules fracture, changing the average particle size and shape during the polishing process.

Shapes of different granules may be significant. Some granules are characteristically spherical, but elliptical, blocky and sharp fractured shapes are also used. In the case of fracturing of larger granules, the smaller ones will tend to present sharper facets under polishing conditions.

Concentration effects may be negligible (in some polishing operations) or significant (in CMP) as described below. Concentrations may be given as weight percent or particles per volume. Weight percentages are experimentally unambiguous, but hide the basic question of how many particles are active.

3.4 Lap

In the context of material removal mechanisms, the lap imposes relative motion between the granules and the work and affects slurry and swarf transport through the contact. The simplest lap is a stiff plate – for example the cast iron plates commonly used with alumina or silicon carbide to generate the base radii on optical elements. A variety of other metals are also used. Metal laps may be faced with pitch or a variety of different “cloths” (Pellon, felt) or pads (e.g., polyurethane foams). Laps are also made using a thin film to face a substrate with a specific texture and by stacking pads with different properties. Pads may contain a variety of groove patterns. In addition to their role in imposing motion, laps can be important in planarizing or otherwise shaping the workpiece. Lap characteristics which affect the removal process depend on the specific lap construction.

Bulk modulus (or in the case of pitch, viscosity) affects the penetration of loaded granules into the lap. Surface pads may have different horizontal and vertical elastic and plastic behaviors which could also affect polishing rates and surface finish. In the case of CMP, the pad is implicated in undesirable with-in wafer non-uniformity (WIWNU), dishing and erosion. There is always a trade-off in CMP between higher compliance, which gives more uniform removal, and higher stiffness, which improves global planarization (flatness).

Porosity, together with imposed groove patterns or structures, determines slurry and swarf transport.

Wear rates change lap surface form and textures, and hence contact mechanics, fluid films, temperature distributions, etc.

In addition, temperature and strain rate dependence of lap material properties may be functionally important.

4 PAIRWISE INTERACTIONS

The six pairwise interactions between system components group into three which do not involve the workpiece (and therefore provide no possibility of material removal) and three which do involve the workpiece.

4.1 Workpiece-fluid

Workpiece-fluid interactions involve both chemical and physical effects. The chemical effects include dissolution, etching and passivation, each of which change the workpiece surface in some way, and each of which has separate applications. Chemical changes in surface properties are sometimes described as "softening" of the workpiece, since they can make it more susceptible to polishing. Physical and mechanical effects involve transport of material and heat away from the workpiece surface during polishing; these processes are typically also affected by the nature of the lap and will be considered as three-way interactions below. All of these processes depend on the nature of the workpiece and the fluid.

Dissolution occurs when the chemical properties of the fluid and the workpiece surface match in specific ways. This match may hold for the bulk workpiece or only for its surface layer. In etching, a chemical reaction removes electrons from metals to produce soluble metal ions, which can then dissolve into the fluid.

Dissolution and etching are two-component methods of material removal. They are equivalent to polishing without either abrasive or lap, and are standard techniques in many applications which are not discussed here.

Passivation in particular, or coating in general, occurs when a chemical reaction between the workpiece and chemicals in the fluid results in a surface film that has different properties than the bulk workpiece. For metals, this film can reduce electrical or thermal conductivity, and is a desired or detested outcome depending on the particular application. For conventional lapping and polishing, the effects of this surface film are usually negligible. However, chemical mechanical polishing uses alternating cycles in which a surface film is chemically created and then mechanically removed. Thus chemical effects can be important. If the surface film is soluble, as is the case for most copper compounds, then this consideration must be included in describing any material removal process.

Other workpiece-fluid chemical effects include changes in the surface charge (or zeta potential) of the workpiece, making it more or less susceptible to material removal - particularly by an adhesion mechanism. The surface charge can be controlled by adjusting the pH of the fluid, and is important in glass polishing. Since water is commonly used as a polishing fluid, the interactions between water and the workpiece surface have to be considered more closely. For glass workpieces, the significance of these interactions has bred an independent branch of science, which examines the corrosion of the glasses experimentally and theoretically.

Most silicates are highly resistant to corrosion, but glass is not inert; some glasses are damaged relatively quickly by acids or caustic solutions. The corrosion of glass in aqueous solutions is a complex process but, basically, two mechanisms can occur. Firstly, the glass can be dissolved and secondly, elution (i.e., separation based on differential solubility or mobility) may occur [6]. The rate of glass dissolution depends on the pH-value and on the salt content of the solution as well as on the properties of the glass.

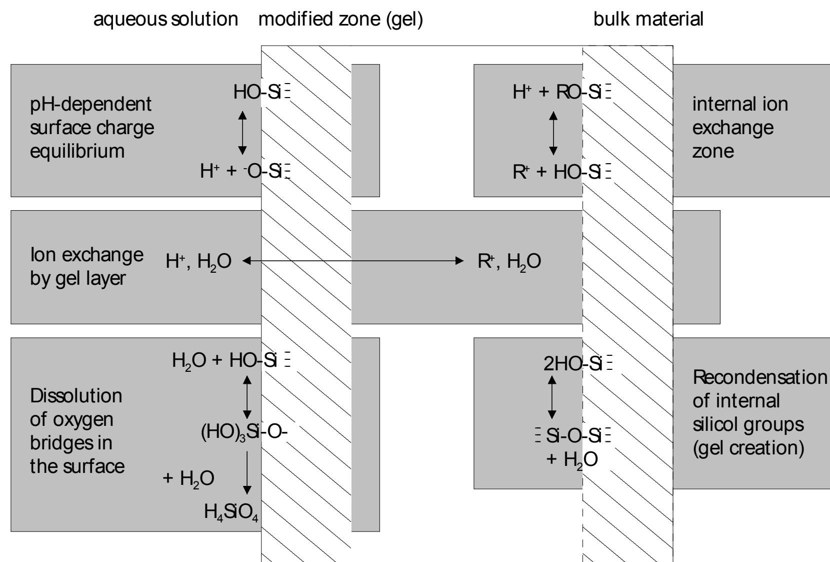


Figure 2: Reaction mechanisms in the glass sub-surface region

In contrast, elution occurs in accordance with the laws of diffusion and the resultant elution depths obey a Root-Time-Law. The progressive elution of the glass can be described by determining an effective diffusion co-efficient. The basic reaction mechanisms in the subsurface of glass materials in aqueous solutions, are shown Figure 2 [7].

4.2 **Workpiece-granule**

Most of the interactions between the workpiece and the granule occur when a load is applied by the lap, and will be considered in the section on workpiece - granule - lap. A variety of abrasive jet cutting and bead blasting processes rely on granule kinetic energy either shearing work material or initiating and propagating fracture. Such two (or three) component processes are generally outside the scope of this paper, although we will consider explicitly elastic emission machining (EEM) and magneto-rheological finishing (MRF) in Section 6.

The important workpiece-granule interactions in polishing were described by Brown [8] as “physical tooth” and “chemical tooth”. “Physical tooth” qualitatively describes the situation where a granule is loaded against a surface with topography such that material removal occurs. “Chemical tooth” is important in the molecular adhesion regime for material removal.

Mechanical aspects of the interaction of a granule and a workpiece surface have been widely studied. Significant insights are provided by a body of work in indentation and scratch testing, although considerable care needs to be exercised when applying such physical insights to polishing. In polishing, penetration depths tend to be much smaller than in most indentation and scratch testing, although this is not true for some of the recent nano-indentation studies. Workpiece surfaces exhibit property variation (subsurface damage) over a depth which will be a larger fraction of the penetration depth in polishing than in scratch testing. For polycrystalline work materials, the relationship between grain size of the material and penetration depth must also be considered.

Lawn and his co-workers’ classic papers (see for example [9,10]) on the initiation of fracture in glasses provide the intellectual foundation for a great deal of work in so-called ductile regime grinding. Combining this with insights from classical cutting mechanics, we can describe granule interactions with materials as a function of load and the mechanics of the contact. Simply stated, if the workpiece yield stress is not exceeded, the granule will simply slide across the surface imposing elastic deformation and removing no material. Larger loads form dislocations, plastically deform material (plowing, forming a “chip”, or an intermediate case described as “wedge” formation [11], or initiate fracture. Attack angle is critical in determining when plowing rather than chip formation occurs in ductile materials [12]. The extensive literature in these fields provide ample descriptions of large scale single grit interactions; the challenge is to define the contact conditions of granules used in polishing processes such that predictive kinetic models (rather than parametric correlations) can be developed.

The experimental studies of Lucca et al.[13,14] on the force system which results when machining at small depths of cut have shown that the cutting process can be considered to transition from a cutting dominant to sliding/plowing dominant process as depth of cut is decreased. In particular, the effect of the tool edge geometry is seen to play an important role in this transition. Whereas at large depths of cut the cutting-to-thrust force ratio is seen to be greater than 1 (typically 4 or 5), as depth of cut decreases there is a rotation of the resultant force vector downward towards the workpiece surface such that this ratio reverses and the thrust force becomes the dominant component. The interaction of a granule with a workpiece surface results in a similar force system dominated by the thrust component as a result of the high negative rake and small effective depth of cut which exists in the workpiece-granule contact region.

Fu et al.[15] developed a model of chemical mechanical polishing by considering that the slurry reacts with the workpiece to produce a hydroxylated interface layer which is removed by the abrasive action of the granules, and by treating the interface layer as a perfectly plastic material. The granules were assumed to be either spherical or sharp particles that remove the hydroxylated layer with no side flow or pile-up of the material during the removal process. For each type of granule two cases were considered: when the wafer and pad are not in contact with each other and when the wafer and pad are in contact with each other.

The computed rate of material removal was compared to experimental results for LPCVD TEOS, tungsten, BK7 glass, copper, and nickel-phosphorous. Good agreement was found for the presented cases. The same group [16] extended this model to include plowing of the workpiece by the granules. They proposed that material is not removed by a single scratch created by plowing but is removed at the intersection of scratches produced by plowing. Also included in this model is an intermediate regime where the pad and wafer are in partial contact in addition to the two extremes of no pad and wafer contact and full pad and wafer contact. Good agreement between the computed and experimentally measured rates of material removal for copper and silicon dioxide was found.

Chemical tooth [17] is observed when the surfaces of the workpiece and the granule are attracted to each other. As they approach, they can interact chemically forming a "micro-reaction zone" [18]. As they separate, some of the workpiece material may stick to the granule and be removed from the surface. Chemical tooth is observed in glass polishing, when some abrasives are more effective at material removal than others. Part of the chemical tooth interaction involves surface charges (e.g., Golini and Jacobs [19]). Each material has an isoelectric point at which its zeta potential (surface charge) is zero. As described in the workpiece - fluid - granule section, when the pH of the polishing fluid is changed, surface charges can change from positive to negative, and polishing granules can be attracted to or repelled by the workpiece surface, resulting in higher or lower polishing rates.

Chemical tooth provides a qualitative basis for understanding material removal in cases where the applied load may be insufficient to cause indentation. In these cases, an adhesion mechanism may operate in which material on the surface of the workpiece is attracted to the surface of the abrasive granule. If the surface layer is not tightly bonded to the bulk, or if the adhesive forces between the surface and the abrasive granule are strong, then material may stick upon contact and be plucked free from the workpiece surface. Alternately, if the granule rolls across the workpiece surface, then surface material may stick to it. The granule will grow and surface material will be removed. The concept of chemical tooth has been used in glass and chemical mechanical polishing processes, as discussed in sections below, through the observation that different abrasives have different removal ability.

Kaller [20] investigated the influence of different polishing media on removal rates. He described material removal in glass polishing as a result of the solid body reactions between the glass surface and the granules. Hence the valence of the metal ion determines removal rate since it determines the level of bonding energy in the ionic crystal lattice. Higher metal oxides with lattice defects, such as oxides of the tetravalent cerium, have better chemical tooth than trivalent metal oxides with similar lattice defects, such as iron oxides. The fracture surfaces of bivalent metal-oxides such as magnesium oxide (MgO), zinc oxide (ZnO) or lead oxide (PbO) have such low levels of bonding energy that they cannot be used alone as glass polishing media, although they are suitable for use only as additives.

