Invited Paper

Manufacturing Plastic Injection Optical Molds

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ABSTRACT

ABCO Tool & Die, Inc. is a mold manufacturer specializing in the manufacturing of plastic injection molds for molded optical parts. The purpose of this presentation is to explain the concepts and procedures required to build a mold that produces precision optical parts. Optical molds can produce a variety of molded parts ranging from safety eyewear to sophisticated military lens parts, which must meet precise optical specifications. The manufacturing of these molds begins with the design engineering of precision optical components. The mold design and the related optical inserts are determined based upon the specific optical criteria and optical surface geometry. The mold manufacturing techniques will be based upon the optical surface geometry requirements and specific details. Manufacturing processes used will be specific to prescribed geometrical surface requirements of the molded part. The combined efforts result in a robust optical mold which can produce molded parts that meet the most precise optical specifications.

Keywords: Lens mold, molded optical parts, optical molds, optical inserts, optically polish, polish holders, lapping and polishing

1. INTRODUCTION

ABCO Tool & Die is a custom mold manufacturer specializing in optical molds. We work with injection molders and end users to manufacture their products. We do not claim to be optical engineers or designers; we build molds for optical purposes that are based upon the optical designs of others. Those designs can be as simple as a plano lens or as complex as an aspheric lens. Achieving success and producing a good optical product ultimately requires considerable expertise, which we have because of our many years of experience.

Building an optical mold is based upon the premise that the mold being built has a proper optical design that would produce a good product. If the optical design were done incorrectly, no matter how we produce the mold, the parts may still not be acceptable. It is important for the mold builder to have an understanding of the optical design so that appropriate decisions regarding specifics like insert design, gate location, ejector locations, flow marks, engravings, etc. can be made.

2. GENERAL PART DESIGN

Like any part to be molded, a well thought out design is key to successful molding. Part design information supplied by the customer should include a CAD model and a control drawing, which indicate requirements for optical specification and surface quality. These items will guide us in the design and manufacture of the mold. For example, if the part had stringent optical requirements, it may be necessary that we use diamond turning as opposed to a straight lap and polish application as a means to achieve the desired optical result.

2.1 Optical part design

2.1.1 Geometric shape

The end use of the product will have to be considered during the design phase. For example, a face shield needs to fit the face form, a pair of safety glasses needs to provide good coverage to protect the eye from impact or possible other contaminants, while a lens for a microscope would have other requirements. After defining the application, the best geometric shape will be chosen, i.e., spherical, cylindrical, flat, etc. Each geometric shape has its advantages and disadvantages, both in performance and in the cost to manufacture. A simple shape, whether it be a flat or spherical, is much easier to manufacture than an asphere which might require advanced manufacturing methods like diamond turning.

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2.1.1.1 Types of geometric shapes

Sphere, cylinder, flat, cone, toroid
Ellipse, parabola, fresnel, asphere, free form, other

Each may be considered to best suit the need of the end product and its optical requirement. Each shape may require a different manufacturing method, and each shape may have a different cost to manufacture the mold.

2.1.2 Optical surfaces and construction points

Once you have chosen the specific geometry to design your product, front and back curves and their associated optical construction points need to be defined. A standard pupil distance may be used to determine the 'as worn' eye location. Inner and outer surfaces must be chosen based upon the product's own special optical requirements. Head form issues and use may need to be considered. All of these things must be considered to develop your part design. You will then create a 3D design that will give the construction points (x, y, and z) and from where those radii were created. These points need to be captured and included in the part and mold design for manufacturing purposes. For example, when designing a face shield, a standard head form would be used to determine the face form fit, pupil distance, distance from face, eye pantoscopic angle, etc. The x, y, and z constructions points that define the inner and outer surfaces would indicate the type of lens, such as plano or other, and if there is an optical correction to it.

2.1.3 Equations and control parameters

Equations and control parameters help to define the optical surfaces of the part. This is especially important for complicated shapes such as aspheric or parabolic shapes. An equation is used in the diamond turning process where it is entered into the machine's controller to generate the machine path for diamond turning. Additional control parameters, such as shrinkage, must be indicated at this time as well.

