Double-Sided Lapping:

Polishing Optical Materials

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Double-sided lapping and polishing utilizes planetary action with the combination of a top and bottom plate to precisely grind and polish precision, parallel optics.

Double-sided processing is a slow, batch-type method which uses planetary action — generally with loose abrasive particles suspended in a liquid vehicle — to abrade material almost equally from both faces of the material (Figure 1). Because of the nature of the process, it is relatively stress-free in that it induces minimal thermal distortion.

In theory, the process requires a minimum of three parts. The actual number is determined by part quantity, part size and machine size. However, new double-sided lapping (DSL) machinery can process a single part at a time.

With DSL, the optical components are held in geared carriers that are driven in a planetary motion covering the full surface of the lapping plates and are subject to continually changing direction of rotation. They are processed between an upper and lower plate that, depending on machine design, can either rotate in the same direction or opposite directions, or remain stationary. The workpiece and plates slide over one another on loosely applied slurry of abrasive particles in a liquid vehicle delivered through the top plate (Figure 2).

The slurry performs the stock removal through the action of the abrasive grains as they roll and slide between the two plates and the workpiece. The size of the abrasive particle, along with the addition of polishing pads, determines the stock removal rates as well as the surface finish. Lapping and polishing slurries can be recycled depending on cost and process performance.

Sequential removal

Each step removes the subsurface damage incurred during the previous process and prepares the parts for parallelism, surface roughness and thickness for the next process. By the completion of the process, the workpiece becomes a mirror image of the lapping plate. Ideally the plates should match in that one is slightly concave and the other equally convex.

DSL machines differ in size and available options (Figure 3). They are manufactured with plates as small as 100 mm (~4 in.) in diameter up to standard sizes around 1320 mm (52 in.), and custom machines are available with even larger plates. Equipment generally runs with five carriers, with less or more possible. Table 1 shows equipment capacity and price variations based on part size vs. machine size. Regularly manufactured DSL equipment costs range from $12,000 to about $350,000, though larger, custom machines can cost more than $1 milllion. Some machines have only carrier rotation (one way) while others have lower, upper plate rotations with the carriers able to rotate independently based on the inside diameter (ID) and outside diameter (OD) gear rotations (four way). Machine pricing also depends on additional options such as automatic machine loading and unloading, automatic thickness control, controllable slurry/rinse delivery systems, custom plate materials and configurations, in-process lap plate conditioning, retractable ring gear and water-cooled machining plates, to name just a few.

Most basic variables, aside from optical material, involve part geometry and size. Parts can be square, rectangular, trapezoidal, round, elliptical or polygonal. Round parts process better because they can rotate around their own axis. Also, thickness limitations are lower with round parts.

Parts can be processed using DSL from 0.025 mm (0.001 in.) in thickness up to the limitations of the specific machine with a general consensus

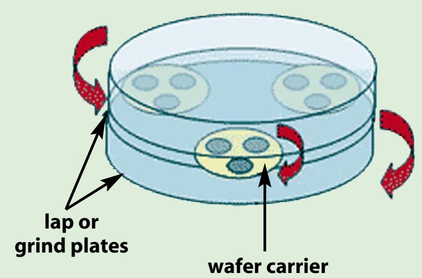

Figure 1. *Planetary action in double-sided processing.*

TABLE 1.
MACHINE CAPACITY

Part Diameter (mm)	Small Machine 410 mm Diameter Plates	Medium Machine 790 mm Diameter Plates	Large Machine 1320 mm Diameter Plates
25.0	40	260	505
38.0	25	125	350
50.0	15	85	205
75.0	1	35	95
100.0	1	20	50
150.0	0	5	25
200.0	0	5	2
300.0	0	0	1

APPROXIMATE COST/PART COMPARISON — BASED ON A 3 HOUR PROCESS CYCLE

Part Diameter (mm)	Small Machine $65/hr	Medium Machine $100/hr	Large Machine $150/hr
25.0	$4.88	$1.15	$0.89
38.0	$7.80	$2.40	$1.29
50.0	$13.00	$3.53	$2.20
75.0	$195.00	$8.57	$4.74
100.0	n/a	$15.00	$9.00
150.0	n/a	$60.00	$18.00
200.0	n/a	$60.00	$225.00
300.0	n/a	n/a	$450.00

of about 100 mm (3.937 in.). With thinner parts, the limiting factor is the ratio of the part's largest dimension (diameter or diagonal) to the thickness. The higher the aspect ratio, the higher the probability that the glass will distort or become damaged during processing. Pricing increases for parts with higher ratios (Table 2).