4.3 **Workpiece-lap**

In many polishing methods, the workpiece and lap are separated from contact by the fluid and granules, so their interactions are unimportant. However, this may not the case under conditions in which the Stribeck Curve indicates that the load is carried by the lap or pad. In CMP, the pad on the lap face flattens against the workpiece and propels imbedded granules across the surface. In this case, the interaction is purely mechanical. For a soft lap pad and a hard workpiece, the contact area is proportional to the applied pressure, and the effective pressure at the surface of the pad - workpiece interface is constant.

For soft laps used in CMP, there is a substantial body of practical experience that "pad conditioning" strongly affects removal rate. Typical conditioning processes involves rubbing a diamond impregnated or other hard surface against the pad. The conditioned pad surface is rougher, presumably reducing contact area and/or increasing fluid transport efficiency on a local scale [21]. It has also been suggested that the pores in some pads directly remove reaction products [22].

Expressed differently, pad conditioning alleviates the detrimental effects of pad wear and glazing [23]. Glazing occurs either due to cold flow of the polymer pad or the deposition of reaction products on the pad, blocking pores, reducing slurry and swarf transport efficiency and reducing removal rates.

4.4 **Fluid-granule**

The effect of the fluid on granules is predominantly chemical, changing the surface of the granule in some way. One such interaction involves the surface charge on the granule. As discussed in the fluid-workpiece section, the granule surface can have a net charge, measured by the zeta potential, that is strongly affected by the fluid. As the fluid pH is changed, the surface charge will also change, and the granule will be attracted to, or repelled by, the workpiece surface. Each material has a characteristic isoelectric point, which is the fluid pH at which the surface charge is zero. This pH is also called the point of zero charge.

Under certain circumstances, granules in a fluid will tend to agglomerate, or form large aggregates of component granules. These large radius aggregates are undesirable since they can scratch surfaces during polishing. Surfactant (surface active agent) molecules are often added to the fluid to minimize granule aggregation. Surfactant molecules have ionic heads and non-polar hydrocarbon tails. The ionic heads are attracted to the charged surfaces of granules and the hydrocarbon tails minimize the attractions between granules that would result in the formation of aggregates. Thus the fluid granule interactions affect polishing outcomes.

4.5 **Fluid-lap**

For non-porous laps, the fluid rests on the lap surface and provides hydrodynamic lubrication for the polishing process. For porous lap pads, the fluid permeates the pad and can significantly change the hydrodynamics of the system by changing the effective lap-pad properties. In addition, long term fluid-lap contact may slowly change the pad bulk material properties [24]. Aqueous and non-aqueous fluids may be chosen to complement the pad composition such that the pad surface may attract or repel the fluid, leading to changes in surface hydrodynamics.

Many laps have some sort of facing (pads or pitch) that is a carbon based polymer - natural or artificial. This material is insoluble and generally impervious to water, so that aqueous polishing fluids do not interact chemically with them. However, there are circumstances under which these materials can absorb fluids and change their

properties. This process is variously described as wetting or swelling, and can occur on the macroscopic scale as pores fill with liquid or on the microscopic scale when the fluid - pad interactions become important. Microscopic interactions would be more important when the chemical structures of the fluid and pad are similar. Thus hydrocarbons like kerosene, for example, could solvate natural materials like felt in ways very different than water. Solvated (swollen) pads may hold abrasive granules differently than unswollen ones. The effect might be investigated as a function of polarity differences between the fluid and the pad material (as with fluid-work interactions).

4.6 Granule-lap

In conventional polishing, the applied load is born by granules embedded in the lap system. As more granules embed into the lap, there are more sites for material removal. However, the load per granule decreases as the granule concentration is increased. These effects cancel each other leading to the observation that in some circumstances the conventional abrasive polishing rate is independent of (granule) concentration. However, since the lap area is finite, abrasive concentration extremes give different behavior. At low abrasive concentration, the individual abrasive particles may be pushed too deeply into the lap or the workpiece and become ineffective. And at high abrasive concentrations the lap can become saturated with granules and form a sliding surface with the excess material.

By contrast to conventional polishing, in chemical mechanical polishing the applied load is born by the pad. Each abrasive granule removes material independently. At high concentrations the removal rate tends to an asymptotic limit as the pad becomes saturated. At low concentrations, each abrasive has an equal chance of embedding into the lap and the polishing rate increases with concentration. Variable surface concentrations of this sort can be described as a Langmuir system which balances the rates at which granules stick onto or come off of the pad surface.

Grinding wheels are combinations of granules and laps. Fixed abrasive pads have been commercially developed in which the granules are arranged in particular patterns. They offer some specific advantages for polishing. Both of these systems can be regarded as extreme cases of strong interactions between lap and granules.

5 TRIPLETS

A variety of three-way combinations of component interactions are possible, based on the two-component interactions discussed in Section 4.

5.1 Workpiece-fluid-granule

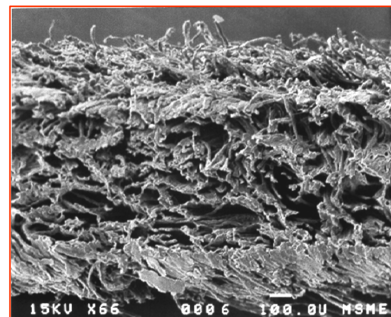
Many granules are oxide materials like alumina, silica, and ceria whose zeta potential and surface charge depend on the pH of the fluid. Other granules like diamond or cubic boron nitride are hydrophobic and not affected by the fluid. Some workpieces are unaffected by the fluid, but others are oxides or form an oxide surface film with a fluid dependent charge. For abrasive granules and workpiece surfaces affected by the fluid, if the fluid pH is below (above) that of the isoelectric points for both the granules and the workpiece surface, then both materials will be positively (negatively) charged and will repel each other. If the fluid pH is between the two isoelectric points, then the surfaces will be oppositely charged and be attracted to each other. This may be one source of chemical tooth [25] since it lowers the energy barrier for abrasion. In one study of glass polishing, a series of non-aqueous alcohols were used as fluids [26]. The polishing rate changed with the fluid polarity, indicating that the interaction of the fluid with the workpiece and granule can be important in the polishing process. The importance depends on the materials themselves. If the abrasive and workpiece are inert with respect to the fluid, then fluid's role is purely mechanical, involving lubrication, transport of heat, and removal of polished material.

An aspect of polishing that seems to have been given little attention to date is the effect of molecular scale fluid films on the workpiece-granule contact. Bhushan et al.'s review article [27] indicates a range of behaviors that may affect removal mechanisms.

5.2 Workpiece-granule-lap

As indicated in Section 3, the lap typically comprises a stiff plate which may then be faced with: solid films (e.g., polymer films or the zinc pads often used in ophthalmic polishing; pitch; or a felt, foam or fibrous pad.

The transitions in material removal mechanisms associated with the workpiece-granule-lap interactions can be understood in part in the context of the load bearing characteristics of the system. One extreme case (Figure 1) is when the entire load is supported by the granules interposed between the lap and the work (e.g., in diamond polishing of electroless nickel optics or silicon [28]). At the other extreme (e.g., CMP, Figure 3), the entire load may be carried on the lap (pad) surface. Frequently, polishing process operate at some intermediate state between these extremes.



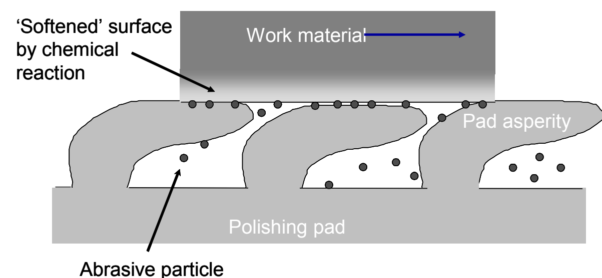


Figure 3: Cross-section through a typical pad used in CMP [29] and an idealization of the contact between pad, work and granule

In a traditional (no pad) polishing process where the abrasive is harder than either the lap or part (e.g., diamond polishing of electroless nickel optics or silicon) it is normal to choose a lap surface which is softer than the workpiece material. The granule embeds into the lap, and material removal can be considered from the perspective of classical cutting mechanics. If the spacing of granules is sufficient that removal rates are controlled by the cross-

sectional area of the ploughed material, it can be shown theoretically and experimentally [30] that the removal rate is independent of the granule size and concentration. Plotting removal rate as a function of particle size (for constant conditions including wt % abrasive and normalized abrasive size distribution) reveals two transitions in mechanism. When particle size is small, there is significant interaction between lap and work, effectively reducing the load carried by the granules. In this regime, removal rate is proportional to granule size and increases with concentration [31]. When the particle size becomes large or a substantial fraction of load is not supported by the particles, granules may roll, reducing removal rates. Alternatively, if the workpiece is brittle, the individual loads may become large enough that fracture is initiated and removal rates tend to increase. Mindek et al. [32] observed diamond polishing of calcium fluoride, noting the initiation of fracture long before rolling commenced. Hesiel and Avroutine discuss the effect of grain form on this transition [33].

At very large particle concentrations, it appears (theoretically [34-36]) that the removal rate per particle will be proportional to the penetration depth. In this case, removal rates will be functions of particle size and concentration. At very low concentrations, load per particle will be large enough to cause the particles to embed to the extent that they no longer carry the entire load.

In polishing with pitch laps, the viscosity of the pitch is an important practical parameter. The pitch flows, when appropriately conditioned, to match the part (or conditioning tool) and provide uniform load over the part surface. When the workpiece is first placed on the lap, the load is carried dominantly by the larger particles, which sink rapidly into the pitch (with a velocity following Stokes Law) until all particles are equally loaded [37,38]. Removal rate is independent of size, within some limits.

For soft laps (or for the soft polyurethane foam pads used on laps in chemical mechanical polishing), sub-micron diameter abrasives can be pushed deep into the lap. Lap asperities make direct contact with the workpiece and carry most of the applied load. The number of active abrasive granules available to remove material depends on the contact area between the pad asperities and the workpiece. It has been shown theoretically [39] and experimentally [40] that the contact area between the lap and workpiece is directly proportional to the applied pressure and inversely proportional to the Young's modulus of the pad. The number of active granules is the product of the contact area and the number of granules per area of lap surface [41].

Luo and Dornfeld [42] model lap-granule-workpiece interactions as a solid contact with active granules embedded in the asperities of the pad performing two-body abrasion. In addition to the variables discussed above, they also show the effect of pad roughness and abrasive size disturibution [43]. Increasing the width of the distribution (Figure 4) brings two countervailing effects; a reduction in the number of granules reduces material removal rate for small mean particle sizes (a so called "number dominant" regime), while the increasing proportion of large granules each remove larger amounts of material, producing a size dominant regime for larger mean granule sizes[‡].

[‡] The same data is fit to a different model in Section 6.4

Samuels et al. [44,45] studied the polishing of metals with napped fiber laps and diamond abrasives. The abrasives either bond to the fibers chemically ("globules" or "films" of carrier paste) or embed in the fibers. Removal rate has a peak at a granule size around 3 μm (Figure 5) which appears to be optimum in terms of the number of active particles and for material removal dominantly by cutting. At smaller abrasive sizes, their micrographs of swarf suggest a transition from cutting (ribbon like swarf) to a mechanism producing platelets.

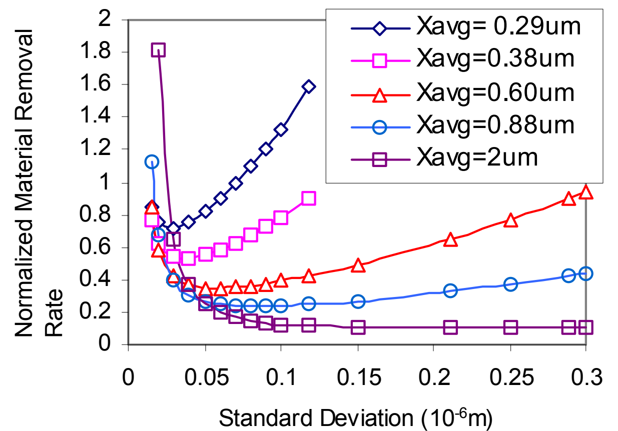


Figure 4: Material removal as a function of standard deviation of abrasive size distribution. Xavg is the mean granule size.

