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IMPROVING THE INJECTION MOLDING OF SMALL OPTICAL ELEMENTS BY INTEGRATING REVERSE ENGINEERING AND MOLD FLOW ANALYSIS

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ABSTRACT

Small optical lenses are usually manufactured by injection molding. The high quality requirement on injection lenses, however, requires a precise control of the mold accuracy as well as the injection process. The purpose of this study is to conduct a comprehensive error study of the injection molding for optical elements by combining the techniques of reverse engineering and mold flow analysis. Reverse engineering is employed to identify the source of errors, and hence provide guidelines for the modification of the mold; Mold flow analysis is employed to construct a parametric study of the injection process, and hence improve the quality of injection parts. Real molds are designed and manufactured, and injection molding is implemented to verify the feasibility of the simulation. The advantages of the proposed method by integrating reverse engineering and mold flow analysis for improving the injection process are discussed too.

Keywords: injection molding, mold flow analysis, reverse engineering, optical lens.

INTRODUCTION

Small optical lenses are getting more and more popular in the market because of the rapid development of consumer electronic products. Most small optical lenses are currently manufactured by injection molding. The surface quality of a lens is much higher than that of other injection parts because the optical properties of the lens are very sensitive to the surface condition; the surface tolerance of the lens is very tight, and the lens surface must be mirror finished. The entire manufacturing process, from mold fabrication to lens injection, must be controlled precisely to satisfy the goal of high quality and high yield rate in mass production.

Current design on lens surface has been improved from conventional quadratic surface to complex freeform surface. This, however, may complicate mold design and manufacturing, and injection process as well. The mold geometry must be larger than the part geometry to compensate for the part shrinkage. The mold shrinkage rate, however, is generally determined by experience, which may vary person by person, and case by case. Moreover, the accuracy of mold surface affects the part accuracy considerably. Current mold manufacturing provides limited information about the accuracy of machined surface, which may jeopardize the judgment of errors. In addition, many factors may affect the defects on the part and its accuracy. When the part surface becomes more complex, so are the factors which should be considered.

Mold flow analysis (MFA hereafter) has been involved in injection molding to simulate the injection process and analyze appropriate parameters before real process is implemented. Many practical and theoretical studies have been presented to investigate the feasibility of MFA to improve injection molding [1-5]. However, the bad quality on the injection part may come from several sources, e.g., the inaccuracy of mold design, mold manufacturing, or inappropriate parameters setting for injection process. How to judge and separate the error sources? Will it be primarily due to mold design, mold manufacturing, or injection process? Also, how to ensure the accuracy of MFA? This requires the integration of several technologies to identify and analyze each of the errors individually.

The purpose of this study is to conduct a comprehensive error study of the injection molding for small optical elements by integrating the techniques of reverse engineering and MFA. Reverse engineering is employed to identify the source of errors either on the injection part or mold. MFA is employed to simulate the injection process. In addition, a feasibility study is conducted to investigate the accuracy of the MFA analysis. It is expected that possible source of errors can be identified and overcome trough computer simulation before real process is implemented. The proposed method can be applied for manufacturing error analysis, part accuracy analysis, mold repairmen, and optical design, for improving the injection molding of small optical elements.

METHOD AND APPARATUS

A systematic approach, integrating MFA, reverse engineering, and mold design and manufacturing, is proposed to investigate the design and manufacturing of small optical elements (Figure-1). In typical injection molding, the CAD model is directly used for the design and manufacturing of mold. The mold is then used in the injection process for part fabrication. In this study, MFA is included for the analysis of injection process. Reverse

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engineering is included to detect the difference among part surface, mold surface and CAD model. The surface model can even be reconstructed from digitized points for the use in optical simulation.

The primary goal of the analysis is to identify the errors in mold manufacturing and part injection, and then feedback for the improvement. The measurement data and CAD models used in the analysis are: the CAD model of lens, CAD model of mold, digitized points of mold (STL data), digitized points of part (STL data), and output from MFA (STL data). Through a series of measurement, analysis and study, the following properties are investigated: (1) the effect of mold inaccuracy on the part, (2) the effect of injection parameters on the part, (3) a comparison of the prediction from MFA and the part, (4) improvement of optical design in accordance with the prediction from MFA, and (5) critical factors affecting part accuracy. The techniques used to achieve the afore-mentioned tasks are described below.

