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Automated Optical Assembly

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ABSTRACT

Automation and polymer science represent fundamental new technologies which can be directed toward realizing the goal of establishing a domestic, world-class, commercial optics business. Use of innovative optical designs using precision polymer optics will enable the U.S. to play a vital role in the next generation of commercial optical products. The increased cost savings inherent in the utilization of optical-grade polymers outweighs almost every advantage of using glass for high volume situations. Optical designers must gain experience with combined refractive/diffractive designs and broaden their knowledge base regarding polymer technology beyond a cursory intellectual exercise. Implementation of a fully-automated assembly system, combined with utilization of polymer optics, constitutes the type of integrated manufacturing process which will enable the U.S. to successfully compete with the low-cost labor employed in the Far East, as well as to produce an equivalent product.

Key Words: Rosettes, Inserts, Flange, Degating, Runner, Shot Size, Auto-degater, MTF Tester, Pick & Place, Steel Safe, Flash, Radius Scope.

1. INTRODUCTION

The U.S. technical lens market has been primarily supported by government military spending driven by the Cold War. This market, unconcerned with cost, funded the development of complex hardware and software systems for lens element design and fabrication which brought modern reconnaissance, night vision, target designation systems, and other spectacular products to the battlefield.

Under this protective umbrella, our competitors utilized these same technologies to develop and manufacture commercial optical products which have captured consumer markets. These products include: camcorders; reflex cameras; copiers, compact disc players, etc. Sophisticated competitors continue to capitalize on the abundance of cheap labor in Pacific Rim and other emerging nations to manufacture glass and polymer lens element systems at very low costs.

If the U.S. is to establish a dominant position in commercial optics, a new direction is essential. The same commitment made by the public and private sectors to technical superiority during the Cold War is necessary now if domestic superiority in this emerging marketplace is to be restored.. This commitment will require major investments of time, energy and finances in order to re-prioritize our technologies to achieve this objective.

Automation and polymer science represent fundamental technologies which can be directed toward realizing the goal of establishing a domestic, world-class, commercial optics business. Such a combination

of polymer material utilization with automation manufacture technology requires re-assessment of traditional optical design concepts. This reassessment must be integrated with the manufacturing and assembly processes discussed in this paper: Optical Design; Tooling; Molding; Degating; Lens Testing; Anti-reflection Coating; Automated Optical Assembly; Facilities Requirements; and Functional Testing.

2. OPTICAL DESIGN

The modern optical lens designer can access a vast array of computational tools which offer complete and varied analytical modeling capability. These software programs most commonly used include: CODE V; OSLO; SIGMA; OPTEC; ASAP; and ZEMAX. This software contains a library of data and specifications on a wide array of materials in polymers and glass. It can also mathematically evaluate the performance of selected materials for a given design. Such data accessibility for numerous speciality glasses and optical-grade polymers with both high and low refractive indices enables the designer to analyze unbelievably complex optical systems within a very short time.

This impressive design capability has focused, almost exclusively, on the creation of military products. Currently, glass is the primary material for construction of visual systems, although more exotic materials have been used in the infra-red spectrum. With the exception of escalating costs, glass lens manufacturing has not changed significantly over the years. To date, the cost factor has always been considered secondary to operational performance--the primary objective in the military environment. The limited array of optical-grade polymer materials available with high and low refractive indices, combined with the problems of thermal expansion, represent but some of the difficulties encountered when designing with polymers. Polymers have also been avoided because of the high cost and lengthy delays in acquiring tooling. Simply put, polymer tooling is too complex and too expensive; and, therefore, has been considered unnecessary for the limited production needs of militarized systems.

Designing with polymer lens materials is made even more complex because of the limited number of optical- grade materials, each with unique design limitations, available to designers. Only four optical-grade polymers are currently available: acrylic; polycarbonate, polystyrene and polyolefin. Although other thermoset materials exist; they require long processing times and have high shrinkage which make them impractical for precision optics. Currently available polymer materials are further limited by their narrow range of refractive indices, a quality which has seriously hampered their usefulness in imaging applications.