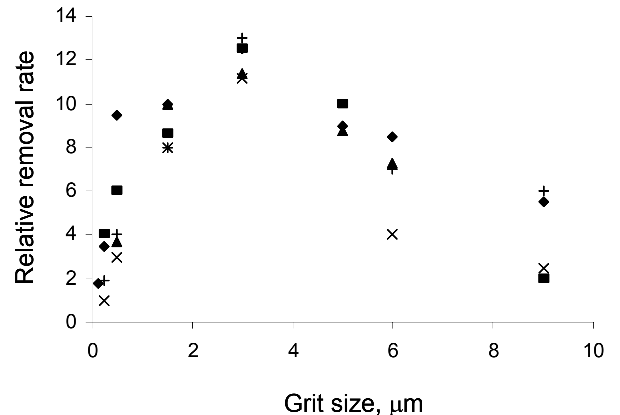


Figure 5: Samuels and Wallace data [44] for brass removal rate as a function of granule size in micrometers (5 different types of diamond) replotted

The transitions between mechanisms reported by Samuels are consistent with abrasive wear mode diagrams [46] which suggest that the transition from plowing to cutting is largely independent of shear strength. The dominant factor is degree of penetration (D_p), the ratio between penetration depth and contact radius. For polished metals, groove (sleek) widths and depths are orders of magnitude different, suggesting $D_p \approx 0$ and hence that plowing dominates.

5.3 Workpiece-lap-fluid

A description of the workpiece-lap-fluid system is needed to understand how the effective force applied at the granule-workpiece interface is affected by the specific polishing conditions. In addition, interface temperature is strongly influenced by friction and contact conditions, affecting reaction rates and material properties. Temperature sensitivity of removal rates in conventional

glass polishing has been widely reported, for example, and Sugimoto et al. [47] show a linear six-fold increase in removal rate in silicon oxide polishing over a 10 C range around room temperature.

5.3.1 *The fluid film*

The recent literature regarding the interactions of the workpiece-lap-fluid triplet in chemical mechanical polishing consists of studies carried out over a broad range of material combinations under a variety of process conditions. As a result, models attempting to capture the resulting physical behavior consist of an equally broad range of assumptions and approaches. The range includes consideration of complete wafer-pad separation and the hydrodynamic modeling of the workpiece-lap-fluid contact to the case where there is pad and wafer contact in the presence of a fluid.

Although the possible existence of both the lubrication regime and the contact regime in chemical mechanical planarization was acknowledged by Thakurta et al. [48] in 2000, in a series of later papers [49,50,51] the group presented models for chemical mechanical planarization principally focused on the hydrodynamic lubrication regime. The work assumed that the applied pressure was low enough and the relative velocity high enough to ensure that there was hydrodynamic fluid film behavior. Their models allowed for deformation of the pad and fluid flow through the surface of the pad including slurry delivery through grooves in the pad. Both two-dimensional and three-dimensional models were presented. Several studies also included a mass transport model to take into account chemical reaction at the wafer surface for the polishing of copper [49,51]. Other work which considered both the fluid and chemical aspects of chemical mechanical polishing includes that by Subramanian et al. [52] who modeled CMP of copper using a repeated cell model. The two-dimensional cell was composed of a pore in the pad, the pad surface, the slurry, and the workpiece. The two-dimensional Navier-Stokes equations and mass transport equations for the reactants were solved using finite element techniques. Other wafer scale purely hydrodynamic models of CMP include the work of Park et al. [53], Cho et al. [54], and Chen et al [55].

An experimental study of the mechanical interaction between the wafer and pad in the chemical mechanical polishing of SiO_2 by Levert et al. [56] investigated the vertical displacement of the wafer relative to the pad, the friction between wafer and pad and the wafer scale pressure distribution. Two conditions were examined: "hydrodynamic CMP", where the experiments were performed at low normal loads and hydrodynamic separation of wafer and pad was maintained (lubrication regime), and "commercial CMP" with conditions more consistent with industrial practice (contact regime). Measured rates of material removal under hydrodynamic conditions were found to be insignificant (less than 0.0004 μm/min, which is three orders of magnitude lower than what is observed under typical commercial practice). It was concluded that "hydrodynamic CMP" cannot account for the removal rates observed in industry and is only a minor contributor. For commercial CMP near zero vertical displacement and a friction coefficient of 0.4 was observed. It was found that conditioned pads result in a suction force between wafer and pad. Pad glazing was found to lead to hydrodynamic conditions. In further work by the same research group [57,58] a physical model was put forward to attempt to explain the sub-atmospheric pressures which had been experimentally observed. An interaction of the pad/wafer contact mechanics and the fluid hydrodynamics was identified as the cause. As shown in Figure 6, a circular wafer with movement relative to the pad experiences the maximum contact stress at the leading edge of the pad which results in the compression of the pad asperities and the expulsion of the fluid within the inter-asperity voids. As the contact stress decreases further back from the leading edge, the asperities elastically recover from their compression and there is an inflow of fluid into the inter-asperity voids. The trailing edge leads to an increased contact stress, a compression of asperities and an expulsion of the fluid from the inter-asperity voids. Further work by the same group [59] showed a relation between measured sub-atmospheric pressures and the within wafer nonuniformity (WIWNU). Whereas sub-atmospheric pressures were also measured by Bullen et al. [60] for non-rotating wafers, with wafer rotation this was not found to be the case. With the use of a technique for the measurement of the dynamic fluid film pressure during CMP, they found that the pressure distribution is significantly different between static and dynamic wafers. Stationary results showed an asymmetrical pressure distribution and some sub-atmospheric pressures. Dynamic experiments showed pressure increasing monotonically from edge to center and no sub-atmospheric pressures.

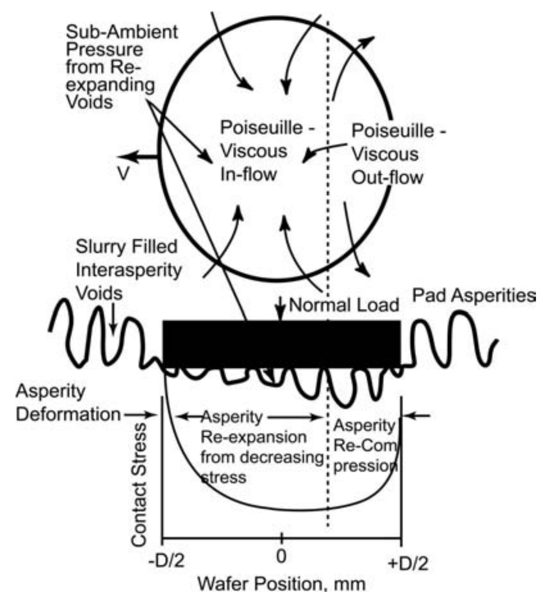


Figure 6: Top and side view of a circular wafer and its interaction with pad asperities under load. Contact stress between wafer and pad is shown in the lower portion of the figure. (from Levert et al.[56])

5.3.2 *Fluid Temperature Distributions*

There are two possible sources of heat during polishing/lapping, a) mechanical friction between the lap, the work piece and the abrasive granules, and b), the exothermic chemical reaction between the workpiece surface and the fluid. An energy analysis of CMP shows that the chemical component is very small compared to the mechanical source of heat [61]. For processes with both mechanical and chemical material removal, isolating how much heat is added to the system by the individual chemical or mechanical aspects is far from trivial. When considering purely mechanical systems, heat generated comes from two sources: pad-workpiece friction and material removal (shearing/ plowing) by the granules.

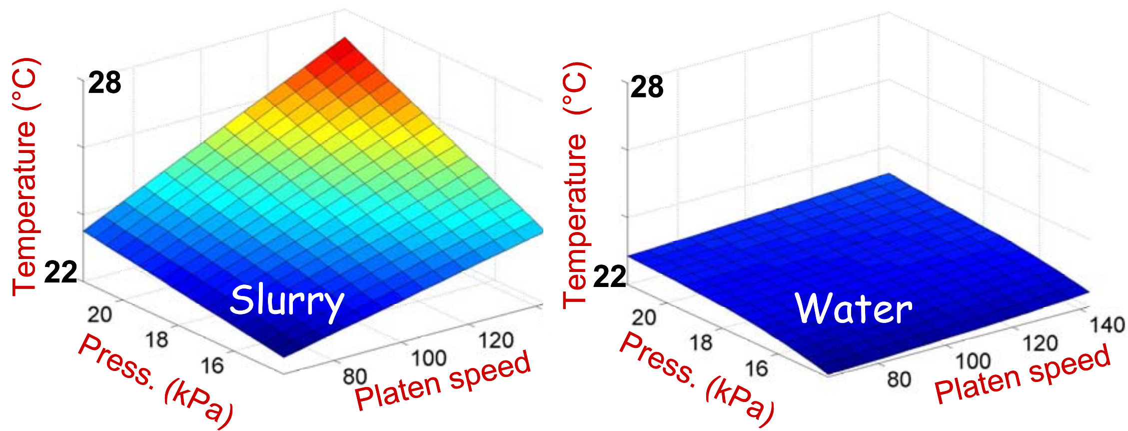


Figure 7: Difference in the average wafer temperature under a range of polishing conditions using water (top) or a CMP slurry (lower) as the polishing fluid [66].

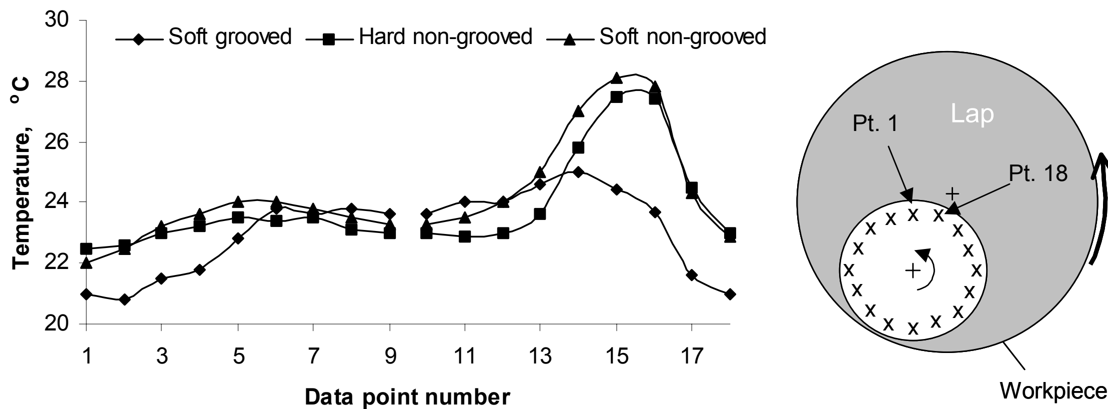


Figure 8: Thermal gradients around a wafer during CMP using 3 different types of polishing pads [66].

Several factors will affect the overall temperature of the system, including pressure, velocity, geometry and fluid supply. Higher pressures can be correlated to higher system temperatures [62,63,64,65]. In purely mechanical processes the increase in the temperature due to increases in the pressure can be simply explained by increased friction. In processes such as CMP, this increased temperature will also increase chemical reaction rates. There is also a suggestion that increasing pressure may increase chemical removal rates, either through increasing effective contact area or through affecting reaction pathways or equilibria.

Increasing velocity also increases average temperature of the systems, but not as dramatically as the pressure. The increased frictional heating may be partially offset by increased load support from the fluid.

