Polishing Pad and Conditioning
Disc Characterization and
Wear Mechanisms
CMP Active Diamond Characterization and Conditioner Wear

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ABSTRACT

Using a pad substitute material, we measure the number of active or working diamonds on a conditioner and find that it is generally a small fraction of the total number on the disc. The number of active diamonds also increases with the applied load and varies somewhat with sliding direction. However, even among the active diamonds, most do relatively little cutting. A few diamonds on a disc do most of the deep bulk cutting, a larger fraction skim the higher areas of the pad surface and most of the diamonds on the disc apparently merely help to support the load. While all of the diamonds that make contact, cutting or otherwise, may show evidence some of mechanical wear, wear of the small number of deep bulk cutting diamonds may be responsible for declining cut rates and for surprisingly low observed conditioner lifetimes.

INTRODUCTION

Pad conditioning is necessary for maintaining polish rate stability on most types of polishing pads. Pad conditioners that employ artificial industrial diamonds are constructed by bonding, plating, sintering or brazing crystals of a selected grit size, morphology and quality to a metal or ceramic substrate. Diamond is preferred because it is a very hard, wear-resistant material that is immune to chemical attack in the environments normally present in polishing tools. Nevertheless, the useful life of a polyurethane pad conditioner in most chemical-mechanical planarization processes is measured in tens of hours at best. Short lifetimes occur even though the nominal pressure on the conditioner working face may be relatively light - often less than 1 psi - and the face may contain thousands of diamonds that could plausibly be participating in cutting the pad. For example, polyurethane pad surfaces that have a total height variation of 60 µm could theoretically contact most of the diamonds on a conditioner constructed to have a mean protrusion from the substrate of 50 µm. Individual diamonds that do contact the pad would of course differ in their quantitative contribution to load balance and cutting. The details would depend on the geometry of the diamond and that of the immediately surrounding grit. Due to the large population statistics involved, however, this scenario implies that the average cut rate produced by conditioners of a fixed, carefully controlled design under given kinematic conditions should fall into an extremely tight range. This, however, is paradoxically often not the case.

One of the basic facts about conditioners that may shed light on conditioner lifetimes and other characteristics concerns the actual proportion of working grit, or active diamonds, that participate in cutting the pad. Many conditioner suppliers understandably claim a high proportion of active diamonds but may or may not describe the method by which this has been determined.
There is also no relevant NIST standard available that can be used as a basis for comparison. We discuss here one realization of a method [1] that may be used to estimate the active diamond population of a conditioner. After describing two variants of the method that have slightly different purposes, we illustrate how the basic data that is obtained may help to provide insight into factors that affect conditioner lifetimes.

EXPERIMENTAL DETAILS

Conditioners tested

The experiments described here were all performed using Mitsubishi Materials Corporation (MMC) triple ring dot (TRD) 100 mm diameter conditioners (Figure 1), which are populated with randomly distributed artificial diamonds embedded in an electroplated Ni substrate. In this design, diamonds are attached to the surfaces of eight raised ring segments on the outer perimeter and to three circles of raised, 2 mm diameter dots. While results are reported only for the TRD conditioner, similar results have been obtained for other MMC conditioners and for conditioners from other manufacturers. While notable differences sometimes exist between conditioners, we focus here on experimental results that seem to be qualitatively common to most commercial CMP pad dressers.

Figure 1. Working face of the Mitsubishi Materials Triple Ring Dot conditioner design used in this study. Diamonds are located on the raised dots and on the outer eight ring segments.