Ideally, the optimum polymer lens element designed for automation will be free of all cemented components. Although index-matching cements and equipment are available, they must be highly controlled to prevent voids, bubbles, de-lamination and excessive cement. Unlike glass, improperly cemented lenses cannot be reworked. In addition, UV inhibitors must be eliminated from the resin if an Ultra-Violet method of curing is to be used. Elimination of the cementing process avoids numerous practical problems that can reduce manufacturing yields.

As a consequence, optical scientists have gained little actual experience with the tooling, molding and coating limitations unique to polymer design. *However, polymers will play a vital role in the next generation of commercial optical products. The increased cost savings inherent in their use outweighs almost every advantage of using glass in high volume situations.* With polymers, flanges and spacers can be molded as an integral part of a lens element, a practical advantage which cannot be achieved with glass.

Such molded flanges and spacers can significantly facilitate the automated assembly process by providing a convenient method to hold lens elements throughout each phase of manufacture and unit fabrication.

To successfully utilize polymer lens elements, optical designers must gain experience and broaden their knowledge base regarding polymer technology beyond a cursory intellectual exercise. New optical design concepts which combine refraction and diffraction within a single lens element can extend the performance of existing polymers far beyond classic refractive-only designs.

3. TOOLING

High volume production of polymer lens elements can achieve maximum efficiency by using multi-cavity injection molding tools. To illustrate, an eight-cavity mold with a sixty second cycle time will yield 640 lenses per hour. This technology is as precise as it is fast. Such lenses can be molded with half a fringe of surface irregularity in elements less than a half an inch in diameter.

Molding tools are constructed from special grades of steel that are free of all voids and pits. The steel is machined into matching halves, along with the flange, runner and gate, which are created as integral parts of the mold base. The "runner" is the material which connects each lens with the core of molten material. The "gate" portion of the mold is located at the interface of the flange and runner.

Optical surfaces within the mold cavity are called "inserts." These are machined independently of the mold base. Inserts for polymer lens elements are ground, polished, and measured in the same manner as for glass lens elements. The grinding and polishing compounds, however, are those specified for metal. These inserts are then assembled into the mold base. Precision interlocks built into the mold base insure alignment and centration of each half of the lens with the other.

Matching "polishing carriers" and "polishing laps" are machined simultaneously with the inserts. The carriers are extensions of the design-specified curves and protect the inserts' edges from being "turned down" while the inserts are surfaced. The laps are machined to match the inserts' curves, and are used with abrasive compounds to grind and polish the inserts to the correct curve and finish. The mold dimensions from the core to the extremities of each cavity must be totally, measurably, consistent.

Optical molds are designed in the form of "rosettes," the individual lenses being evenly spaced around a rosette's circumference. The "runner system" forms from the core of the mold to the gate. The thickness of the runner is roughly equal to the diameter of a specified lens element, and approximately four to five times longer than its diameter. The gate necks down to create a restriction for the runner as it enters the lens cavity in order to control the flow of material into the cavity. Specifics vary considerably with different parts and materials. Attention must be given to the smallest detail if multi-cavity molds are to consistently produce identical parts, cavity to cavity.

4. INJECTION MOLDING

Once the tool is fabricated and installed into an injection molding machine and an appropriate polymer material has been selected, a lens element is ready to be molded. Raw material (resin pellets) must be completely dried before being fed into the barrel of the machine through a hopper/drier. An injection screw,

located inside the barrel, rotates to generate the heat and pressure necessary to melt the resin and to inject it into the mold. The amount of resin in the barrel is the "shot size." Heating bands introduce heat in a controlled manner along the length of the barrel and assist in keeping the resin molten. This process melts the polymer and forces it into the core of the runner system. The runner carries the molten plastic through individual gates into each lens cavity. The molten material then polymerizes within the cavity into a lens. Initially, the mold is run until each cavity is completely filled, leaving no voids or inclusions. This requires that machine operating temperatures and pressures achieve equilibrium; and that the mold temperature control unit reaches a stable condition. Precise machine size is critical; and is a function of the clamping force required to hold the mold closed against injection pressure, and of the shot size of the polymer material. Shot size is specified in ounces; machine size, in tonnage.