Geometry, both local and global, affects the ability of the lap to transport fluid under the workpiece during polishing/lapping and hence will influence the frictional heat generated (Figure 7). Higher volumes of fluid transported by the lap improve the lubrication of the system and reduces the effects of friction. Higher fluid volumes will also remove heat from the workpiece and thus minimize workpiece temperature. In pitch polishing, for example, grooves provide significant fluid transport. In CMP, pads may be grooved and have local texture or structure which enhances fluid transport. Fibrous pads are able to absorb greater volumes of fluid than porous pads. As a result process temperatures are lower when the fibrous pads are used. Grooves lower system temperatures and provide more uniform temperature distributions.

Large temperature variations across the workpiece typically result from uneven pressure distribution or fluid distribution (Figure 8). In addition to lap material and surface geometry effects discussed above, these can be attributed to velocity or fluid supply effects. Lap rotational velocity can affect the radial distribution of fluid across its surface. Higher speeds induce greater radial movement of fluid across the lap surface. Grooves on the lap surface can either improve or hinder radial fluid movement depending on the grooving sizes and patterns used [67,68] Higher workpiece rotational speed induces mixing/movement of the fluid between the lap and the workpiece with higher speeds inducing greater mixing. Fluid supply should be optimized to avoid areas of the workpiece being ‘starved’ of fluid, giving higher frictional forces and temperatures.

5.3.3 Abrasive-less polishing

Three component “abrasive-less” polishing systems have been developed for CMP in which slurry chemicals react with the surface of the workpiece to form a soft film which can be wiped free from the surface and removed by the

polishing pad alone, without the need for abrasive granules. The mechanism for this is similar to chemical etching. In both cases, a surface film is formed which is weakly bound to the workpiece surface. In the case of etching, this film dissolves into the fluid without mechanical encouragement. In the case of abrasive-less polishing, a small amount of additional mechanical energy is required to pull it free from the workpiece. In abrasive polishing, the additional energy required for material removal is supplied at the abrasive - workpiece contact.

5.4 Lap-fluid-granule

In conventional polishing, the abrasive granules cover a small fraction of the lap surface. The lubricant facilitates an even spread of the granules. As the concentration of abrasive granules in the fluid increases, it is possible that the lap surface would become filled. This is the condition in chemical mechanical polishing (see Section 6.4), where slurry concentrations of the small abrasive granules is relatively high. In this case, the system has been modeled [90] using a steady state balance between the rate at which abrasive granules from the fluid attach to the lap surface and the rate at which granules leaving the lap surface to return to the fluid. The finite lap surface area leads to the result that the number of abrasives per surface area depends on abrasive concentration in the fluid. At low abrasive concentrations, this surface density increases with abrasive concentration because there is space on the lap for additional abrasives to stick. At high abrasive concentrations the lap becomes saturated and the surface density is constant because there is no more space for additional abrasives [69,70].

Quantitatively, the surface density of granules on the lap can be written as proportional to n_{oP} [A]/([A] + K_{Pad}) where n_{oP} is the number of sites per pad area, $K_{Pad} = k_{off} / k_{on}$ is a pad equilibrium constant ratio of off and on rate constants, and [A] is the concentration of granules in the fluid. Both n_{oP} and K_{Pad} are the properties of the particular pad or lap used. Since the workpiece contact area for soft pads is proportional to pressure (section 5.2), the number of active granules is also proportional to pressure.

This same approach can be applied in other regimes. As indicated above, for pitch polishing or polishing with "hard" continuous laps (eg by Brown [71] and Evans et al. [72]), saturation implies granules in a close packed array. For napped or felt polishing pads, however, the number of lap sites is clearly related to the number of individual fibers. In this case, the probability of a site becoming active is related to "tooth" (physical or chemical) between lap and granule (eg Samuels observation on embedded abrasives).

"Tooth" between lap and granule has also been observed by Evans et al. [73] using the rapidly renewable lap to diamond polish electroless nickel. Commercially available matte mylar (colloidal silica coated) gave removal rates an order of magnitude larger than bare mylar. If the mylar was roughened using an electroplated diamond pad conditioning tool to provide "mechanical tooth", removal rates were identical to those with the matte mylar.

Section 5.1 discussed the concept of "chemical tooth" in the context of the fluid-granule-workpiece interactions. Except in the case of erosion, a granule only removes material from the work when there is relative motion, imposed by the granule being (temporarily) locked to the lap. Hence all the concepts of chemical and mechanical tooth should also be considered in the context of the lap.

6 SYSTEM EXAMPLES

In this section of the paper, we discuss a series of systems which exemplify the interactions discussed in the previous sections. Section 6.1 contains brief comments on diamond lapping adding to the coverage of this topic in earlier sections. In Section 6.2 we discuss Elastic Emission Machining (EEM), a process in which it is claimed that granules remove material from the work surface via an erosion mechanism. Magneto-rheological finishing (MRF) described in Section 6.3 has some conceptual similarities, but forms the "lap" unconventionally. In Section 6.4 we discuss the tungsten CMP using the formalism of chemical kinetics to capture a number of mechanical and chemical aspects of the process. Finally, we consider glass polishing in Section 6.5.

6.1 Diamond lapping of ductile materials

The essential features of the diamond lapping of ductile materials have been discussed in Section 5 and the relevant references. Provided the granules embed in the lap, simple mechanical models based on the lap-granule-workpiece triplet adequately describe trends in material removal rate (see also Section 8).

Observations of electroless nickel and silicon surfaces lapped with diamond slurries on polymer coated laps show that individual granules embed in the lap for long periods. Under many conditions, individual "sleeks" (or ductile troughs) can be tracked across large parts with no apparent change depth or width. There is some suggestion that the granules move on the lap when not loaded by the part.

Similar "tooth" is observed when diamonds are used with soft or napped felts. In post polishing diamond turned optics, Parks and Evans [74] showed that individual diamonds had sequentially machined many peaks, suggesting "tooth" of some sort even when the granule is not loaded.

6.2 Elastic Emission Machining

Elastic Emission Machining (EEM) was described by its originators [75] as a new "atomic-size machining method". EEM uses a soft (hence easily deformable under pressure) spherical polyurethane ball as the polishing tool ("the lap"), with a rotating axis controlled to always stay at 45 degrees from the tangent line of the workpiece. The polishing load is applied from the normal direction and designed to stay constant. EEM uses sub-micron size abrasive powder particles ("the granules") mixed in water, and polishes a workpiece by forcing the abrasive particles underneath the rotating polyurethane sphere in a thin gap (approx. 1 μm, i.e. larger than the abrasive particle size) between the sphere and the workpiece [76]. The abrasive particles are accelerated by the flow of fluid in the gap, but gradually leave the fluid flow lines to intercept the workpiece surface as illustrated in Figure 9.

In perhaps one of the first mentions of a material removal mechanism driven by shearing, the inventors noted that "the material removal proceeded by the powder particles in the fluid contacting and moving on the workpiece but not by the mechanical scratching of the workpiece by the direct force load exerted by the polyurethane sphere through the powder particle, and the workpiece surface did not suffer any damage". The amount of material removed at a given point could be controlled by the dwell time at that particular point (as with other sub-aperture finishing processes), allowing complex surfaces shapes to be manufactured.

Later work [77,78,79] confirmed EEM's ability to "form the perfect surface both geometrically and crystallographically" by observing polished surfaces by various methods such as photo-luminescence, scanning tunneling microscope and surface voltage measurements. They also confirmed the presence of a chemical effect by noting a relationship between the chemical properties of the abrasive particles chosen in the EEM process and the workpiece being polished. They went further by drawing a comparison between EEM process and chemical etching, but through careful analysis of the surface, showed that EEM polished surface did not exhibit nanometer size pits that could be typically be found on etched surfaces. They concluded that the chemical effect in EEM is the chemical activity of the solid surface of the abrasive particle (instead of the etchant in chemical etching processes)[79-82].

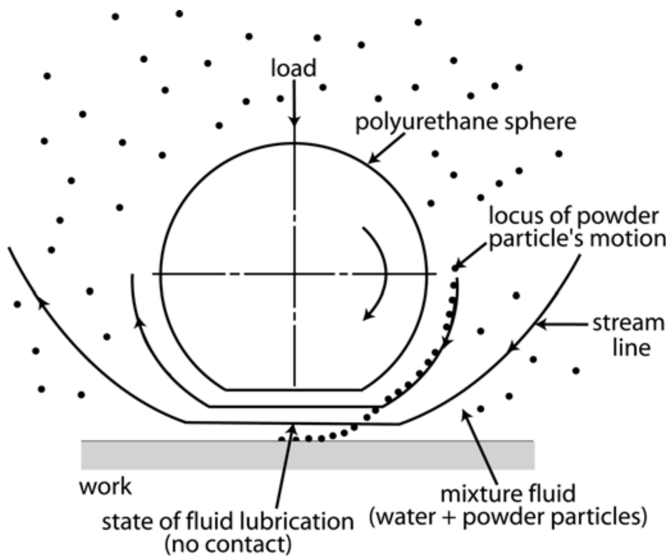


Figure 9: EEM schematic.

A similar process was described by Sakaya et al.. using a copper toroid and 70-95 nm diameter colloidal silica. They noted a threshold gap (~ 5 μm for their conditions) above which no removal took place [83].

6.3 Magneto-rheological finishing

Invented in the mid-80's by Kordonski [84], Magneto-Rheological Finishing (MRF) uses the property of MR fluids to change viscosity in the presence of a magnetic field. This MR fluid (consisting of deionized water, iron particles, abrasives and stabilizing agents) is constantly kept circulating between the pumps, alternating between its solid phase where the electro-magnet is present (i.e., at the top of the wheel in Figure 10) and liquid everywhere else [85]. The magneto-rheological polishing fluid is sent on the rim of a rotating wheel, which transports the fluid to the polishing zone. The workpiece to be polished is held in the computer-numerically controlled machine, and immersed into the ribbon of fluid. Similarly to the EEM process and other computer controlled polishing methods, the amount of material to be removed at a given location is driven by the dwell time [86] .

The wheel rim and the surface to be polished form a converging gap that is exposed to the magnetic field. The moving wall, which is the rim surface, generates a flow of magnetically stiffened MR polishing fluid [87] through the converging gap. Such flow results in high shear stress in the contact zone and material removal over a portion of the work piece surface. This area is designated as a polishing "spot".

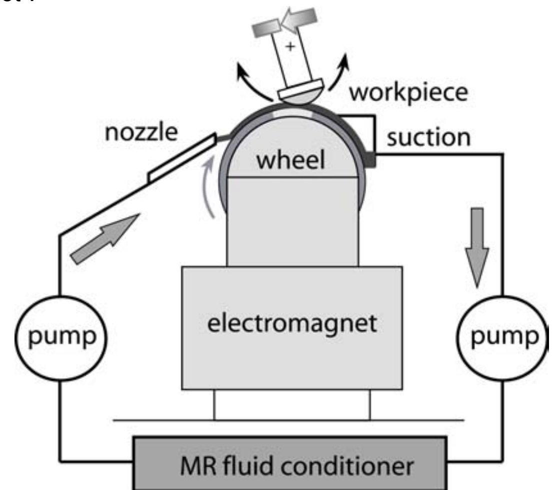
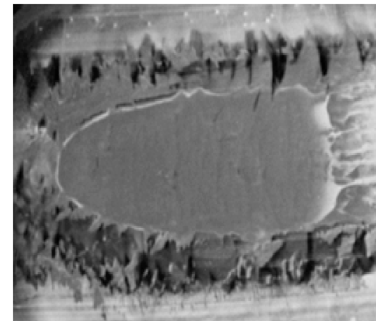
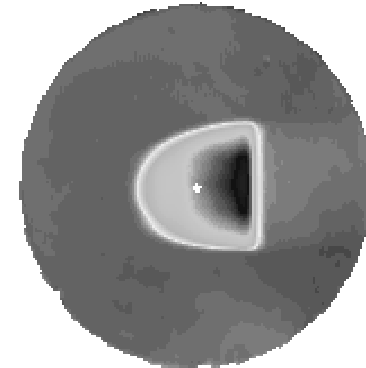