2.1.4 CAD files and other optical specifications

The customer should provide a 3D CAD model, a 2D control drawing, and an equation if required, along with a SAG table, which is a 2D plot of a spline that confirms the curvature of the equation and the CAD geometry. The 2D control drawing will have all of the specific notes regarding the optical and molded part requirements, such as engraving, texture, other markings, logos, cavity ID locations, gate locations, and optical callout in the different optical zones. The customer should also provide a full 3D model, including all aspects of the job: shrinkage factor, engraving, possible choices for gate location or areas where we cannot locate a gate, ejector locations, and any critical features.

2.1.5 Optical correction

Many times a part is designed with an even wall thickness. This may create a product that does not meet current standards. When designing an optical part which is worn on the face, customers may chose to put an optical correction into the product design. If they do, the wall thickness may have to be optimized in order to achieve the desired optical results. Optical correction will allow the product to meet some of the newer standards, such as the Z87 standard for power and prism, so that the wearer will avoid possible eye fatigue.

However, the optical correction can cause manufacturing difficulties at times. Depending on the product, thick to thin cross sections need to be optimized so that they do not work against each another during the mold fill process. This can present a problem if the thin area may be more difficult to fill than the thick area. The worst case scenario would be filling from thin to thick since you may not be able to fill-out the thick area. However, if you fill from thick to thin, you must make sure that the thin section is not too thin that it becomes difficult to fill and adds undue fill pressure and stress to the part. It is also important to make sure the part is designed to avoid having trapped gases and voids in the mold.

2.1.6 Ray tracing

Ray tracing is a method used to verify an optical design in order to confirm that proper optical performance will be achieved in the finished part. All optical designs should be tested before a mold is built and a part is molded. Real world factors, such as face form fit and manufacturability, must also be considered.

2.1.7 Form, figure, lines of resolution

The optical designer or product designer will define the different optical zones of importance so that the mold builder will know the objective and requirements for surface accuracy and surface quality. Sometimes a mold will require additional inserting to achieve optical performance based upon your design. Is the objective general optical clarity or does the molded product need to be extremely accurate, not only in its geometric shape, i.e., its form and its figure, but also in its surface finish and its surface quality.

3. MOLDING MATERIAL

The customer and product designer, who are working together, will choose the molding material and the material manufacturer. The material manufacturer will advise if the correct material is being chosen for the product based upon the product's use, coatings and additives required, and other factors. The type of molding material will be factored into the mold design in order to develop a proper optical design. For example, two materials at opposite ends of the performance parameter spectrum, polycarbonate and polyurethane, each require different mold considerations. Polycarbonate needs a great deal of venting in the mold, whereas polyurethane requires an extremely tight parting line shut-off; polycarbonate requires a hot mold, while polyurethane needs a cool mold. Hopefully, the product was designed so that one or two materials with similar shrinkage rates could be used so that if one does not perform as desired, another option remains.

3.1 Considerations

- Polycarbonate – hard, for impact
- Acrylic – optical clarity
- Zeonex – optical clarity
- Polystyrene
- Ultem – high heat
- Urethane – soft
- Other

The different types of material must be evaluated for optical purposes so they produce the desired part. The material manufacturers will provide product specifications indicating for which application they are best suited.

3.2 Selection of optical molding materials

The molding material selection should consider several material specifications, such as optical clarity, impact resistance, heat and chemical resistance, viscosity/melt flow index (how easily the mold fills), and transmission/refractive index. The material selection should also consider the type of coatings that may be used on the molded part (see Section 3.3).

3.3 Additives

The material selection will determine what coatings can be applied such as anti-scratch, anti-fog, mirror coat, or heat reflective coatings. These considerations will be a factor in the product design and optical design.

3.4 Coatings

There are also additives that can be used with the molding material depending upon the product's specific use. For example, a laser dye additive may be required in a military product that will protect the eyes. A UV stabilizer or lubricant might also be required. These additives should be considered up front when designing the mold. They may have an impact on gating, venting and thermal mold management.

4. MOLD DESIGN

4.1 3D part model

The 3D part model (Solidworks, ProE, Unigraphics, etc.) will be our guide in the part and mold design. The difference between a regular mold and an optical mold are the optical parameters used to design a mold that will produce optical parts.