Just as there are specialists within each optical manufacturing discipline, there are specialists within DSL processing. There is some overlap between the various machines, capabilities and vendor experience. Some specialists have more experience with thinner, smaller optics while others favor medium to larger parts. Some vendors are more successful at transmitted wavefront and parallelism while others add surface flatness to this list. The variability in DSL vendors also extends to different materials as well as the diversity of available quality ranging from commercial to precision.

Different materials present different stock removal rates along with other concerns for achieving the required specifications. The importance of surface and thickness preparation prior to DSL operations is related to the expected finished product. It is best to start with all parts within the batch at under 0.1 mm (0.004 in.) in thickness variation.

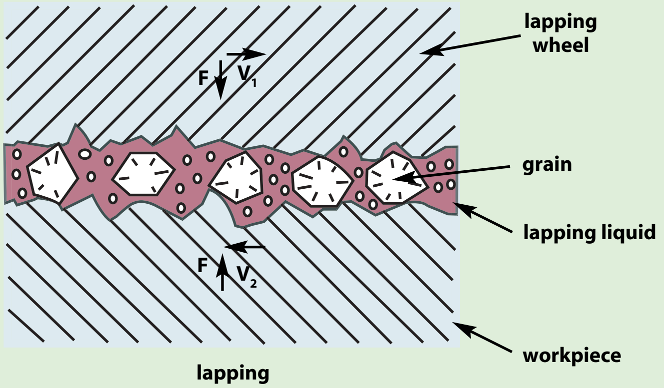

Figure 2. *A cross section view of abrasive particles in a liquid vehicle.*

The major variables in the process design that are controlled by the machine are plate rotation (presence of rotation along with the direction and speed of rotation), force and time. DSL machines have sophisticated computer-controlled systems with a variety of programmable process variables that can be set for repeated use in the future as well as cloning and modifying for other programs. They enable a smoother process and minimize the risk of crash by allowing the force and speed to be ramped up and down slowly. By using load cells, the top plate weight or downforce can be adjusted and maintained to provide a precise application of force onto the parts.

What's available

Process design determines the limitations of the equipment in regards to the number of planetary actions provided. Available are two-way planetary motion, usually on smaller machines that allow the carriers to rotate around their own axis as well as around the axis of the plate. With three-way planetary action, the bottom plate may be fixed in a nonrotating position with the carriers orbiting the sun (center) gear and the addition of the top plate rotating around its axis. With four-way planetary motion, there is independent rotation of the upper and lower plates along with the sun (ID) and ring (OD) gears.

Some DSL vendors prefer four-way planetary action because the more variables they can control, the better they are able to equalize material removal rates from both sides of the workpiece. Others prefer fewer variables and simplicity in process design. Each user must also consider the proper variables to help maintain plate/pad flatness for optimal running conditions.

The performance of the process consumables are as important as the performance of the machine-controlled process variables. The carrier (workpiece holder) design is one of the most important. This can range from simple to complex, utilizing corner reliefs, additional holes for slurry and sacrificial glass (outriggers) based on the required specifications.

Specifications for size and location of the clear aperture, surface flatness, transmitted wavefront and parallelism requirements can lead to complex designs. Parts that require more precise specifications are generally placed closer to the center of the carrier without overlapping it, so they do not extend out past the edge of the polishing pad. Some DSL vendors make carriers for grinding that overlap the plate's edge while their polishing carriers do not. Most vendors offering DSL services use similar rules when designing carriers with minor changes. Some companies that specialize in precision use very strict rules, such as only using an odd number of cavities for parts and always using an odd number of carriers per run. Commercial optics companies use the rule that more parts equal higher yields equal lowest piece prices.

An additional advantage to processing parts using DSL is that carriers can be designed to run several different parts together if they have the same finish thickness. Although carriers are usually a specified fraction of the part's finish thickness, there is some flexibility in the guideline, allowing their use with parts of the same shape and different thickness. This eliminates unnecessary tooling costs in most instances.

