



Diamond Dynamics

Evolution of Diamond for Optical Component Finishing

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Monocrystalline diamond, both natural and synthetic, has been widely used in the lapping and polishing steps of optical component manufacturing. As we will see later, the structural defects inherent in monocrystalline diamond will eventually limit usage in next generation products.

Recently, diamond manufacturers have made some key morphology refinements to compensate for the limitations of monocrystalline diamond. As a result, engineers are achieving higher removal rates and finer, scratch free surfaces. We will examine, from a form-function perspective, the evolution of diamond into these fascinating new abrasive types.

Nanoparticle technology will play a key role in diamond synthesis, as the functional utility of all diamond types is increasing with decreasing particle size distribution. Diamond with an average diameter of 0.100 micron or less is now measured in nanometers. Nanodiamond has more pieces per carat than traditional micron diamond used in finishing (Table 1). How small is nanodiamond?

One carat (200mg) of 100 nanometer (nm) diamond abrasive contains slightly over one hundred trillion pieces! Since the number of pieces per carat is proportional to the cube of the radius, the quantity of three micron diamond equivalent to the number of pieces in 100nm diamond jumps to 100000 carats or roughly 44 pounds. The equivalent mass of 30 micron diamond, a size typically used in cutting wheels, is 22 tons.

Another diamond type that will be reviewed later, Ultra Dispersed Diamond, (UDD) contains about one hundred thousand trillion primary particles per carat. If we compare this number to 300 micron Bermuda beach sand at

4000 pieces per 200 mg, the equivalent mass now becomes 22 million tons (Figure 1). This mass will fill a 50 yard beach one foot deep with dry-packed sand 550 miles long, or roughly 14 times around the entire Bermuda perimeter. Certainly, a carat of UDD may be added to the old adage "as much as the stars in the sky or grains of sand on the beach."

Monocrystalline Diamond

Monocrystalline diamond is a highly ordered crystalline solid. The carbon atoms are linked together in a regular fashion. Each atom shares one of its outer shell electrons with four other carbon atoms in an equally spaced tetrahedral environment. Monocrystalline diamond, both natural and synthetic, was the primary abrasive source of the finishing industry before the turn of the millennium. By volume, synthetic monocrystalline diamond (SMD) is used 30 times more than natural diamond for two reasons: cost and supply.

In order to meet industry volume demands, artificial synthesis requires pressures exceeding 60 kilobars to emulate the production conditions of diamonds found in nature. First attempts to convert graphite to diamond at low temperature and high pressure were unsuccessful. The reaction speed was too slow for the process to be considered cost effective. To increase the reaction kinetics, higher temperatures were needed, which, in turn, required even higher pressures. The reason for this dilemma is due to the positive slope on the P vs. T phase diagram along the graphite/diamond stability line (see Figure 3). The transition conditions certainly influenced the evolution of the

Table 1: Nanodiamonds offer more pieces per carat.

	One Carat 100 nm Diamond	One Carat UDD diamond
Pieces per Carat	1.1×10^{14}	5×10^{17}
Equivalent pieces 3.0 micron diamond	44lbs	22 tons
30 micron diamond	22 tons	22,000 tons
Bermuda Beach Sand	5000tons	22,000,000tons

modern diamond press which has 50 years of refinements since its birth in the 1950's by GE. A general sketch is given in Figure 2.

Nickel catalysts are now used to lower the temperature to about 2000K and 60 kbar. Mechanically, presses differ slightly throughout the world, however, all SMD production will fall within the shaded region of the phase diagram (Figure 3). SMD production factories may have hundreds of presses since the reaction chamber is quite small. One synthesis may produce fewer than a hundred carats per run. The raw diamond then must be crushed, milled, cleaned, and graded.

SMD has a good material removal rate which increases with particle size distribution. Workpieces finished with SMD are the roughest compared to other forms of diamond outlined in this review since the edges are large in comparison to the total crystal size, sharp, and not friable. It is this toughness that enables micron and sub-micron SMD to retain some of the shape characteristics such as pyramids and trigons of the parent crystals after the crushing and milling process. The probability of diamond cleavage increases along defect lines or impurity regions. However, SMD is resistant to acids and hot caustic solution so the surface can be cleaned to very low impurity levels. Batch-to-batch quality from SMD suppliers is very consistent. The cost per carat of SMD is the lowest. Prices are currently 0.25-0.75 per carat depending on cleanliness and standard deviation.