4.1.1 Shrinkage

A shrinkage rate should be determined and applied to the part. Some customers chose to apply shrinkage at an industry standard rate, while others do material testing and chose their own shrinkage rate in order to fine tune an application as opposed to using the general rate that the manufacturer recommends.

4.1.2 Optical/surface equations

Some optical geometries are defined by equations as opposed to pure geometries. If we have been given an equation, it is very important to know whether the shrinkage rate has been applied to the equation, and if not, we need to work with the customer to apply shrinkage. It is ultimately better for the customer to have their optical designer apply the shrinkage value as opposed to relying on the mold maker or the diamond turner, as it takes some risks out of the mold building process.

4.1.3 Optical insert design

Optical insert design is very important because it ultimately determines how we manufacture the mold. Insert "break-out"/fabrication design is a very important part of the manufacturing process. The part design and optical surface geometry dictate our approach. Is it an optical insert that needs to be turned? Is it an optical insert that needs to be milled? Do we have to EDM sections of it? Extracting the optical insert from the rest of the mold design will give us the optical surface on a piece of steel so we can determine how to manufacture and optically polish those surfaces.

4.1.4 Split lines/fabrications and clear aperture

The customer and mold builder will have to choose where the split or fabrication lines will be in the mold. There will be a witness line around the optical boundary of the part at the fabrication line. This needs to be discussed with the customer during the design phase so that they understand what marks will be on their part. Overall part appearance, clear aperture and geometric shape may factor into where these fabrication lines may ultimately end up.

4.2 Mold flow

A 3D part and mold design is analyzed for fill, cool and pack scenarios so that we can see the results of our part and mold design. Mold flow analysis will prove out our part design, wall thickness cross-sections, gate size, cooling circuits, filling capabilities through the runner, and gate. This verification can be critical in the design and manufacturing of an optical part and mold.

4.3 Optical mold inserts

Once again, optical insert "break-out" design is determined by the geometric shape, clear aperture, overall part appearance, etc. Once the insert design is complete, the mold insert material is selected: steel, aluminum, nickel, or another alloy. Sometimes weight or polishability becomes the determining factor in choosing the mold material. We typically would try to design an optical insert so that it had adjustability. For example, a spacer behind the optical insert might be used to adjust the thickness of the molded part. Therefore, if you mold a part and determine that it is a too thin or too thick, an adjustment can be made with the spacer. We also consider manufacturing tolerances when designing the optical insert so that we achieve the correct optical alignment from one half of the mold to the other. This consideration may determine the actual manufacturing process such as milling, boring, wire EDM, or jig grinding of a hole.

4.4 Thermal considerations in an optical mold

Several questions need to be answered to determine the thermal considerations of both the molding (plastic) material and the actual mold material. For instance, does the molding material need to be run at normal heat levels or extremely high heat (polycarbonate vs. ultem)? Does the mold need to run hot or cold? Are the cooling and heating lines in the mold plates only, or do they need to be in the inserts to prevent hot or cold spots? Will the customer be running water, glycol or oil? Once again, the mold requirements are determined by the temperature of operating parameters of the molding material and the specific part considerations. Does the mold require insulation boards to retain heat in order to prevent a heat sink in the molding press? Is it a large mold or a small mold? A large mold will have more mass and require more time to heat and cool. A smaller mold will normally require less soak time which means that it can be brought up to temperature fairly quickly.

Ultimately, all optical molds need to achieve thermal balance to produce good optical surfaces on the molded parts. The rule of thumb is that the larger the mold the longer it will take to achieve thermal balance. Once thermal balance is reached, then optimum mold performance is achieved and good parts will be produced.

4.5 Type and size of mold

The type and size of mold needs to be determined, i.e., single cavity mold or multi-cavity mold. Cavitation may be determined by estimated mold cycle time and the product's annual requirement. The optical considerations become more complex in a multi-cavity mold where circuitry of water and runner/gates become important. Is it a straight injection mold? Or will it have injection with compression due to part thickness or in some cases thin wall section considerations? Sometimes with modern presses, injection alone will be able to do much of what is required in the manufacture of a thick cross section product. But in those cases where you need more fill pressure or there is a stress component that must be alleviated or reduced in the product, you can use a compression "coining" feature that will assist in that manufacturing process.