Pad substitute material

Since diamond furrows are usually not visible on commercial polyurethane pads, especially for diamonds making only light contact, one approach to counting active diamonds is to substitute a different material with similar mechanical characteristics but with more favorable optical properties for detecting contact. We show in this paper results obtained using 0.093" thick GE Plastics XL10 polycarbonate sheets. Diamonds that make even very light contact leave a detectable scratch on polycarbonate, making it very easy to locate and count them.
The relevance of polycarbonate test results to actual pad conditioning is an important but complicated question. Manufactured polycarbonate sheets and polyurethane-based polishing pad materials can have a wide range of material properties, depending on the source, formulation and process used. A single test material is therefore not appropriate for all purposes. XL10 appears to have comparable tensile and compressive yield strengths [2] to commonly used IC-class hard pads, though it has a somewhat higher Shore D hardness. Thus, we would expect a test based on XL10 to undercount the active grit realized in practice on an IC pad.

Because the faint furrows produced by the active diamonds that are likely to be undercounted on IC, one way to evaluate the relevance of XL10 polycarbonate to IC conditioning is to compare the surface height distributions (probability density functions, or PDFs) that develop when the two materials are conditioned to steady state with the same conditioner at the same load. A surface height PDF is constructed by making a histogram of surface heights from interferometry or profilometry data and then normalizing it so that the area under the histogram is 1. Figure 2 compares measured PDFs for XL10 and for an IC pad conditioned with the same 100 grit MMC TRD disc. Since the IC and polycarbonate loads are not perfectly matched in this figure, we note that we typically find that load has an often detectable but secondary effect on the PDF; see for example [3]. In Figure 2, we can see that the polycarbonate surface has similar PDFs at both 3.6 lbf and 6.1 lbf and that these are both narrower than the PDF of the IC surface at 4.0 lbf. This occurs for two reasons. First, voids in the bulk of the IC pad that have recently been exposed by conditioning lengthen the left-hand tail of the PDF by an amount roughly equal to the mean void diameter. Polycarbonate, by contrast, is solid and therefore has a PDF left-hand tail that is totally determined by conditioning. For IC, this effect should lengthen the left-hand tail by about 30 \( \mu \text{m} \) relative to XL10, as in fact happens in Figure 2. Second, diamonds should penetrate polycarbonate a little less than IC because of the hardness difference. Nevertheless, the surfaces display nearly identical height variations in the right-hand tail, suggesting that contact and cutting by less aggressive diamonds is similar in both cases. Consistent with the PDFs, we usually find that XL10 and IC have cut rates that, while not perfectly matched, are still comparable in magnitude, with XL10 usually having a somewhat higher rate than IC.

![Figure 2. Comparison of surface height probability density functions of XL10 polycarbonate and an IC pad conditioned with the same MMC TRD 100 grit disc.](image-url)
Another important question concerns the thickness non-uniformity of the test material. Thickness non-uniformity ideally should be as small as possible to ensure that test results reflect the properties of the conditioner, not the geometry of the test material. While XL10 sheets individually can have thickness variations of two or three mils over an 8"x10" area, a potentially serious disadvantage, such variations are acceptable if they are nearly linear over the testing area since the loaded sheet will then still present a nearly flat surface to the conditioner. Thus, it is important to inspect the surface quality and uniformity of sheets that are used for testing and use only sheets that meet quality criteria.

**Active diamond characterization**

Two tests will be described, both of which involve sliding the conditioner over a polycarbonate sheet that has been positioned on a precision optical mirror. The optical mirror ensures that the sheets, which bend easily when lateral forces are applied, conform to a flat surface under load. Prior to each test, the conditioner is attached to a holder equipped with a mechanism for exactly and reproducibly controlling the orientation of the conditioner relative to the sliding direction. The holder also prevents the conditioner from turning while it is being tested. The holder itself fits into a frame that fixes the location of the conditioner center relative to the left edge of the polycarbonate sheet. The left edge, or a scratch made parallel to it, is used as a reference axis for measuring the locations of active diamonds.

In the first test, called the short draw test, the conditioner is set on the polycarbonate sheet, a load is applied using dead weights, and the conditioner is slowly pulled for a distance of about 1 cm parallel to the left side of the sheet. Scratches are then counted using backlighting to highlight them. The origin of each scratch is also carefully marked. The total number of visible scratches, no matter how faint, is then taken as the active diamond count. The counts obtained by this method are very reproducible, usually with a variation substantially less than 10%.