It is necessary to determine appropriate shot size, because if too much material is present it may cause it to burn inside the barrel and attach to the screw. The burnt material will cause black specks to be randomly injected into the mold. The screw and barrel must then be removed from the molding machine and thoroughly cleaned before molding can be resumed. Prevention of such randomly-sized and located black specks is one of the most serious problems encountered in the manufacture of polymer lens elements.

Optical molds are designed to eject the lens elements by having the inserts push each element out of the mold cavity. Ejector pins assist in this process by pushing on the runner system to prevent sticking. In a complex system with multiple lens cavities, the ejector system must remove the complete rosette without distorting the lens elements. Proper ejection is critical to preventing the hot, polymerized elements from becoming distorted while being pushed out of the mold. This distorts the lens radius, and is called the "potato chip" effect because the lens curls up like a potato chip.

Generally, optical molds have machined and polished flange cavities which act as spacing elements. During processing, lens thickness can be adjusted with mold spacers. This adjustment is made when molding conditions are established as part of the mold qualification process. Flange thickness is a control dimension, and must be qualified along with the lens element.

At this point, the machine is cycled to produce lens elements which are tested on a "radius scope" -- a microscope designed to optically measure radii. Process conditions for the mold, the molding machine and the molding material are run repeatedly until manufacture of a consistent part is established. Mold temperatures, machine temperatures, pressures and injection speeds are varied until the radius falls within design specifications and tolerances.

Once the proper radii and other physical parameters are achieved, a lens element is then evaluated with an interferometer which certifies the radii, surface finish and overall curvature. In addition, the lens diameter, including flange, is measured, as are lens thickness, decentration and wedge. Molding stress is measured with cross-polarizers in order to determine the amount of bi-refringence present in the lens.

All cavities are certified in a similar manner until the mold is fully qualified to all design specifications and tolerances. In some cases, imbalances in the mold, gate, vents or runner system can prevent the mold from meeting design objectives and must be reworked. As this re-work may require several iterations, it is important to make the mold "steel safe," particularly with regard to lens diameter. "Steel safe" means that a

molded part is smaller than the specified tolerance. If an adjustment is to be made, excess steel is removed from the mold. An over-sized part frequently requires that additional steel be added to the mold or insert by welding. If this is necessary, the part must then be re-machined. When this becomes necessary, there is always concern that the mold may become distorted from heat generated by the welding process. If the mold id designed to be steel safe, this situation can be avoided.

Modern molding machines are very repeatable. Once the specified conditions have been established, the parts produced will be consistent time after time.

5. DEGATING

As previously stated, the area on the flange through which the polymer is fed into the insert is termed the "gate." Lens elements that are to be tested, assembled or coated must first be removed from the runner system one at a time, placed into a fixture, and held in place. This process of separating individual lens elements from the runner system is called "degating." The degating machine places lenses in the fixture at fixed addressable locations, with identical orientation, in order to be consistent with subsequent manufacturing steps.

A preferred method of degating involves automating this process with an "auto-degater"--a machine which systematically dis-assembles the lens elements from the rosette, and which combines automated degating with automated "pick-and-place" activities. The auto-degater uses a fine-cut saw to remove the lens from the rosette, then indexes to a milling cutter to smoothly remove any vestige from the gate area. The automated "pick and place" station then removes each element from a cutting anvil and places it into a fixture at a known addressable X-Y position on the fixture. A new element is then indexed into place with each cycle of the degating operation. Other degating methods utilize air driven diagonal cutters and ultra-sonics for gate removal. However, these methods can generate too much heat, leave vestiges, or are too imprecise for the task.