Figure 10: MRF machine schematic





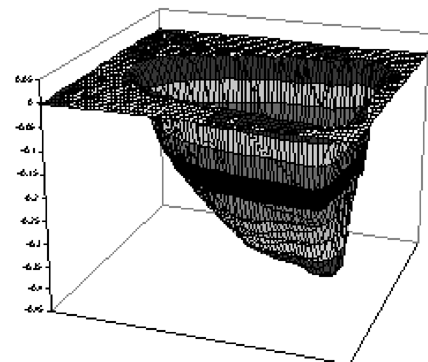


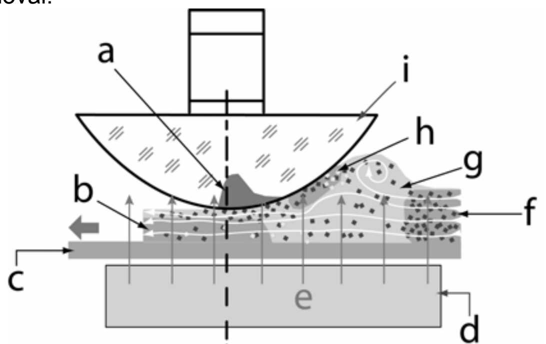
Figure 11: High speed photograph (top) and interferometric data from the polishing spot in MRF

An actual MRF "spot" is shown in Figure 11 (consisting of a through the workpiece photograph and interferometric data) with the fluid flowing from left to right. High concentrations of light colored polishing abrasive particles

are seen to decorate the edges of the spot, extending in streaks off to the right. The nonmagnetic polishing abrasive particles are concentrated at the workpiece surface by the action of the magnetic field gradient on the magnetic particles. The magnetic particles form a compacted and field oriented structure underneath. This separation occurs in milliseconds after the MR fluid enters the region of high magnetic field. The MRF process is extremely efficient at delivering polishing abrasive particles to the workpiece surface. Removal rates within the polishing zone are some two orders of magnitude higher than those seen in traditional pitch or polyurethane pad polishing processes.

The polishing spot, with a typical removal function area of 1 cm^2, is used to preferentially polish based on dwell time. The maximum depth of the spot gives the peak removal rate for a given material, and its volume indicates the volumetric removal rate. The former is critically related to the MR fluid composition, whereas the latter is more a function of the penetration depth of the part into the MR fluid. Stability of removal comes primarily from the consistency and long-term stability of the MR fluid, while tolerances on geometry and the positioning of the part are somewhat relaxed. For example, the MR fluid viscosity must be controlled to within ± 1-2%, but the gap separating the part surface and the wheel can vary by a generous ± 25 μm or more.

The removal function is extremely stable because removal rate correlates with fluid viscosity, which is continuously monitored and controlled to within ±1%, leading to a deterministic process. The removal function (size and removal rate) can be adjusted by changing simple controllable parameters such as wheel speed, part position in the fluid, or magnetic-field strength. Relatively high, stable removal rates are achieved while creating a smooth, damage-free surface finish. Unlike conventional polishing where normal loads on the abrasive particles can result in scratching, MRF creates no normal load on the abrasive particles, relying instead on a shearing mode of material removal.



a. material removal zone & pressure distribution
b. unsheared MR fluid (core)
c. moving wall (wheel)
d. electromagnetic polepiece
e. magnetic field
f. abrasive particles
g. sheared MR fluid
h. unsheared MR fluid
i. workpiece

Figure 12: MRF material removal model

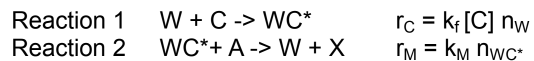
Kordonski et al. have proposed a model [85] for this shear mode of material removal in MRF (Figure 12). Here the MR fluid flows from right to left, being carried by the wheel into a zone of contact with the workpiece surface. The nonmagnetic polishing abrasive particles are designated by squares. Darkened areas represent un-sheared regions of magnetic fluid, and lighter areas denote MR fluid under shear. Bingham lubrication theory of these non-Newtonian fluids as applied to the hydrodynamic flow of the magnetically stiffened MR fluid through the converging gap formed between the workpiece and the wheel predicts the existence of sheared and un-sheared regions. One prediction from this model is a thin – but highly sheared – layer close to the part surface, where the high shear stresses enable the nonmagnetic abrasives to polish the part. This constitutes the removal zone for MRF. A more complete understanding of the MR fluid flow is being sought, but there is sufficient experimental evidence to support the model. The cross-section indicating removal that is superimposed on the lens in this figure agrees with predictions based on calculated shear stresses.

6.4 Tungsten CMP

Chemical Mechanical Polishing (CMP) is used to planarize ICs and MEMS devices. Specific processes have been developed for oxides and a variety of metals, including copper, aluminum and tungsten. CMP has been described [89,90,91] in terms of alternating chemical and mechanical cycles. In the first step, slurry chemicals react with the workpiece to form a surface film. In the second step, the film is mechanically removed.

Many characteristics of CMP differ significantly from those of conventional polishing. In particular, the polishing rate depends on the concentration of abrasive in the slurry and does not follow the Preston equation (R = k Pv) except in limiting cases. The polishing rate also depends on the concentration of chemical in the slurry and on the chemical properties of the abrasive used. In conventional polishing, the surface finish depends on the size of the abrasive particle, but for tungsten CMP it is independent of abrasive size [92]. A simplified model of the process for tungsten CMP, based on a chemical kinetics approach, has been developed to explain these observations [93]. It is described below.

Standard methods of chemical kinetics for surface reactions involve choosing a set of elementary reactions, with their concomitant rate equations, to describe the overall process. In this case, chemical and mechanical reactions and their respective reaction rates r_c and r_m are:



Reaction 1	W + C -> WC*	$r_C = k_f [C]\, n_W$
Reaction 2	WC*+ A -> W + X	$r_M = k_M\, n_{WC*}$

Reaction 1 is the reaction between tungsten atoms W on the workpiece and oxidizers C in the slurry to form a surface complex oxide WC*. The rate of this reaction is proportional to [C], the concentration of chemicals C in the slurry, and to n_W, the number of W atoms on the surface of the workpiece. Here, k_f is the chemical reaction rate constant.

Reaction 2 is the mechanical removal of the WC* surface film by abrasive particles A to reveal fresh tungsten atoms W on the surface and to remove detritus X which consists of abrasive and tungsten oxide complex. The rate of this process is proportional to n_{WC*}, the number of WC* surface complexes, with mechanical proportionality constant k_M.

The material removal rate R is equal to the mechanical removal rate times τ, the thickness of the removed film divided by the workpiece area as shown in Equation (1). Without knowing n_{WC*} however, Equation (1) cannot be used. It is transformed into Equation (6) which shows how

the polishing rate depends on the concentration of oxidizer chemicals in the slurry, on the abrasive concentration and on the polishing pressure and speed. To compare predicted removal rates to experimental data under specific conditions, Equation (6) is used in the forms shown by Equations (7)-(9) as discussed below.

$$R = \tau \; k_M \, n_{WC^*} \quad (1)$$

To find how n_{WC^*} depends on the polishing conditions, it is helpful to use a chemical kinetics approach which focuses on the rate of change in the number of tungsten oxide complex sites on the workpiece surface. This can be written by inspection from the elementary rate equations as

$$dn_{WC^*}/dt = k_M \, n_{WC^*} - k_f [C] \, n_W \quad (2)$$

where the first term is for the formation of the WC* complex and the second term is for its destruction. The total number of sites on the workpiece surface is $n_o = n_W + n_{WC^*}$. At steady state, the rate dn_{WC^*}/dt is small, although the number of sites n_{WC^*} is not. Under these conditions, Equation (2) may be set to 0 and solved for the steady state value of n_{WC^*} to give $n_{WC^*} = k_f [C] / (k_f [C] + k_M)$. This can be substituted into Equation (1) to provide an expression for the material removal rate

$$R = \tau \, C \, M / (C + M) \quad (3)$$

where C is the chemical formation rate k_f [C] and M is the mechanical removal rate, k_M. This equation shows that at high chemical concentrations, the polishing rate is limited by mechanical processes, while at high mechanical removal conditions the polishing rate is limited by chemical processes.

The expression for mechanical removal can be given in more detail following a qualitative description of the behavior of the pad and abrasive during this process, which differs in significant ways from conventional polishing.

In conventional polishing, individual abrasive particles bear the applied load. They are pushed into the workpiece surface and then pulled across it, plowing a furrow to remove the workpiece material. The surface roughness depends on the size of the indentation, and thus on the size of the abrasive particle. The indentation depth depends on the applied load (and therefore on the applied pressure) but not on the number of particles because if there are more particles, then the load per particle (and thus the force per particle and indentation depth) is smaller. These conditions do not apply in tungsten CMP.

Because of the small particle size and the relatively soft pads used in CMP, the applied load is carried in a mixed mode by the slurry fluid and by asperities on the polishing pad. Abrasive particles embedded on the surface of these asperities contact the WC* complex and remove it from the surface. The removal rate is proportional to rate v at which the abrasive particles pass across the surface and to the number of active abrasive particles, n_A, which is itself proportional to the contact area of the asperities on which the abrasives are embedded [91]. Various models [94] of elastic materials show that the asperity contact area is proportional to the applied pressure P. The number of active abrasives also depends on the equilibrium process in which abrasives in the slurry attach to and release from the pad surface. The net result of these considerations is that the mechanical polishing rate may be written, using an explicit form of k_M, as

$$r_M = k_{ooM} \, n_{ooA} \, k_{ooP} \, [A]/([A] + K_{pad}) \, Pv \; n_{WC^*} \quad (4)$$

Here k_{ooM} is the abrasive - surface complex mechanical removal rate constant, n_{ooA} is the abrasive site density on the pad, and k_{ooP} is the proportionality constant between the contact area and the external pressure P. The Preston Pv relationship is due to the increase in polishing contact area that comes with the flattening of pad asperities as the external pressure increases. The expression $[A]/([A] + K_{pad})$ is due to the abrasive - pad equilibrium, where [A] is the concentration (in particles per volume) of abrasives in the slurry and K_{pad} is an equilibrium constant for the on/off process. This expression implies that at small abrasive concentrations, the removal rate is proportional to [A] while at high [A] the removal rate will be independent of abrasive concentration.

The abrasive particle concentration [A] is related to the experimentally convenient weight percent concentration %A by the expression

$$[A] = \frac{6}{\pi d_A^3}\left[\frac{\%A}{(1-\rho_A/\rho_f)\%A + 100\rho_A/\rho_f}\right] \quad (5)$$

for spherical abrasives, where d_A is the abrasive diameter while ρ_A and ρ_f are the densities of the abrasive and slurry fluid. Since d_A^3 is needed to convert between abrasive particle concentrations and weight percentages, an implication of this expression is that for constant %A there are more small particles in the slurry than large particles.

Defining the proportionality constant $k_{oM} = k_{ooM} \, n_{ooA} \, k_{ooP}$ and $f_A = [A] / ([A] + K_{pad})$ leads to a full expression for the overall polishing rate.

$$R = \frac{\tau k_f [C] k_{oM} f_A Pv}{k_f [C] + k_{oM} f_A Pv} \quad (6)$$

For all else held constant except the abrasive concentration expressed in terms of [A] or %A, this equation leads to the simpler forms

$$R = a_1[A] / (b_1 + [A]) = a_2 \, \%A / (b_2 + \%A) \quad (7)$$

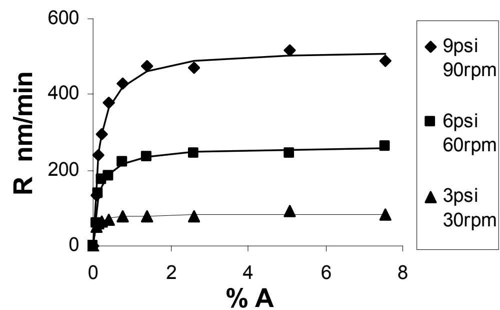


Figure 13: Data from Stein et al.[64] curve fit to model

Equation (7) has been fit to experimental data [95] for three different sets of P,v conditions as shown in Figure 13 and explains in detail the observation that the polishing rate depends on the abrasive behavior. Qualitatively, at high abrasive concentration in the slurry, the pad surface becomes saturated and additional abrasive particles are ineffective, while at low %A additional abrasive particles

find space to embed onto the pad surface and are available for polishing. The asymptotic limits represent the maximum rates possible for a given chemical concentration at given values of P and v. In these cases, each active abrasive is removing material as fast as it can be replaced chemically. At higher pressures, more abrasive particles are active because the flattening of pad asperities under pressure leads to more contact area between the abrasive loaded pad and the wafer surface.