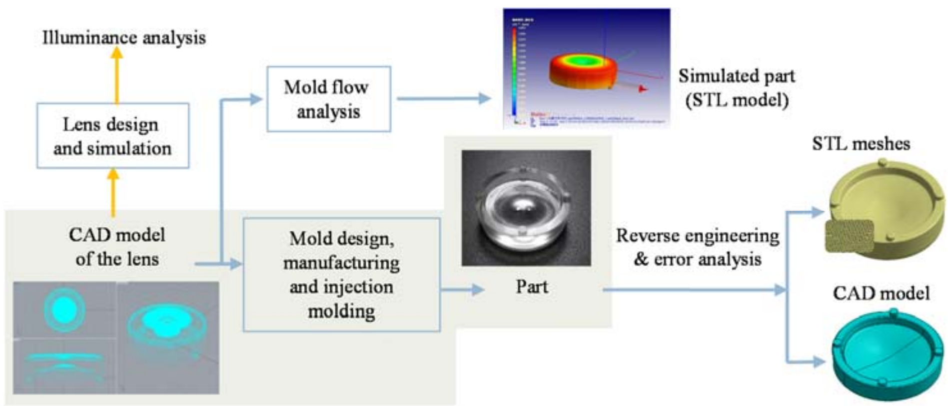


Figure-1. Proposed structure for improving the quality of small optical elements in injection molding.

Reverse Engineering

The reverse engineering techniques used in this study include digitization of the object, CAD model reconstruction from digitized points, and error comparison between two sets of data. Regarding digitization, the part surface is digitized by a camera-type scanning device-COMET 400. The accuracy of this scanner is 5.7 μm and its repeatability is 2.2 μm. The part is scanned from multiple views. Each scan can yield a set of triangular meshes. A registration process is implemented to align all sets of points. All overlapped points are then removed to yield the final set of triangular meshes, expressed as a data format *.stl. Both injection part and mold are digitized. The scanned data are saved separately for further analysis later. Figure-2 illustrates the photo of the LED lens used in this study and the scanned points, expressed as triangular meshes.

Figure-3(a) shows the data of multiple sets of scanned points before registration. Each set of scanned points represents the partial shape of the object in a specific viewpoint. The coordinate systems of these sets of points are different. Some of the points are overlapped too. Therefore, two steps are used to process the data.

First, it is necessary to implement a coordinate registration algorithm to align different sets of points so that all data points are with respect to the same coordinate system. Second, a mesh process algorithm is used to remove overlapped points, and yield the final triangular model representing the object surface. Figure-3(b) shows the final result of the data after registration. It is noted that the scanned points are processed in the form of triangular meshes.

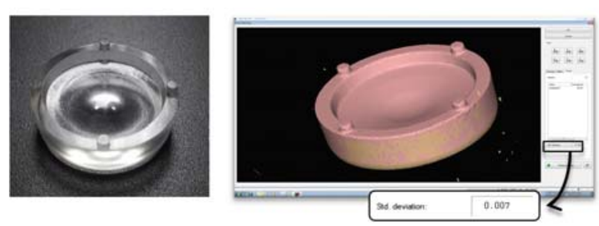
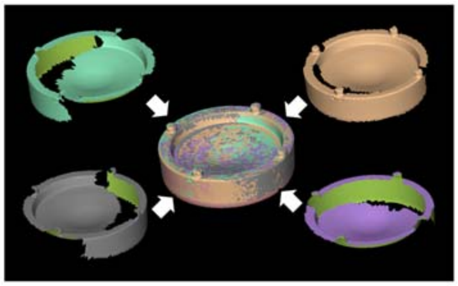


Figure-2. LED part and the scanned data of the part.



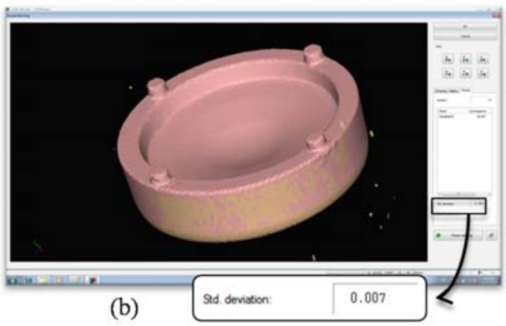


Figure-3. Multiple sets of scanned points for the part, (a) before registration, (b) after registration.