Most cutting processes generate enough heat to melt polymers. A fine-cutting saw or milling machine cutter can generate sufficient heat to cause the flange edge to distort or "turn up." Should this occur, flange thickness would no longer be uniform and could cause wedge during assembly. Therefore, the auto-degater must establish an appropriate cutting rate, and be supplemented with coolant to prevent heat distortion during the process. The flange thickness is critical; and consistency must be maintained around its entire circumference. All plastic remnants from degating and molding which might create a binding point during assembly must be eliminated. In addition, "flash"-- excess material forced outside individual lens cavities by improper or worn molds that fail to properly close or which are pushed open by high pressure --cannot be tolerated.

6. LENS TESTING

All precise optical systems require that individual lens elements be tested for radii compliance and surface finish if acceptable yields are to be achieved. An interferometer is normally used to qualify lenses for both specifications, generally through systematic testing on a statistical basis. The use of this instrument is vital to qualification of the mold inserts. Molded lenses are only as precise as the inserts from which they come. It is, therefore, standard practice to compare the quality of the insert with the quality of the lens. This

evaluation is considered sufficient if tolerance parameters fall within the scope of the insert and molding process. Many optical systems require that only a few lenses receive 100% testing. A designer's knowledge of the processing tolerances for tooling and injection molding processes is critical to limiting the number of lens elements which must be fully tested.

A new variation of interferometer has been developed for optical applications that require 100% testing. This instrument can be computer-interfaced with automatic "pick and place" machines that permit lenses to be mounted and tested prior to coating or assembly. A "pick and place" machine removes an individual lens from the holding fixture; places it into the interferometer; initiates a measurement; and processes the data. Rejects, obviously, are removed. This automated screening capability can significantly increase product yield by permitting only good lenses to progress through the entire process. Specialized software can extend the interferometer's capabilities by enabling it to monitor the molding process and, thus, to identify mold cavities which are out of tolerance and no longer producing satisfactory lenses.

7. ANTI-REFLECTION COATINGS

Surface reflections accumulate with the number of air/lens interfaces. For complex, multi-lens optical systems, as the number of lens elements is increased, substantial transmission loss can derive from multiple surface reflections. As noted above, cementing lenses is discouraged for automation purposes. However, doing so necessarily creates more air/lens interfaces with subsequent transmission loss. To prevent such loss, efficient anti-reflection (AR) lens coatings must be applied to multi-lens imaging systems.

AR coatings are applied in a "vacuum" coating machine--a large chamber in which a vacuum is created. Such machines utilize an electron beam gun to evaporate specialized coating material contained in a crucible. The electron beam releases molecules from a source material at energy levels that create a bond with the lenses placed and rotated at the top of the chamber.

The application of AR coatings to polymer lens elements requires greater attention to individual coating thermal characteristics than when these same coatings are applied to glass. Materials that bond to glass may not adhere when applied to plastic. For example, magnesium fluoride requires that the substrate be heated to a temperature that softens most polymers (TG--the glass transition temperature). When applied at low temperatures, magnesium fluoride lacks adequate adhesion for many polymer applications. However, vacuum-deposited, AR coatings must be applied to polymer elements at much lower temperatures than when applied to glass equivalents. Thus, more complex, multi-layer AR coatings than magnesium flouride are necessary for both adhesion and performance for imaging optics with polymer lens elements. Coating application requires constant monitoring of temperature, layer thickness, and distribution of the bonded material over the full deposition range within the coating chamber. Care must also be taken to insure that the lenses are not shadowed by the holding fixture, as this may cause uneven distribution of evaporant over the lens surface.

The out-gassing of impurities and/or additives contained within polymer resins frequently creates a "surface haze" which can generate significant problems in multi-element systems. With elapsed time and moisture, such impurities can migrate to the lens surface, causing development of haze. Accumulated surface haze can result in substantial transmission loss. Although difficult to identify in low resolution systems or in

individual lens elements, such loss is cumulative with each additional lens, and can critically, and negatively impact, higher quality, multi-lens imaging systems.