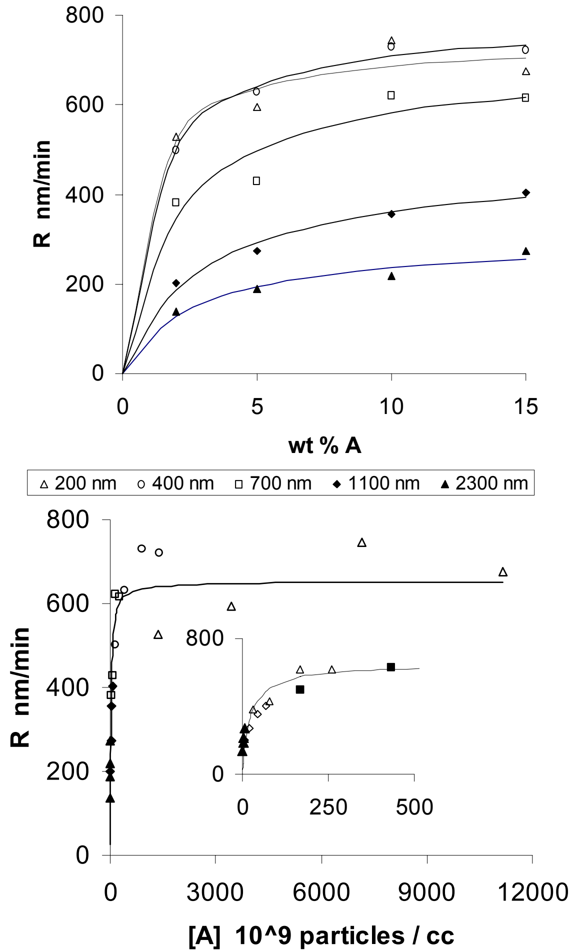


Figure 14: Data from Bielmann [92] curve fit to model using Equation 7 as %A (top) and as [A] (lower plots).

Another experimental study [96] of polishing rate as a function of abrasive concentration, using abrasives of different sizes, can also be interpreted in the same way. This data is plotted in Figure 14, fit to Equation (7). When the polishing rate is plotted as a function of %A, the graph implies that small abrasives are more effective than large ones. However, the same data plotted as a function of [A] shows that the effect is due to the larger number of small particles, rather than to an inherent dependence on abrasive size. The fit against number of particles in Figure 14 extends over several orders of magnitude. It implies that each particle removes the same thickness of material, independent of particle size. This correlates well with experimental measurements which show that the surface finish is also independent of abrasive size. The difference between these observations and those for conventional polishing is significant.

When the concentrations of chemicals and abrasives in the slurry are held constant, Equation 6 takes the form

$$R = a_3 Pv / (b_3 + Pv) \quad (8)$$

which is linear for small values of Pv and which approaches a limiting value for large Pv. Experimental data (Stein et al. [62]) is plotted in Fig 15, with a fit to Equation (7), which show this behavior for two different pads. Qualitatively, the asymptotic behavior at large Pv appears in the region where mechanical removal is faster than chemical replacement of the surface film. The maximum rate is determined by the formation rate of the WC* complex and faster mechanical removal is not possible. When the mechanical removal is relatively small, an increase in the polishing parameters will increase the material removal rate. Different pads have different mechanical characteristics (including asperity surface area available for abrasives and compressibility under pressure) which affect their behavior. Thus the different pads in Figure 15 have different values of both a_3 and b_3.

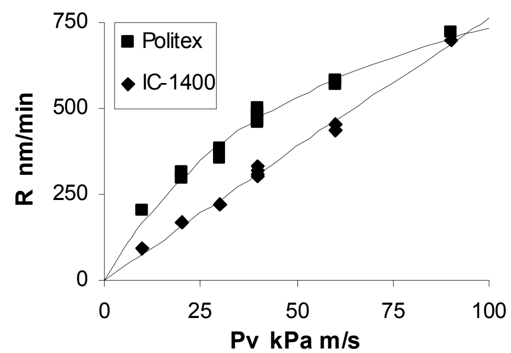


Figure 15: Data from Stein [64] fit to model (Equation 8).

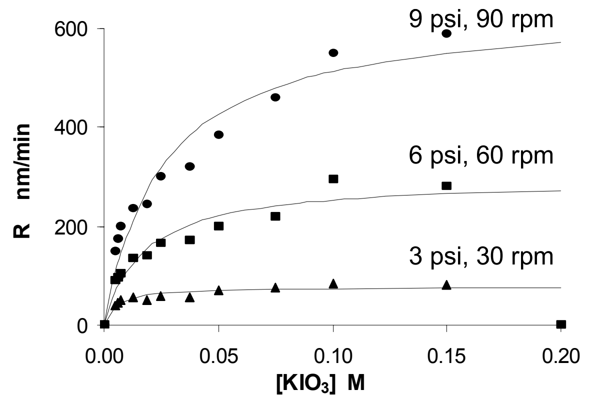


Figure 16: Data from Stein[64] fit to model (Equation 9)

The effect of slurry chemical concentrations on the polishing rate is predicted from Equation (6), as generalized in Equation (3), to be

$$R = a_4[C] / (b_4 + [C]) \quad (9)$$

Experimental data are shown in Fig 16 with curves fit to Equation (9). The asymptotic rate at high [C] is for regions where the chemical replacement of WC* is much faster than its mechanical removal, and the workpiece surface is fully covered with oxide. The removal rate is limited by the removal parameters Pv. Here, faster removal leads to higher polishing rates, as contrasted to the case in Figure 15 where the chemical formation limited the process. At lower values of [C], the rate is determined, in part, by how fast the WC* surface film can form, which depends on the chemical concentration.

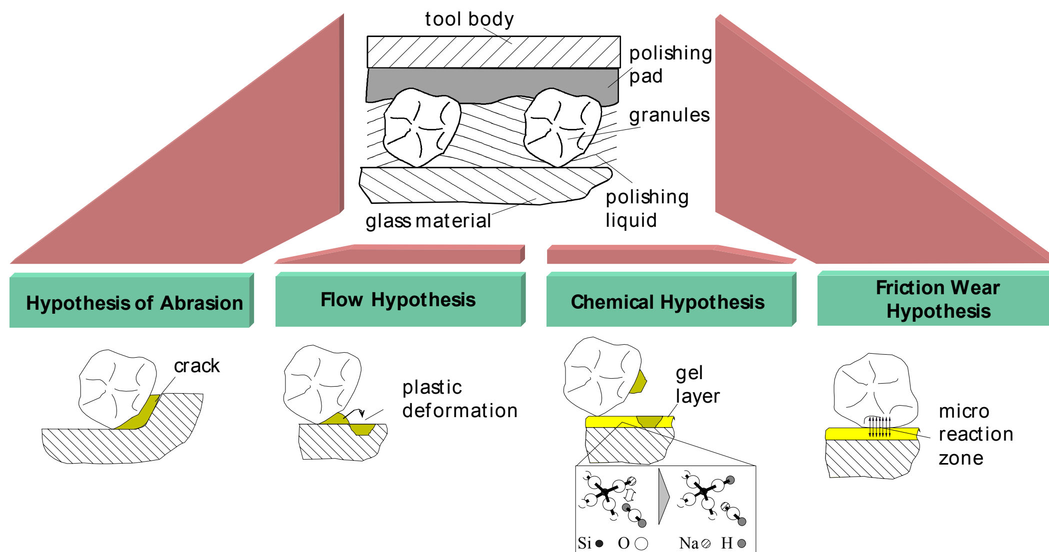


Figure 17: The four removal hypotheses are described in Sections 6.5.1-6.5.4 [97,98,99,100]

Details of the removal process on the nanometer scale which lead to insights into the constant k_{ooM} are not yet well understood. Different abrasive materials have experimentally different polishing rates [101]. This implies a chemical interaction between the abrasive particle and the surface complex. This "chemical tooth" has been observed in glass polishing, and may be associated with surface charges characterized by the zeta potentials and isoelectric points of the materials involved.

These examples of tungsten CMP illustrate some differences between CMP and conventional polishing.

6.5 Mechanical-chemical glass polishing

Glass polishing has long been practiced and studied. One of the first theories relating to the material removal which occurs when optical glass is polished was formulated as early as 1695 by Sir Isaac Newton: “The smaller the particles of the substance (abrasives), the smaller will be the scratches by which they continually fret and wear away the glass until it is polished.”

A number of other eminent scientists such as Lord Rayleigh, Sir George Beilby (1921), Professors Bowden and Tabor (1950), Adolf Kaller, 1960, Brüche and Poppa (1960), Izumitani (1980) and Cook (1990), (1991) have investigated the physical and chemical aspects of polishing over the years. Four main hypotheses, which are still the subject of lively discussion, have emerged (Figure 17).

6.5.1 Abrasion

Newton’s abrasion is based on a mechanical machining operation similar to grinding. Material removal is achieved by inducing very fine cracks. Generally speaking the hypothesis of abrasion applies only to the very first phase of the polishing process. The severely fissured material peaks provide an excellent contact surface (“mechanical tooth”) for the polishing grain. Material removal relies on mechanical fracturing processes[100-103].

6.5.2 Flow Hypothesis

The flow hypothesis links plastic material displacement with local material softening due to the frictional heating. These effects can be observed, taking account of the viscoelastic characteristics of the chemically modified glass subsurfaces, even when there is only a slight increase in temperature. The fundamental concepts of the flow hypothesis were developed by Rayleigh and Beilby. The fundamental principle of the plastic flow of glass under pressure, is shown by the early investigations of Klemm and Smekal [106] and others [107,108,109,110,111].

6.5.3 Chemical Hypothesis

In the chemical hypothesis, material removal is attributed to the formation and removal of a layer of gel. This layer is produced by the incorporation of water into the subsurface area of the glass. Various forms of interaction between the constituents of the glass and the slurry have been observed. These depend on the composition and properties of the polishing fluid and on the characteristics of the glass materials. In addition to the dissolution of the glass due to water, certain elements may also be affected by elution from the subsurface.

6.5.4 Friction Wear Hypothesis

The friction wear hypothesis was developed in response to the lack of information provided by the chemical hypothesis regarding the influence exerted by the polishing medium. The interaction between the polishing medium and the glass material is not disputed. Instead, the mechanical material removal has been replaced by a chemical reaction between the polishing grain and constituent parts of the glass (“chemical tooth”). The solid body reaction tends to take place at defects in the crystal lattice of the metallic oxide used as a polishing medium. This bond is stronger than the bond within the glass matrix, causing removal of glass. Correspondingly, there are two means of increasing the effectiveness of a polishing medium. On one hand, the active surface can be increased by reducing the size of the polishing medium in the polishing gap or, on the other hand, faults can be produced selectively in the crystal lattice or particularly reactive metallic oxides can be selected for the production of the polishing medium [112].

Kaller subsequently introduced the Tribo-Chemical Friction Wear Polishing Theory [113] to reduce the remaining gaps in the explanation of certain polishing results. All of the process components involved, i.e., polishing medium, polishing medium carrier, glass and water, were included in this study, which provides general characterisations of the role and the influence exerted by each component. However, he was unable to derive a quantifiable hypotheses from this theory or to use it to control the polishing process.

The four hypotheses presented concentrate on the various possible interactions of the components in the system. Actual polishing will proceed through a combination of material removal mechanisms, depending on the conditions in the system.