Active diamond locations and diamond counts in the short draw test vary somewhat with the rotational orientation of the conditioner relative to the sliding direction. Figure 3 shows measurements taken for a 100 grit TRD conditioner at two loads using eight sliding directions in equal increments of 45°. As the disc is rotated, the count changes slowly. Data at different loads

![Figure 3. Variation of active diamond count of a 100 grit TRD conditioner with sliding direction at two loads. Eight sliding directions are used in increments of 45 degrees.](image)
show similar trends, indicating that changes are not due to measurement error. By overlaying plates made at different orientations, the majority of diamonds are typically found to be common to all directions. Orientation dependence may be due to the statistics of diamond protrusion on the conditioner face, which would affect the pitch of the disc during sliding and bring a slightly different subset of diamonds into contact as the orientation is changed.

We find using this test that the number of active diamonds increases as the applied force increases (Figures 3 and 4) and that even at loads substantially in excess of those used in practice (> 22 lbf on a 100 mm disc), the number of working grit is still only a small fraction of those present on the conditioner. This suggests that even given the differences in the properties of polycarbonate and commercial polyurethane pads, the number of active diamonds on the latter is still likely to be a small proportion of the total grit on the disc. While it may be true that many more diamonds make contact with asperities in the case of a pad, the active diamond count results suggest that these diamonds merely help to support the load and play no active role in maintaining the surface of the pad by cutting.

![Figure 4. Dependence of active diamond count on load for an MMC TRD 200 grit conditioner.](image)

Note that the regression line does not pass though the origin when there is no load because some diamonds are always required to support the conditioner.

By carefully aligning a marked polycarbonate sheet from the short draw test with corresponding alignment marks on the conditioner, it is possible to find the approximate locations of the active diamonds to within approximately a millimeter. This is sufficient to restrict a search for each active diamond to just a few potential candidates. Using low magnification optical microscopy and an undamaged piece of polycarbonate to create a test indentation, it is then straightforward to isolate the specific diamond that produced each scratch. In Figure 5, we show a scan of a plate from the short draw test overlaid on a 200 grit TRD disc. Small black marks in the figure indicate the origins of short draw test scratches. Many of the 2 mm diameter islands on the disc can be seen to contain one or more active diamonds. The active diamond marks are sufficiently precise that they can easily be used to focus the search to a specific area of each island. We can also see by examining the outer rings that there is a slight bias of the active diamond locations toward the leading edge of the disc, which is at the bottom of the figure. This would be expected from moment balance.
The second test, called the long draw test, uses the mechanical device from the short draw test, but the conditioner is now pulled over a distance that exceeds its diameter. This guarantees that all of the active diamond furrows will cross at least one common line that runs perpendicular to the left edge of the polycarbonate sheet. Sometimes, color is added to the sheet prior to the test to highlight the furrows. A stylus profilometer is then used to scan perpendicular to the furrows starting at a reference mark near the left edge. Figure 6 shows a scan from a polycarbonate sheet scratched at 5.9 lbf with a 100 grit TRD disc. A total of 117 active diamonds were found in the short draw test for the same orientation. The raw profilometry data has been processed to remove slow, long wave length height variations due to manufacturing distortions in the shape of the sheet. We see that each furrow evidences both subsurface cutting and plastic displacement of the polycarbonate to the sides of the furrow. Also, deep furrows are clearly much less numerous than the total active diamond count might suggest. A one-to-one comparison of the optically visible furrows with the furrows that are detected by profilometry shows that some very faint furrows have depths that are less than the natural height variation present on an unscratched polycarbonate surface. Such furrows are visible to the eye but cannot be separated from surface noise with profilometry. Thus, if one counts furrows from a profilometry scan, the active diamond count is always less than the optical count from the short draw test. It is also difficult to count diamonds by finding furrow origins in the long draw test since furrows sometimes overlap, obscuring the starting points of some diamonds. In the short draw test, by contrast, furrows of even nearby diamonds are usually easily distinguishable.
Figure 6. Profilometer scan of the surface of a polycarbonate sheet across the furrows produced by active diamonds in the long draw test. Several furrows are shown in detail in the inset.