Regarding CAD model reconstruction, the reconstructed CAD model is primarily used for optical simulation. The LED lens shown in Figure-2 can mainly be divided into three regions, top surface, side surface, and bottom surface. Two kinds of surface fitting techniques are employed to reconstruct the surface models, including the one which yields the sectional profile of a revolution surface, and the other one which yields a freeform surface for each region of digitized points. A detailed description of the surface reconstruction methods can be shown in [6, 7]. It is noted that before reconstructing the surface model, it is necessary to align the position and orientation of the digitized points. The 3-2-1 method is employed to align the coordinate system of the data points (Figure-4). The datum plane is firstly determined using the points on a plane. Ideally, three points are good enough to determine the datum plane. Actually, the points lying on a plane are extracted and fitted into a plane, acted as the datum plane (e.g. the XY-plane). The points on an axis are then employed to yield the datum axis. Ideally, two points on a line are good enough to determine the datum axis. Actually, the points lying on an axis are projected onto the datum plane. The projected points are then fitted into a line, acted as the datum axis (e.g. the X and Y axis). Finally, the origin is obtained by projecting a point on the datum axis. The point to be projected can be either the center of a circle or a point on a plane. Figure-5 indicates that different surface fitting techniques must be employed to fit each region of points into an appropriate type of surface.

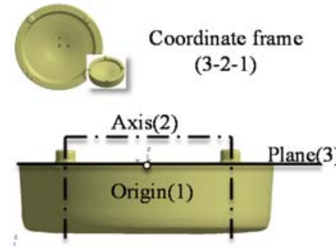


Figure-4. The 3-2-1 registration method employed for part localization.

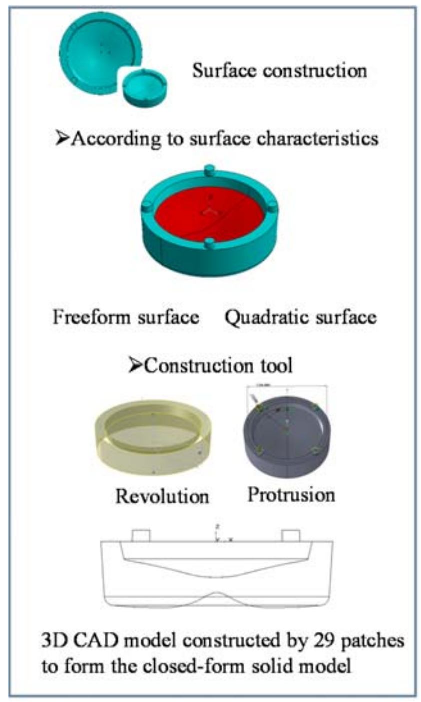


Figure-5. Procedures for the reconstruction of the CAD model.

Error comparison is employed to check the difference of a set of data related to another set of reference data. The data to be tested is generally the scanned points of the part or mold, and the reference data can either be a triangular model or a CAD model. To fully understand the source of errors for the entire process, the following five kinds of error comparison are performed: (1) the scanned data of part vs. the original CAD model, (2) the scanned data of part vs. the output of MFA, (3) the output of MFA vs. the original CAD model, (4) the scanned data of mold surface vs. the original CAD model, and (5) the scanned data of part vs. the reconstructed CAD model from scanned data.

For each of the tests, three kinds of error comparison can be implemented, namely total surface comparison, partial surface comparison, and sectional

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curve comparison. For total surface comparison, the entire set of scanned points is compared with the reference data. Figure-6(a) illustrates one example of total surface comparison between the scanned points of part and original CAD model. The result can show the overall deviation between the part and the CAD model. It can also show the maximum error and root-means-square error for the entire set of data. However, it is difficult to check the detailed error on each surface because all errors are displayed together. For partial surface comparison, the original CAD model is divided into several regions and the errors are analyzed region by region. Figure-6(b) shows one example of partial surface comparison for top and bottom surfaces, respectively. As both plots indicate, it is easy to realize the error distribution on each surface region. Finally, the sectional curve comparison provides sectional comparison between the scanned points and CAD model. As Figure-6(c) indicates, it is obvious that the error on the bottom surface is much larger than that on the other regions. With these error comparison studies, the accuracy of part, mold and reconstructed CAD model can be evaluated individually. In addition, the accuracy of output from MFA can be analyzed too.

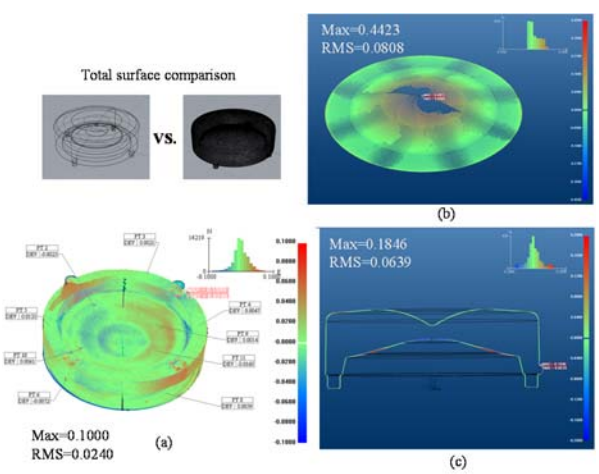

Figure-6. Three types of error comparison, (a) total surface comparison, (b) partial surface comparison, (c) sectional curve comparison.