6.5.5 *Combined hypotheses*

Each hypotheses outline above fail to explain some aspect of glass polishing, reinforcing the idea that the polishing process involves more than one mechanism. Additionally, no one has succeeded in developing a quantifiable material removal model to date. Consequently hybrid hypotheses, using certain mechanisms from all of the available hypotheses, have been developed and tested experimentally, for example by Holland [114] and Izumitani [115] among others. Izumitani selected 18 different types of borate and silicate glass with various levels of hardness, softening point and chemical stability (Table 1).

Glass Type	Refractory Deformation Temperature T107.6 [°C]	Vickers Micro Hardness HV	Acid Resistance (% weight loss)	Water Resistance (% weight loss)
BK7	615	707	0.08	0.13
KF2	490	627	0.07	0.07
SK2	700	707	0.70	0.05
SK16	680	689	3.30	0.58
SF6	470	413	1.30	0.03
FK1	750	666	1.90	
SF13	480	437	0.34	0.02
KF3	500	627	0.04	0.05
BaF4	580	613	0.11	0.04
BaK4	620	657	0.43	
F3	480	548		
LaLF2	675	803	1.30	0.25
LaK12	670	743	1.70	0.35
LaLK3	650	762	1.90	0.70
CdF1	650	824	1.00	0.01
TaF2	685	847	0.74	0.01
LaK10	670	803	1.20	0.02
CdSF3	650	803	0.76	0.01

Table1 Glass characteristics

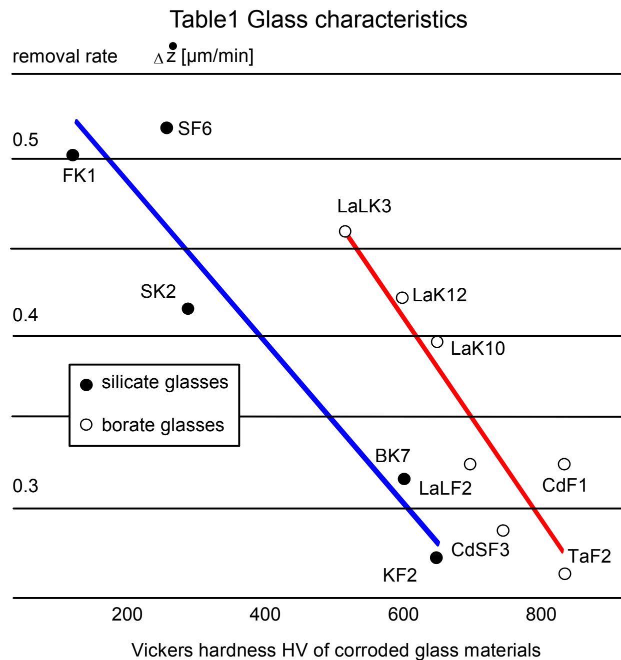


Figure 18: Removal rate for various glasses

If the character of the material removal was predominantly abrasive, the removal would correlate with the hardness of the material. Conversely, if material is removed by the plastic processes described, there should be a correlation with the softening temperature. The rate at which glass dissolves in aqueous media is likely to correspond with the polishing rate when the material removal is the result of a chemical reaction.

Izumitani identified the chemical stability of various types of glass by placing the glass in water and in a 0.01 molar HNO_3 solution and recording the weight lost. He concluded from the dependence which emerged that the chemical stability of the glass correlates with the polishing rate. Glass corroded selectively, i.e., glass left for several hours in a 0.01 molar HNO_3 solution then polished showed that there is a correlation between the polishing rate and the level of Vickers hardness measured after corrosion (Figure 18).

Both the subsurface characteristics and the polishing rates change as a result of the chemical attack on the glass. Accordingly, it is important to determine the characteristics in the subsurface. Izumitani's hypothesis must be regarded as a combination of removal and chemical hypothesis. The concept underlying this model owes much to the theories previously outlined.

The influence exerted by the polishing medium remains unclear; why certain polishing media are more effective than others is not explained by the model. They are, however, addressed in the investigations and studies conducted by Cook and Brown. Cook lists five reaction steps of relevance to the material removal [116]:

1. The diffusion of water into the glass surface is accelerated by the application of load to the polishing granule.
2. The glass dissolves under the load applied by the polishing grain. The absorption of a proton by a hydroxyl group of the water produces a Bronsted-base (Si-O-) and a water molecule on the surface of the glass.
3. Material is removed as a result of the absorption of the solutes on the granule material, provided there are some hydroxyl groups on the surface of the granule which lead to an Si-O-M linkage. The movement of the granule stresses the compound and, under optimum conditions, detaches the silicon. This is followed by a reaction with the water and with the reaction products attached to the granule $Si(OH)_4$. Again, hydroxyl groups are formed on the surface of the granule.
4. Under certain conditions, the $Si(OH)_4$ can be re-bonded with the glass material. An additional option is to form complexes with neighbouring metal ions. Any formation of complexes of this nature is heavily dependent on the pH. In the case of silicon the optimum pH-value is 9.8. The maximum removal rate should be reached at this value [117].
5. The glass is exposed to further stress by aqueous corrosion between two particle impressions. This corrosion also affects the removal rate.

The diffusion of water in glass is the determining mechanism in this theory. This diffusion is increased by mechanical stress exerted on the glass by the grains. However, the absorption characteristics of the polishing materials also play a significant role. This polishing mechanism described by Brown is shown schematically in Figure 19 [118] .

The majority of the investigations conducted by Cook, Izumitani, Kaller etc. used pitch. By contrast, those carried out by Cumbo [119] used polyurethane foam pads. No account was taken of the role of the polishing surface and

the resultant differences. In 1980, Kaller noted [120] that “A tribo-chemical wear process which is extremely difficult to control and which takes place in the action interstice when polishing operations are conducted on the functional surfaces of brittle, optical media, affects all partners involved in the process, i.e. the surface of the optical medium to be machined, the polishing agent and the carrier of the polishing agent. The suspending agents fluid also exerts considerable influence on the level of wear sustained by the partners”. It has not been possible, to date, to develop a hypothesis which combines all of these aspects, although it is known that the polishing process is determined by the reactions which take place at the contact surface between glass and the polishing medium win aqueous solutions.

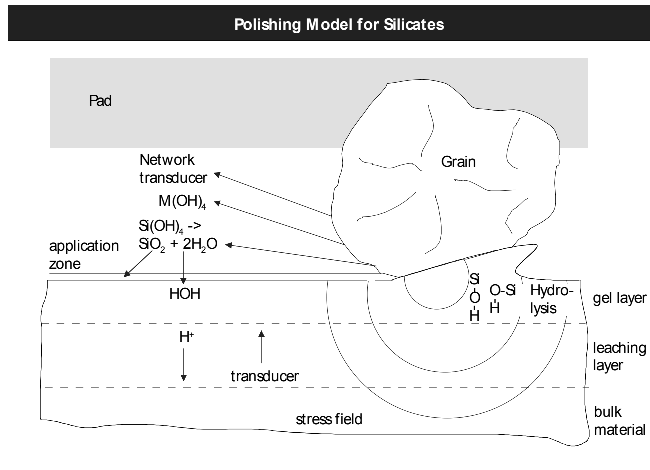


Figure 19: Removal model based on Cook and Brown

6.5.6 Removal characteristics of various glass types

The results referred to in this sub-section of the paper were obtained using machines which work with synchrospeed kinematics. When synchrospeed kinematics are used, the polishing tool and the glass to be polished rotate in the same direction of rotation at the same rotational speed. The relative speed is produced by the eccentricity between the tool and the workpiece axis. The relative speed therefore remains constant over the entire glass surface.

Figure 20 shows that material removal behaviour is highly reproducible in BK7 glass. This also applies to quartz, BaK4, B270 and BaSF64a. By contrast, the material removal characteristics are not reproducible in polishing operations conducted on KzFSN4.

The characteristics demonstrated by glass types SF6, SK16, LaFN 21 and FK51, are similar. The types of glass investigated, differ considerably in terms of composition, chemical, mechanical and thermal characteristics [123]. The following analysis will show which of the mechanical, chemical and physical effects are most likely to dominate the material removal characteristics.

Hambuecker [124] has shown that the non-reproducible behaviour when KZFSN4 glass is polished is attributable to pad wear. “Pad wear can occur only when there is intensive contact between pad and the glass material. The contact intensity depends on the carrying capacity of the liquid film. Contact between the polishing surface and the glass is prevented when the polishing material used separates the two surfaces”. This is the case when there is a minimum concentration of granules in the suspension and when the liquid wets the glass surface efficiently. The development of a stable suspension film separating the surfaces is guaranteed only when this interaction occurs. When this is the case, there is no contact between the pad and the glass material. According to the concepts of micro and nano-tribology, these fluid films increase in thickness somewhere between a few molecules to a few nanometers [125]. These thin fluid films are also known to demonstrate material characteristics corresponding to those of solid bodies when subjected to shearing strain. The stability of the film of fluid depends on the interaction between glass and fluid, as shown schematically in Figure 21

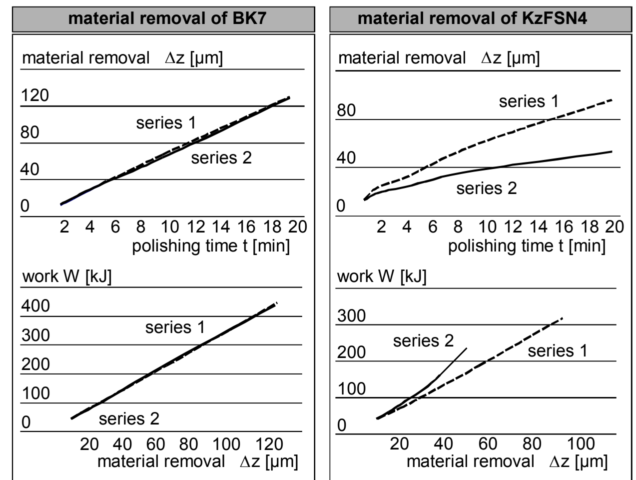


Figure 20: Polishing behaviour of different glass materials (Hambuecker [122])

	SiO2-cont.[%]	HK [-]	E [N/mm²]	Dens. [g/cm³]	µ [-]	Tg [°C]	AR	SR
Quartz	100	580	72000	2.20	0.170	980		
BK7	68.9	610	82000	2.51	0.206	557	2.0	1.0
B270	68.0	542	71500	2.55	0.219	533	2.0	2.0
BaK4	50.0	550	77000	3.10	0.241	555	1.0	1.2
BaSF64a	30.0	650	105000	3.20	0.264	582	1.2	3.2
SK16	29.8	600	89000	3.58	0.264	636	3.3	53.3
SF6	26.9	370	55000	5.18	0.244	423	2.3	51.3
KzFSN4	10.0	450	60000	3.20	0.275	492	4.3	52.3
LaFN21	0	780	126000	4.34	0.294	663		
FK51	0	430	81000	3.73	0.293	420	2.2	52.3

Table 2: Glass characteristics (Hambueker [122])

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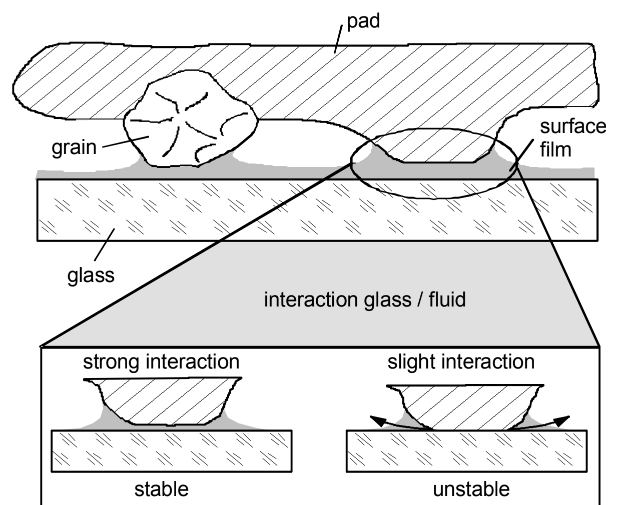

Figure 21: Influence of the interactions between glass and polishing suspension on liquid film stability

	χ_{total} [mN/m]	χ_{pol} [%]
LaFN21	33.78 ± 0.70	0,38
SK16	30.36 ± 0.25	0,82
KzFSN4	31.56 ± 0.94	4,37
FK51	40.67 ± 0.77	3,81
BaK4	34.32 ± 0.70	8,51
SF6	35.12 ± 1.37	11,22
BaSF64a	35.00 ± 1.72	13,71
Quartz	42.40 ± 1.30	23,35
B270	46.04 ± 1.29	24,91
BK7	46.24 ± 1.81	25,30

Table 3: Polar proportions of surface energy of different glass types

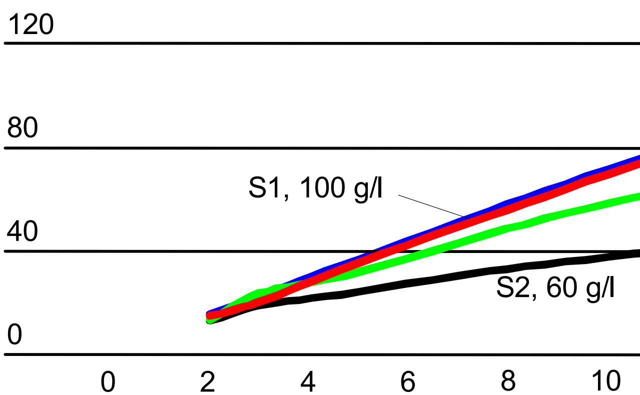

Figure 22: Effect of abrasive loading on pad wear [119].