The disadvantage to SMD is the inclusion of slivers (needle-like pieces) and plate structures (thin, flat pieces) in feed batches. Slivers or plates form when the 011 crystal plane cleaves during the crushing process (Figure 4). When the orientation of these elongated structures is perpendicular to the workpiece during finishing, sub-surface damage may occur from the excessive pressure at the point (Figure 5). Irregular finishing patterns and lower removal rates can also occur if a plate glides horizontally across the workpiece.

Reducing excessive slivers and plates from a SMD feed batch presents a considerable challenge to diamond suppliers. The reason is that the plates and slivers are hydrodynamically equivalent to smaller, more regularly shaped pieces. During elutriation, slivers gather momentum from the added frictional component and carry over into the graded batch. This phenomenon is similar to dropping two pieces of paper, one crumpled and one flat, from shoulder height to the ground. The crumpled paper will hit the ground faster since the frictional force of air "floats" the flat paper. Slivers and plates may be removed in milling if the energy selected is above the cracking energy of the thin pieces, and below the cleaving energy of regular-shaped pieces (Figure 6). The smaller fragments will then be removed in the grading process. Extra tight distributions add significant time and cost to SMD powders.

Polycrystalline Diamond

Polycrystalline diamond (SPD), unlike SMD, is produced via an explosive shock synthesis (Figure 7). Several tons of explosives are used to generate about 250 kilobars (equivalent to about 3 million psi) of pressure on the graphite feed. Each SPD piece contains smaller diamond "microcrystallites." The microcrystallite planes are oriented in different crystallographic directions every 10-50nm, regardless of the particle size distribution of the parent pieces. The hardness of an individual microcrystallite is comparable to that of SMD. The difference between SPD and SMD is discernable in SEM, however, transmission electron microscopy (tem) allows the operator to clearly see the microcrystallite structure (Figure 8).

SPD has a higher material removal rate (mrr) than SMD. Most studies show that the mrr is up to ten times that of SMD. The reason is that SPD has more cutting edges and higher surface area than SMD. Multiple edges and corners are in contact with the workpiece simultaneously, thus reducing the probability of sub-surface damage from excessive pressures (Figure 5).

The most obvious disadvantage is the sticker shock. SPD costs on average 10 times as much as SMD (2.10-8.00 per carat). However, dollar losses up front can be easily recovered by using less diamond in the finishing process, not to mention the labor savings for shorter mrr times.

In comparison to SMD, batch-to batch consistency is more challenging



Figure 1. Size comparison of Bermuda beach sand with Ultra Dispersed Diamond. One carat of UDD has as many pieces as the surface of a beach 550 miles long.

Schematic section through a typical belt type apparatus

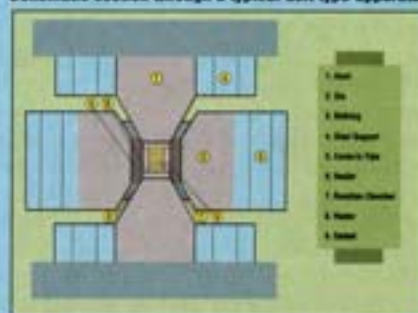


Figure 2. General features of a monocrystalline diamond press. Configurations differ slightly throughout the world, however, all SMD production falls within the shaded region of the carbon phase diagram in Figure 3.

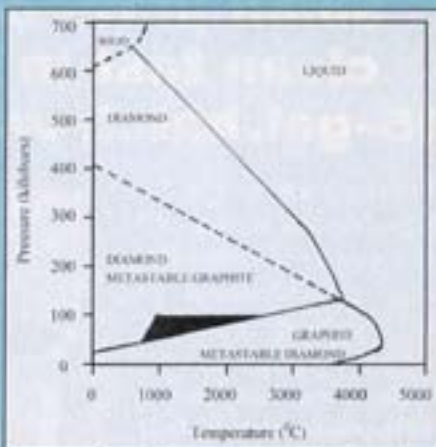


Figure 3. Phase diagram of carbon showing the shaded region of synthetic diamond production.



Figure 4. Sliver resulting from the cleavage of the 011 crystal plane of diamond.



Figure 5. Diamond-workpiece interactions during the lapping or polishing process. Synthetic Monocrystalline diamond slivers that interact perpendicularly with the surface can lead to sub-surface damage from excessive pressures at the point. If the direction is parallel to the workpiece, removal rate will decrease. Polycrystalline diamond of the same size as monocrystalline diamond will contact the workpiece with "microcrystallites" instead of flat planes or sharp points. The result is an increase in material removal rate compared to SMD. Heat treated monocrystalline diamond has excellent removal rate with less scratching since sharp points are lubricated with a graphite shell. Ultradispersed diamond is used for ultrafine finishes. There are no large irregularly shaped pieces present in UDD.

for SPD suppliers for two reasons. First, unlike SMD, the edge sharpness and crystallinity can vary with milling conditions. Under-milled material tends to produce a rougher surface with a relatively (in comparison to SPD), but far fewer than SMD) higher scratch rate. Over-milling dulls edges and lowers mrr. Secondly, impurity pieces of transitional carbon often reach unacceptable levels. The transitional carbon can be thought of as SDP oriented in one direction (Figure 9). The only drawback of transitional carbon is lower mrr. Transitional carbon can easily be spotted in the SEM, while TEM analysis is required to control and select batches with consistent edge definition.