One advantage of the long draw test is that the profilometry data can be used to estimate the proportion of the total cut rate that can be accounted for by each of the more aggressive active diamonds. This is done by calculating the cross sectional area of the subsurface portion of each furrow and comparing it with the total subsurface area. Diamonds can then be sorted by their relative contributions. We then hypothesize that the relative cut rate contribution is approximately the same as the relative furrow area. As in the short draw test, individual contributions depend on sliding direction because of irregularities in diamond shape and variations in load distribution. A typical result, however, is that about half of the total cut rate can be accounted for by the top ten most aggressive diamonds (Figure 7). By combining the location of each furrow relative to either the left side of the polycarbonate sheet or a parallel reference scratch with the diamond origins measured with the short draw test, each of the most aggressive diamonds can usually be positively identified on the disc. Occasional ambiguities can be resolved by using short and long draw data from two orthogonal sliding directions.

Figure 7. Profilometry scans (black curves) of furrows from two 100 grit TRD conditioners. The red curve on each graph shows the accumulated fraction of subsurface furrow area along the scan. Vertical jumps in the red curve indicate the fraction of subsurface area contributed by each diamond. The top ten diamonds account for about half of the subsurface area.
Wear experiment

We describe next a wear experiment that utilizes the above tests and provides some confirmation of the importance of the aggressive diamonds. The wear experiment was performed with two nearly identical experimental MMC TRD discs populated with 100 grit diamonds with different physical characteristics. Disc A contained diamonds with greater fracture toughness and a longer mean cutting edge length than disc B. The mean exposure of the diamonds on A was 57.9 μm while on B it was 67.0 μm. In factory testing on IC, A was found to have a mean cut rate of 39 μm/hr and B had a rate of 36 μm/hr. Furrow scans for the two discs prior to the test are similar and are shown in Figure 7.

First, the active diamonds of both discs were counted with the short draw test at 5.9 lbf using two orthogonal sliding directions, referred to as orientations 1 and 3. A long sliding test at the same load combined with scanning profilometry was also used to measure the cross sections of the diamond furrows. The general locations of the diamonds that had cut the 10 deepest furrows in orientation 1 were then found by combining the results of the long and short tests. Optical microscopy was used to locate the individual aggressive diamonds, and SEMs were taken of them. Aggressive diamond identification was verified in each case by requiring that the diamond make an indentation on a lightly loaded polycarbonate sample. Ambiguities were resolved using orientation 3 data.

After this initial characterization, each disc was used to condition a series of polycarbonate sheets for a total of 8 hours at 6.1 lbf. Tests were done on a 200 mm experimental polisher [4] using a platen rotation rate of 111 RPM with water at 200 ml/min as the lubricant. The conditioner rotation rate was 30 RPM and the disc executed a 6° sinusoidal sweep with a frequency of 12 full sweeps per minute. Changes in weight were used to measure the mean cut rate after each hour of conditioning. At the end of the wear test, the active diamond count and furrow cross sections were re-measured and SEMs were taken of the original top ten aggressive diamonds.

For both discs, the active diamond count increased after the wear test. The count for disc A increased from (101, 113) in orientations (1, 3) to (146, 149), while the count for disc B increased from (117, 138) to (153, 155). The mean polycarbonate cut rate decreased only slightly for disc A but declined substantially for disc B (Figure 8). At 8 hours, disc A was cutting

![Figure 8. Polycarbonate mean cut rate vs. time for identical conditioners populated with diamonds of type A and type B. Type A diamonds have longer edges and higher fracture strength.](image-url)