When projects require quick delivery, parts can sometimes be run in existing tooling with minor alterations, allowing the tools to be multi-functional. An example of using this emergency guideline would be to run 100-mm-diameter parts in carriers with workpiece holes of 100 mm square, given sufficient thickness of the parts and carriers for reasons of strength and integrity.

Standard carrier materials used in optics manufacturing include spring steel (ideal for thin work), Lamitex (ideal for thicker parts), PVC (for processing relatively thick parts) and Lexan (for scratch-free polishing). There are also custom carriers that have an insert feature such as PVC lining to protect the edge profile of a wafer while providing the strength and durability of a traditional steel carrier. This type of carrier is commonly used for processing glass wafers. Although most vendors offering DSL services purchase their carriers, few design and make their own.

A range of prices

Carriers are considered consumable tooling with a finite lifetime. The price for a set of carriers can range from under $100 per set for a small machine to more than $1,500 per set for a large machine, depending on the number and shape of the workpiece holes, carrier material and thickness and other features.

Another major variable in the performance of the DSL process is the proper combination of consumables. In lapping, one has the option of choosing plate serrations and plate materials. The majority of DSL fabrication firms grind with high-density cast iron lap plates with a cross-hatch of serrations to evenly distribute the slurry. The waffle pattern helps release the suction bond between the top plate and the parts when the cycle is complete. Few applications require the use of glass lap plates, which are quite convenient because of their ease in correcting plate flatness. The lapping plate is monitored using a flatness gauge consisting of a straight line spherometer indicating deviation from the ideal plane.

TABLE 2.
SIZE VS. MINIMUM THICKNESS GUIDELINE

Diameter (mm)	Minimum Thickness (mm)
12.5	0.030
25.0	0.050
50.0	0.100
75.0	0.150
100.0	0.250
150.0	0.375
200.0	0.500
300.0	0.750

The most widely used abrasive for lapping is aluminum oxide (Al_2O_3). Other materials such as garnet, silicon carbide (SiC) and boron carbide (B_4C) are also used depending on costs and the optical materials being processed. Using them involves mixing the abrasive particles with a liquid vehicle and a suspension agent that evenly distributes the abrasive over the lap plate and reduces settling, thereby aiding in the recycling of the slurry. Additional factors that affect performance are slurry concentration, Baume and pH.

Diamond pellets are used infrequently because the pellets might loosen during processing. The introduction of a slurry-free, fixed diamond abrasive product manufactured by 3M — Trizact diamond tile (Figure 4) — has offered a solution to this problem. These fixed abrasive pads are applied to the lap plates via pressure-sensitive

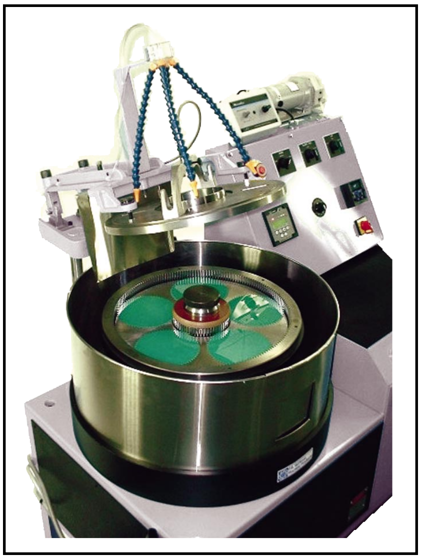

Figure 3. *PR-1 double-sided lapping machine. Courtesy of PR Hoffman.*

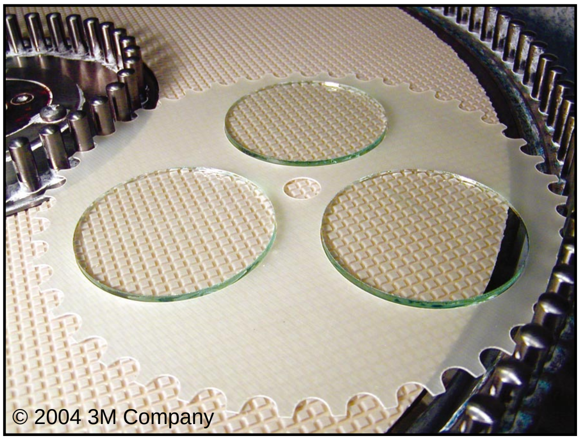

Figure 4. *3M Trizact diamond tile pad. Courtesy of 3M.*

adhesive and are used with water-based, mineral-free grinding coolants. They are material-specific and have different abrasive sizes for different materials. They also produce a lapped surface with greatly improved surface finish and reduced subsurface damage, substantially shortening polish time. Another advantage is that the abrasive pads prevent the lap plates from being consumed, which results in further savings.