Surface haze can be removed by cleaning lens elements prior to coating. An automated ultra-sonic cleaning line using de-ionized water, similar to those used in semi-conductor cleaning processes, can adequately remove such impurities. Care must be taken, however, to remove all water from both the lens elements and the holding fixture prior to coating. Failure to do so may cause water spotting during the coating process. In addition, such excess moisture will extend the time required to pump the vacuum. Therefore, the coating fixture must be designed to hold the lenses for cleaning; to prevent shadowing during coating; to prevent trapping of any water; and to have fixed locations for automation.

8. AUTOMATED OPTICAL ASSEMBLY

Lens elements which have been molded, degated, tested, cleaned and coated must be installed individually in order to fabricate a complete assembly. Optical assembly automation requires specialized equipment to "pick and place" each element from its coating fixture, and to place it correctly into a lens tube.

Component handling is simplified by not having thick, heavy elements. Lenses are picked up by the flange with vacuum pickers and placed into the lens tube. The assembly sequence is programmed to select from an array of lenses and spacers. It gently places each lens into the assembly tube in the proper sequence, pushing it with a programmed, controlled motion. The "flange pick-up" method prevents touching and marring of the coated surface. Automatic "pick-and-place" can also install spacers and aperture stops into the assembly. It should be noted that pushing longer spacers into the assembly tube requires a different programming sequence to control the motion which inserts the spacers. Again, flanges provide an area on which to exert pressure without damaging the individual components.

A fully automated assembly system typically consists of a gantry with vacuum picker; an X-Y Stage with addressable lens positions; and vertical tube holders linked together by a computer controller. A common fixture used to hold individual lens elements throughout the entire assembly process eliminates manual handling of individual components. *Implementation of this precise, automated system constitutes the type of integrated manufacturing process which can compete with the low cost labor used in the Far East as well as to produce an equivalent product.*

9. FUNCTIONAL TESTING

Modern test equipment enables comprehensive evaluation of all aspects of a fully assembled optical device Such testing guarantees specified product performance prior to shipment. Automatic MTF (Modulation Transfer Function) testers maybe used to measure the "on" and "off' axis resolution of a given optical system. MTF testers can effectively determine whether an individual lens element fails to meet specification requirements; whether an element is incorrectly placed, i.e. reversed; or whether it contains an incorrect component. In addition, such testers can auto-focus, measure for distortion and color, and transmission. A "Go-No-Go" tester will complete all the necessary tests within a few seconds, including storage of an individual unit's history. This last feature can be extremely useful in monitoring for unit/system performance; in tracking for specific problems; and for regulatory purposes.

10. FACILITIES REQUIREMENTS

The "manufacturing cell" described in this paper requires that all equipment and personnel be located in "clean room" conditions, with appropriate environmental controls for air quality, temperature and humidity. This is because the suspended particulate found in uncontrolled air flow is a major source of contamination which must be eliminated. In addition to "clean room" surroundings,, de-ionized water must be used for cleaning if water spots on the lens elements are to be prevented. If the twin goals of production efficiency and high yield are to be achieved, the establishment and maintenance of such conditions is essential. i

For this system to achieve maximum effectiveness, all operators and technicians must wear smocks, hair protectors, shoe covers, and gloves. Such precautions prevent dust and dirt from being carried into the production environment. Because polymers are immensely sensitive to moisture contamination, de-humidification is also necessary. Hepa filters for major pieces of equipment such as the interferometer and assembly machines are also essential to remove suspended dust and dirt. Additionally, in order to protect work-in-progress not only from moisture, but also from dust and suspended particulate, unfinished components should be stored in "dry boxes" while waiting to be assembled into completed units.

11. SUMMARY

This level of automation is both complex and expensive. However, it offers the opportunity to manufacture optical-quality, polymer imaging systems at a fraction of the cost of those produced in the Far East using glass fabrication methods. *A `domestically molded polymer lens element from a multi-cavity mold, when compared to an equivalent glass element system manufactured in China, generates a ten to one cost advantage for the molded lens.* Such technology, beginning with the utilization of new refractive/diffractive design concepts and carried through all phases of automation system assembly, offers the greatest opportunity to compete in the commercial world market for high quality optical products.

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