4.6 Gating

Runner and gate design should be very balanced for all optical molds. Gating is very important because we do not want to put undue stress into a part. There are many types of gate considerations: cold sprue or hot sprue, cold runner or hot runner, direct or indirect gate, edge gate, fan gate, etc. The type of gate needs to be determined during the part design phase, which will be incorporated by the mold builder during the mold design phase. The gate needs to be properly sized, along with the associated fill features in the mold, to the size and volume of the part in order to achieve optimum performance relative to pressure, injection speed and cycle time for an optical mold. In most cases, sub-gates are not used in optical molds because they cause too much sheer and super heating of the molding material at the gate, which can put stress, splay and other blemishes into a part. Gate locations for optical parts are critical relative to thick vs. thin sections. It is preferable to gate into thick sections and to let the melt front flow into the thinner section. Part fill speeds may need adjustment based on part cross-section variations. "Race tracking" needs to be avoided. For example, when producing a uniform wall thickness part such as a dome, if the flanges that run around the outside diameter are thicker than the dome itself then race tracking can occur which is problematic; it may produce a void or a back fill situation which would be detrimental for an optical part. It is preferable to fill the part considering the optical surfaces first.

Mold flow can be evaluated to determine if this can be mitigated by using a flow channel feature, a balancing feature in the runner, or thermal adjustments in the mold. If this is not possible, the customer may have to alter the part thickness so that a proper fill condition can be achieved. The object is to avoid the obstructions and flow fronts that cause knit lines in the part.

4.7 Ejection

The customer should decide the location and type of ejection used in the mold, whether it is standard pin ejection, blade, stripper, air assist, or core ejection. The choice may depend on the size and type of the molded part. We do not want to produce parts without considering the overall part aesthetics. Each type of ejection has pros and cons, with pin ejection being the simplest and most common. However, in some cases you cannot have pin marks on the part so core ejection will be required where the entire core lifts. In other molds, there will only be a pin on the runner and the rest of the part has an air assist, whether it be an air blast and/or an air popett. Some molds use blind ejectors, which is an ejector hidden under another feature like a side action. When the side action pulls away the ejector can come up and knock the part off which leaves no witness mark on the part. Stripper ring ejection can be used on some round parts.

4.8 Side actions

Many times optical parts will have undercut features that are needed fit into some type of an assembly and may require an internal, external or threaded side action. Again, this needs to be discussed during the mold design phase to review fabrication/witness lines. Several questions need to asked. Do you heat or cool those mold features? How are they actuated? In the case of a side action on the "A" side of a mold, you may be able to do plate splits or hydraulic cylinders will have to be used to pull wedges. Engraving markings may need to be considered because if engraving is on the “A” side of a mold a side action might be required.

4.9 Miscellaneous optical mold design items

4.9.1 Hang tabs

A hang tab might be required for coating purposes or some other secondary operation on the part, such as alignment or orientation for secondary milling operations. A part might need stand off feet for stacking to prevent the scratching other parts. Sometimes tabs are used to orient a part for optical inspection and/or a secondary machining operation.

4.9.2 Pressure sensors and thermocouples

If the customer needs specific repeatability of process in the mold, pressure sensors and thermocouples can be used. They need to be located properly for information gained to generate a process that can be repeated. Pressure sensors can be as simple ‘off-the-shelf’ under an ejector pin or more complex and special ordered for a specific application. These can be tied into the molding machine controller for direct loop feedback and process control.

4.9.3 Venting

Venting is critical to the optical molding process and critical to maintaining the mold’s optical surface finishes. Some molding materials will require more venting than others, but in essence, all optical molds require good venting. It is best in an optical mold to have as much venting as possible so that the volatiles and gasses that come out of the molding process while molding do not cause damage to the cavity surfaces. Without good venting, more human intervention will be required with cleaning on a regular basis, and human intervention means, unfortunately, scratches or other damage. If the mold is vented properly, you will produce a better part with less pressure and less stress.