With polishing, either cast iron, stainless steel or glass lap plates are used in conjunction with polishing pads. Polishing pads, primarily polyurethane-based with additives, vary in that each provides different polishing performance on various materials when combined with different polishing slurries. The combinations of polishing pads and slurries are made with guidance from suppliers, personal experience and the experience of fellow optics companies. For the most part, they vary in compressibility, method of adhesion and patterns of grooving and embossing. Polishing compounds are primarily aluminum, cerium and zirconia oxides along with colloidal alumina and silica. The use of diamond as a loose abrasive for DSL polishing is also common with crystalline optical materials.

Conditioning the polishing pad is important for maintaining consistent performance. This can be accomplished by using either one or a combination of hand brushes, brush carriers or bonded-abrasive, diamond rings. All perform the function of removing embedded materials that are glazed onto the surface of the polishing pads. They are used frequently, usually a couple of times a day, depending on the point in the pad's useful life and the polishing pad/polishing slurry combination.

Benefits

Although DSL utilizes slower stock removal rates, it is quite fast in relation to conventional or pitch polishing techniques. Combined cycle times of lapping and polishing generally start around 2.5 hours and can extend to over 10 hours based on part size, quantity of parts, thickness and required stock removals at each production step. Within this timeframe, it achieves exceptional transmitted wavefront and parallelism while providing a first-rate surface finish. The process itself is relatively stress-free and suitable for most optical materials. An additional advantage is that size control is consistent over small to large batch sizes. Finish thickness of parts can be controlled to better than ±0.001 mm based on proper selection of the process variables.

As a function of the plate flatness and the process design, the parts generally have fractional wave transmitted wavefront and can achieve typical specifications of better than $^{1}/_{20}$ wave on smaller parts and better than $^{1}/_{4}$ wave on larger parts. Although surface flatness does not match the exceptional results of transmitted wavefront, it commonly falls within a range of several waves down to a fraction of a wave over the entire clear aperture. The DSL process also yields superior parallelism with typical results under 30 arc seconds with designed results in the subsecond arena. Another by-product of this process' slow and controllable stock removal rate is size control and total thickness variation that is consistent over small or large batches. As for surface quality, scratch-dig specifications can be better than 20-10 with surface roughness in a range between 3 and 20 Å primarily based on the pad/slurry combination.

The same machine can accommodate a variety of part sizes and thickness with a quick change in tooling. From the end of the current run, the following run of parts can start processing in under 10 minutes based on the quantity of parts to be unloaded and loaded onto the machine. The tooling change takes place in under one minute.

Overall part size and weight limitations are dependant on machine size. The smallest machines are able to run parts as small as 3 mm in diameter with the larger, custom machines able to run parts in excess of 1000 mm in diameter/diagonal with weights exceeding 25 kg (55 lbs).

DSL process can manufacture parts that are either transmissive or reflective in function with the most popular being filters, plate beamsplitters, wafers and windows.

The fabrication of wafers from the semiconductor industry has been transferred to the production of glass wafers for the ever-increasing need of substrates for diffractive optics, MEMS, circuit and display industries. The precision of the process also yields very high precision optics such as debris shields for high-power laser applications (Figure 4).

For optical-quality mirrors, it is cost efficient in that one can process large quantities while achieving the desired results. Optical materials such as ULE and Zerodur are also processed using DSL.

Materials processed with DSL can be used in applications from the UV to the IR. Although DSL process can be used for a large variety of materials, the majority of products manufactured are usually made out of a small handful of materials such as B270, BK7, Borofloat, calcium fluoride, filter glasses, fused quartz, fused silica, germanium, magnesium fluoride, Pyrex, sapphire, silicon, soda lime, ULE, Zerodur, zinc selenide and zinc sulfide. ☐

Acknowledgement

The author wishes to than the following for their assistance with this article: PR Hoffman, SML Products, Salem Distribution, Speedfam, 3M and Universal Photonics.