Mold Flow Analysis

The commercial MFA software- Modex3D is employed in this study for predicting the injection process and determining appropriate parameters for real injection process. Moreover, several gate designs are tested and the best one is chosen in real experiment. However, the accuracy of prediction must be checked before further parametric study is conducted.

The MFA process is briefly described as follows (Figure-7). Each of the CAD models must be converted to surface meshes first, and then solid meshes. The CAD models mainly include the part, gate, mold and cooling channel. The parameters that should be set include molding temperature, injection pressure, injection speed, holding pressure, holding time, and cooling time. The others related to the injection machine may be accessed from the data base or input by the user. Once all solid meshes and injection parameters are set, the following four analyses can be performed: filling, holding, cooling and warpage. Different kinds of graphical and numerical results for each of these analyses can be shown for further study.

In this study, the warpage analysis is particularly investigated as it represents the deformation of part geometry, which can be compared with that form the measurement. In addition, several common defects, including short shot, voids and welding line, are also investigated to test the appropriateness of the parameters setting.

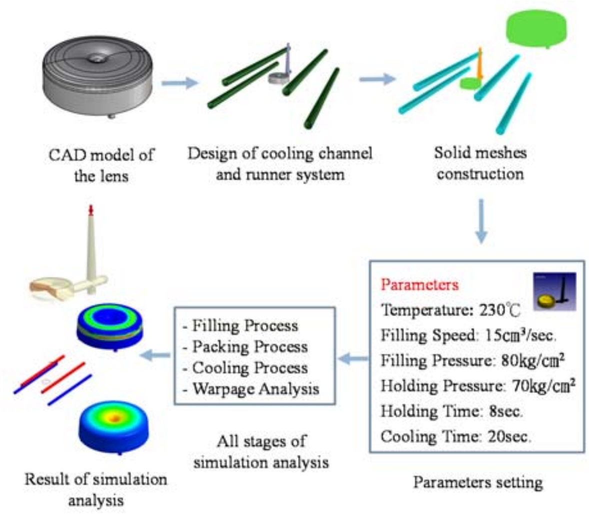

Figure-7. Procedures of mold flow analysis.

Mold Design and Manufacturing

Mold design and manufacturing is typically performed by a mold manufacturing company. Specific data and plots that must be provided are as follows: (1) End-product drawing: the two-dimensional end-product drawing is drawn in accordance with the 3D CAD model of part. It is used for the purpose of quality inspection during the production of injection parts; (2) Determination of shrinkage rate: the shrinkage rate is determined in accordance with the material and the end-product drawing. The material used is PMMA; (3) Mold drawing: the end-product drawing is multiplied by the shrinkage rate to yield the mold drawing. It is used for the manufacturing and inspection of the mold; (4) Determination of parting line: the parting line is determined by experience. It is generally set along the boundaries of different features. The part geometry is divided into two parts, the cavity side and core side; (5) Gate location: the gate location is

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generally set on the place that does not affect the functionality or outward appearance of the part. (6) Number of cavities: In general, even number of cavities is chosen to balance the flow. Once all above steps are completed, the cavity and core are manufactured, respectively, and then assembled on the mold.

RESULTS AND DISCUSSIONS

The aforementioned technologies have been applied for rapid manufacturing of a mold for the LED lens shown in Figure-2, and for the investigation and improvement of the injection process. In this mold (Figure-8(a)), the following three gates were designed and tested: flat type, fan-shaped type and ramp type (Figure-8(b)), where each type had two different sizes. Modex3D™ was employed to test the effect of all three designs. The simulation results were evaluated in accordance with the degree of defects found on the simulation results; the defects that were considered were welding line, degree of saturation and existence of voids. It was found that for all smaller gates, different degrees of defects were found on the simulation results. The reason is that both injection pressure and holding pressure are not built up completely during the process because the cross sectional area of the gate is too small. By contrast, when gates of larger sizes were tested, both injection pressures and holding pressure were increased rapidly, and hence the process can be completed under the operating pressure.