Heat Treated Synthetic Monocrystalline Diamond

Heat treated synthetic monocrystalline diamond (HTSMD) is manufactured by heating well graded and cleaned SMD in an inert atmosphere to about 1,200°C. Under these conditions, the powder darkens from light grey to black (Figure 10). The color change represents a reorganization of the surface into a more disordered, graphite-like layer (Figure 11). The particle size distribution of HTSMD is often tighter than SMD and SPD since unwanted pieces on the fine end tend to fuse into larger clusters or disappear completely in the heat treating process.

The graphite sheets provide a lubricating region between a sharp diamond edge and the workpiece (Figure 5). This shell coating lowers the scratch and defect rate compared to SMD. Recall that slivers in SMD are very difficult to remove completely from a batch since they are hydrodynamically equivalent to well shaped pieces. Since the entire batch is engulfed in the high temperature oven, this process shapes and lubricates all slivers that would otherwise scratch or damage a surface. MRR is comparable to SPD, however, HTSPD has one distinct advantage over SPD, reduced diamond embedding in the workpiece. Customer feedback indicates that workpieces have up to 33% less embedding when using

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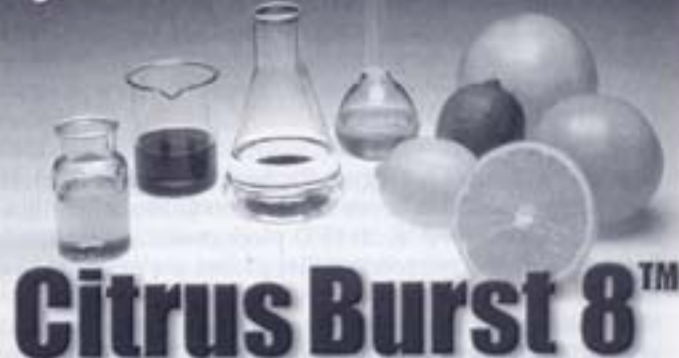
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Table 2. Comparison of the top indicators for choosing diamond for a lapping or polishing.

	SMD	HTSMD	SPD	UDD
Cost	lowest	Moderate to high	highest	Moderate
Removal Rate	good	Moderate to high	highest	Lowest
Scratch Rate	highest	low	low	Lowest
Workpiece Roughness	highest	Full range	Full range	Lowest
Dispersion	Disperses easily	challenging	Disperses easily	challenging

HTSMD compared to other diamond sources.

Great care must be taken when preparing dispersions of HTSMD. The heat treating process decreases the surface polarity resulting in a tighter stability region. In fact, the heat treated diamond must undergo a proprietary surfactant soak to add polarity to the surface, otherwise the material will settle clear in an aqueous environment in a matter of minutes. The cost is about 10% less than comparable SPD, but the benefits, once again, more than compensate for the price.

Ultradispersed Diamond

Ultradispersed diamond (UDD) is produced in the diamond stability region at $T > 3000K$ and $p > 00\text{kilobar}$. However, there is one critical process difference that distinguishes UDD from other diamond types.

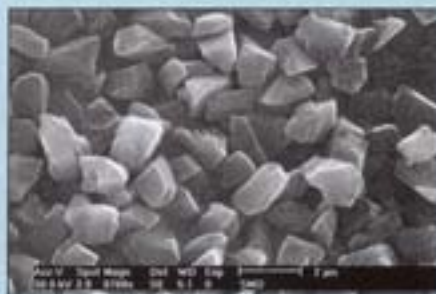


Figure 6. SEM of milled monocrystalline diamond with a reduced sliver concentration.

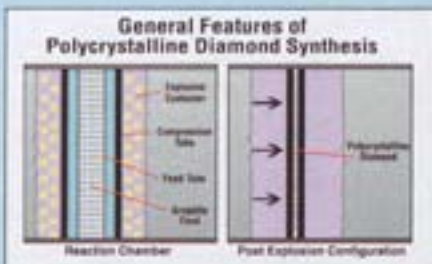


Figure 7. General features of polycrystalline diamond synthesis. The transition occurs via an explosive compaction process.

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