5. OPTICAL MOLD SPECIAL TOOLING CONSIDERATIONS

Special fixtures, which are required to produce a good optical mold, need consideration in the design and manufacturing process, and yet are rarely ever seen by the customer. Laps, fixtures, guide plates, and holders are required to build the mold, to put the proper optical surface finish on the mold inserts, and to put the geometric surface in the proper locations. These fixtures help to manufacture and inspect the mold inserts so we can build a proper optical mold that produces a good optical part.

5.1 Optical geometry and design of special tooling

The optical geometry or the geometry of the insert design will determine the manufacturing process. A simple part such as a sphere will require machining/turning and then lapping, grinding and polishing with abrasive grits. A more complex part such as an asphere will require a different finishing method, most likely diamond turning and post polishing. A free form lens would require some type of hand polishing with soft laps.

The design of the special tooling needs to be done at the same time as the mold design, as we discussed: the fixtures to hold the inserts during manufacture, the polish holders required for any special holding operations, fixtures that might be required for inspection, laps required for any lapping and polishing processes, or diamond turning holders. These things need to be designed at the same time and done in a manner that allows both the manufacture of the mold and the manufacture of the optical insert. For example, there are times when the optical insert design for diamond turning is not conducive to the mold design and there needs to be compromise so that the two operations can be done in a cooperative manner. Size and weight are good examples because diamond turning machines have maximum weight capacities and maximum swing clearances. Surface finish specifications on the optical inserts will have an impact on how we design some of this tooling as well.

5.2 Optical surface finishes

The optical surface requirements of the part will determine the method by which the mold inserts are to be finished. Simple pure geometries may lend themselves to abrasive grit lapping and polishing. Aspheres may require sophisticated diamond turning methods. Insert material selection and manufacturing processes along with polishing techniques can yield micro-finishes measured in angstroms.

5.3 Optical alignment

One of the most important things that have to be considered in an optical mold is the alignment of the “A” to “B” half sides of the molds, and the optical inserts respective to those halves of the mold. We have to interlock the cavity/core sets, interlock the mold halves together, and make sure that the inserts themselves are aligned properly. The inserts need to be installed so that the optical axis are located properly to one another without any skew or any wedge. Many times the optical components and the mold design have to consider the thermal expansion and growth of inserts. If there was an “A” vs. “B” side difference in heating and cooling rates of the mold, there could be a problem with the mold alignment and stringent optical requirements.

6. INSPECTION

6.1 Steel vs. plastic results

The first step is to determine if the steel is where it should be based upon the mold design. Each of our components, inserts, surface finishes, and parts of the mold that will produce the plastic part are inspected to make sure that they have been manufactured correctly. We then verify that all of those fabrications match properly in the design by checking the miters. Does the optical insert meet the retainer? Does the retainer match to the opposite side? Does it match to the parting line? If all of those things match properly, we have a general understanding that we have build a mold that will produce the proper molded part. Then the next step is to test/inspect the plastic part. The optical testing criteria must be used, such as 40/20, scratch/dig specification, resolution, power, etc. The optical zones of importance need to be inspected based upon the desired design specifications.

6.2 Optical testing methods

Optical testing methods can be contact measurement, such as coordinate measuring machine (CMM) or a tally surf machine, or non-contact, such as a laser scan. When checking the plastic part, an optical telescope can be used to look for optical clarity and lines of resolution. The molded part can also be checked with projected lights to see if there is any banding or distortion. Polarizing sheets can be used to look for stress. The form and figure can be measured by an interferometer. Outside testing labs can also be used for testing.

6.3 Common defects

There are common defects that can be looked for, and depending on the complexity of the product, some of those things can be tested easily while others might require very specific and complex fixtures and test equipment. Some questions to ask are: Does the molded part have a haze? Has the mold been polished properly? Is there an orange peel on the surfaces? Does it have a clean polished finish? Is there optical distortion? Does the distortion come from a bad optical design or was the part not properly molded?

7. CONCLUSION

An optical mold design and mold build is a specialty unto itself in the mold building industry. When the customer provides us with the detailed information discussed, they can rely on ABCO’s expertise to be able to ask the right questions and to get the right answers to proceed. Our experience gives us a depth of knowledge that allows us to contribute to decisions on how the mold is designed, built and ultimately run in order to produce good parts for the customer.

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