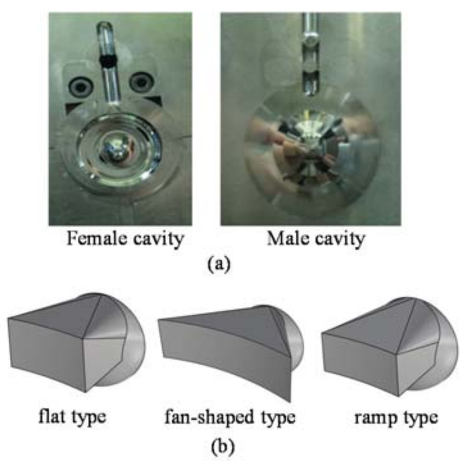

Figure-8. Mold design, (a) cavity of the mold, (b) three types of gates tested in this study.

The simulation results for two kinds of flat-type gates are illustrated to demonstrate the feasibility of MFA and error comparison for improving the injection process. On each pair of plots in Figure-9, the left side represents “smaller gate”, whereas the right side represents “larger gate”. In Figure-9(a), total surface comparison is performed between the deformed model after MFA and original CAD model. The MAX error and RMS error are 0.259 and 0.135 mm, respectively, on the left plot; whereas they are 0.09 and 0.047 mm, respectively, on the right plot. This result indicates that the gate of larger size can reduce part shrinkage considerably. In Figure-9(b), the sectional curve comparison again verifies the fact that the shrinkage on the left plot is much larger than that on the right plot. Moreover, the result shows that the shrinkage on the side face is larger than those on top and bottom faces. This deviation on the side face might result from the error on the mold. Figure-9(c) compares the degree of welding lines for smaller and larger gates. For the smaller gate (left plot), the welding line appears almost across the left half region of the part; whereas for the larger gate (right plot), the welding line has been reduced to a small area near the boundary region. Figure-9(d) compares the degree of voids for the smaller and larger gates. For the smaller gate (left plot), the voids appear all around the part; whereas for the larger gate (right plot), the voids almost disappear. From these simulation results, it is evident that the larger gate is better than the smaller gate.

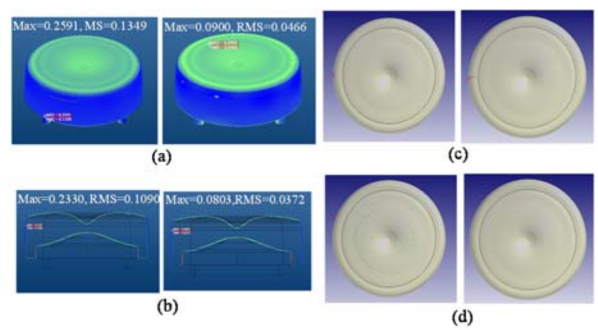

Figure-9. The simulation results for two kinds of flat-type gate, (a) total surface comparison, (b) sectional curve comparison, (c) welding line comparison, (d) voids curve comparison.

Figure-10 makes a comparison of the results from the prediction with those from real injection molding. In this test, four sets of parameters are tested both for the simulation and real injection molding, where the plots on the first and second columns represent the simulation and real experiments, respectively. The results obviously indicate that the MFA simulation can simulate the effect of the injection process accurately. The welding line and void on two injection samples are indicated, which are compared with those from the prediction. Although the defects on real injection samples and the prediction are not fully identical, the trend is similar. Therefore, the MFA simulation can predict the appearance of defects very well.

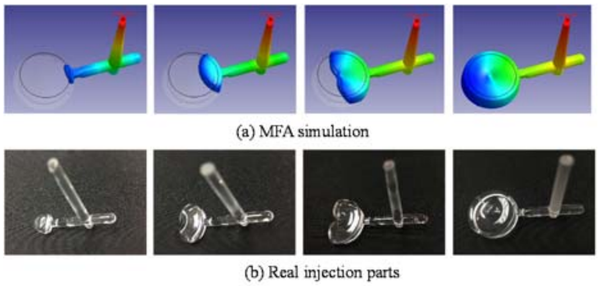

Figure-10. Simulation of short shot vs. test of short shot, (a) MFA simulation, (b) real injection parts.

CONCLUSIONS

It has been found that the inaccuracy in mold design and manufacturing could be a factor affecting the accuracy of the injection part. However, in current mold manufacturing, the inspection data is usually not broad enough to cover the entire machined surfaces, which may not reflect the real situation of mold accuracy. Reverse engineering technique was employed in this study to acquire digitized points of the cavity and core, and extensive error comparison was performed to investigate mold accuracy. Through this technology, the mold accuracy can be evaluated accurately. In addition, mold flow analysis has been implemented to predict the injection process and to improve the quality of part. Through the comparison of real injection molding and mold flow analysis, it has been found that mold flow analysis can achieve the goal successfully.

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