Neutral liquids which have no affinity with the glass material are more easily squeezed out of the contact zone than fluid ones which interact strongly. When water is used as the suspension medium, the polar characteristics of the glass materials are decisive for the interaction between water and the surface of the glass. These can be characterised by the polar proportion of the surface energy of various types of glass. Based on the idea of Owens, Wendt, Rabel and Kaeble, the surface energy can be divided according to the kind of interactions between molecules. They differentiate between polar and disperse fractions. The polar interactions are the sum of the Coloumb interactions between permanent dipoles and between permanent and induced dipoles. The interactions due to temporal fluctuations of the electric charge allocation within the molecules are the disperse fractions. Water is bonded to the glass surface mainly by physisorption [128]. BK7 has a high level of polar surface energy and promotes the formation of a stable separating film; KzFSN4 has low levels of polar surface energy. In this case, it is very easy to push the fluid out of the contact zone and there is direct contact between the pad and the surface of the glass.

6.5.7 Controlling glass polishing processes

How can the polishing process be influenced, given that the glass cannot be changed and the chemistry proceeds as permitted by thermodynamics and kinetics. What can we change in order to produce reproducible, optimum polishing conditions?

As described above, lap wear can only occur when there is intensive contact between the soft pad and the hard workpiece material. One goal during the polishing process is therefore to avoid tool wear in order to stabilize the process. Hence mechanical contact between the pad and the workpiece should be avoided. Since a stable separating film cannot be guaranteed at any time, in particular in combination with “difficult” glasses (e.g., KzFSN4), polishing grains have to fulfill this task.

To test this effect, the two series of polishing tests with KzFSN4 glass were repeated with two slurry concentrations (c = 60 g/l and100 g/l). Figure 22 shows that the higher concentration gave a more stable process.

6.5.8 Glass dissolution

Numerous investigations into the corrosion of water on glass surfaces, are described in the literature [129,130,131]. One of the principal conditions for the dissolution of glass is that the reactions on the surface of the glass occur more swiftly than the material removal itself. The concentration of the hydrogen over the diffusion depth is a measure of the chemical corrosion of the water.

This example shows one possibility to stabilize the polishing operation process even in polishing glass types as KzFSN4. A further possibility is also the deployment of pad materials with a different contact behavior whereby the wear can also be reduced (Figure 22).

7 FINE FINISHING PROCESSES

The processes discussed in this paper are characterized by:

- Production of surfaces with roughness typically in the regime of ~1-2 nm rms or less;
- Produce surfaces by the interaction of a slurry of solid particles with the work surface; and
- Give a surface shape on the part driven by dwell time of the lap as a function of part position.

For completeness, it should be noted (eg Komanduri et al.[1] and references therein) that a number of other process produce surface finishes in this regime, but do not fall within the scope of the paper. Single point diamond turning and ultra-precision grinding can produce surface finishes well below 2 nm rms using displacement controlled processes on typically very stiff, precision machines. Plasma assisted chemical etching, ion milling, and reactive-atom plasma technology (RAPT) can all produce fine finishes and complex contours by programmed variable dwell times as a function of “tool” position on the part; no abrasives are used.

8 TRANSITIONS AND PROCESS MAPS

Lapping and polishing process outputs vary with external variable – but the relationships sometimes show significant transitions. To ease conceptualization of the system behavior, such transitions can be captured in process maps. Here we give some examples; given the focus of the paper on kinetics, we chose removal rate as the dependent variable.

Figure 23 shows removal rate (which is generally proportional to velocity) as a function of granule size for an essentially mechanical lapping process(i.e., not CMP) such as the ductile mode diamond lapping of silicon or of electroless nickel. It is assumed that:

- the load and granule concentration (wt%) are constant;
- that the granule size distributions are self-similar;
- that there is good “tooth” ; and
- that the lap asperities are large compared the granule size.

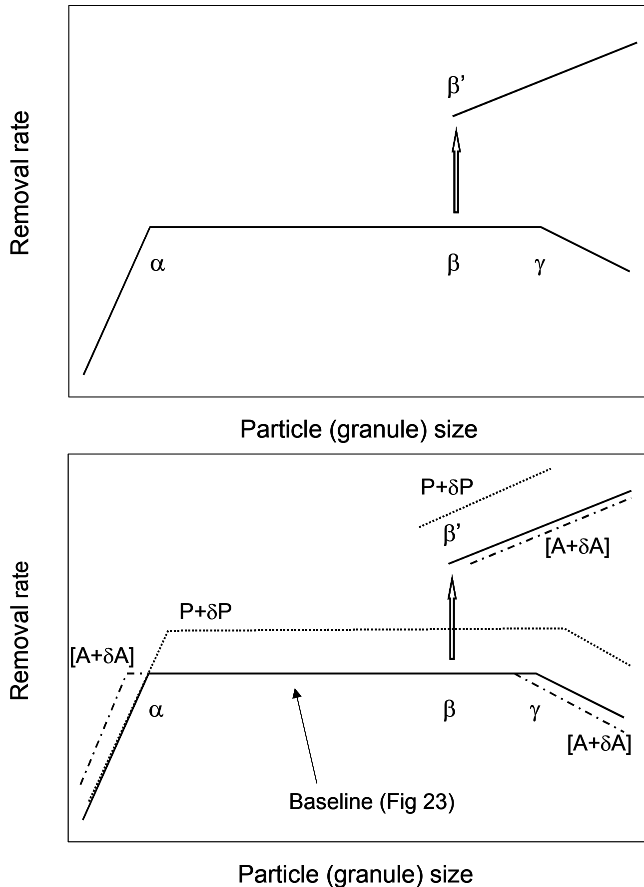

Figure 23: Process map for “mechanical lapping”.

Figure 24: Process map showing effect of changing load or concentration.

For small granules (left of α in Figure 23) the load is partially supported either by direct lap-workpiece contact or a hydrodynamic film. Removal rates increase with granule size until the load is entirely supported by the granules. For granules larger than α, removal rate is independent of size. For brittle materials, there is a granule size at which the penetration into the work of individual granules is sufficient to initiate fracture ($\beta\beta'$ in Figure 23). At this point, removal rate jumps significantly, after which it is again a monotonically increasing function of size. For ductile materials, removal rate remains independent of size until the granule becomes sufficiently large that it begins to roll (γ), decreasing removal rates.

For a given lap, the granule size at which the transition α takes place depends on workpiece hardness. Increased workpiece or lap hardness also changes the sliding to rolling transition γ.

If we increase the abrasive concentration ([A=δA] in Figure 24), the removal rate increases for small abrasives, the onset of fracture is suppressed, but rolling initiates earlier. If we increase load, we suppress rolling and initiate fracture earlier; removal rate is increased between α and β, while below α the rate of increase with granule size changes depending on the relative hardness of the lap and workpiece.

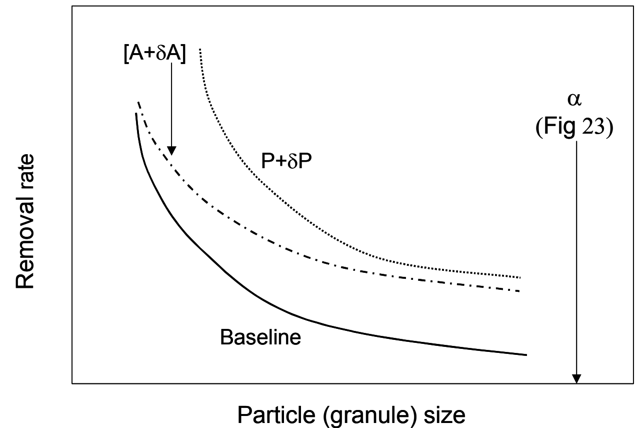

Figure 25: Tungsten CMP process map showing the effect of pressure and concentration changes. Note that the process map for copper or interlayer dielectrics may be significantly different.

The process map for tungsten CMP, as we have seen in Sections 5 and 6.4, is a little more complex (Figure 25). All CMP processes operate below the transition α in Figures 23 and 24. Increasing particle size at constant abrasive loading reduces removal rate non-linearly; broadening the size distribution decreases the removal rate for small granules and increases it for larger. Increasing abrasive (or oxidizer) concentration increases removal rate (provided the conditions are far removed from saturation). Increasing pressure increases pad-work contact area, and hence increases removal rate. Increasing velocity will increase frictional heating and hence reaction rates, while reducing viscosity, thus moderating any increased hydrodynamic lift.

9 CONCLUDING REMARKS

The physical scale of material removal processes in polishing is such that it is difficult (practically impossible) to observe them directly. Much of what we know about the fundamental mechanisms involved in the process has been derived either by correlating macroscopic measurements of process outputs with models, or by extrapolation from experiments at scales which can conveniently be observed. Process complexity and the murky nature of some of the scaling laws make such extrapolations risky. It is not surprising, therefore, that good predictive models of material removal in polishing processes are the exception rather than the rule. All, however, is not bleak. As we have shown, improvements in understanding of the basic interactions in polishing are providing models that correlate with some of the counter-intuitive behaviours observed experimentally. None of the models seem to treat transitions well. The paper has also shown areas where substantial further work is required, for example in the (elasto)-hydrodynamics of CMP. Perhaps the least well understood aspect of the system is the lap, especially when that lap is faced with a pad.

Loading conditions appear to be key to understanding removal mechanisms. It is notable that the diamond

polishing results of Samuels and others, where pads are used, show a relationship between granule size and removal rate more similar to CMP than to diamond lapping processes. As noted above, frictional heating and hydrodynamic effects modulate the loading conditions.

The process maps introduced in Section 8 offer a means to conceptualize transitions between mechanisms and their effect on removal rates. The idea may be extended to other important dependent variables (for example surface finish) and other process inputs (fluid viscosity etc.).

This paper has attempted to characterize polishing via the fundamental interactions between four critical elements of the process. Understanding these interactions seems critical to improving our ability fto relate changes in process input variables to productivity and part quality. Currently the bulk of such predictions require that many of the less well understood process variables be "held constant". Longer term, development of new processes will be accelerated by fundamental physical understanding of the entire system.

Aksu and Doyle's recent papers [132,133] describing in-situ electro-chemical measurements during polishing provide insight into the formation of passivation films in copper CMP. They also provide a much needed (but perhaps unintentional) brake on our enthusiasm; as they point out, the optimum removal behavior (at pH 12) provides poor selectivity for oxide layers.

The "*system examples*" presented in this paper discuss only a single material removal system. Such models must be subsumed into a system model of all the technologically important features of an economically viable production process.

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