실험계획법을 적용한 비구면 Glass 렌즈 성형조건 연구
A Study on the Molding Condition of Aspheric Glass Lens Using Design of Experiment

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1. Introduction

As an alternative to the traditional glass lens manufacturing process−polishing, glass molding press (GMP) of aspheric optics has become an attractive approach. In case where the process parameters are properly designed, GMP is considered as one of the reliable methods in the fabrication of aspheric glass lenses. However, due to the extremely high hardness (R_c>90) of popular mold material such as tungsten carbide (WC), the grinding process used to fabricate such molds becomes expensive and thus it becomes difficult to find the optimum grinding condition. In addition, there are some difficulties in controlling many parameters of molding process (e.g., pressing force, slow cooling rate, and molding temperature, etc.). This is because the study of these parameters may require numerous case studies and may be time-consuming and expensive as well. Thus, to reduce such efforts and expenses, an efficient strategy for process design is required, and the related results should be analyzed systematically. Design of experiments (DOE) is one of the solutions to properly control these parameters and is a useful tool in the process design and analysis of complicated industrial design problems. An extensive study using the DOE have been previously carried out, but these previous studies have focused on issues concerning the injection molding process of plastic products or grinding of raw glass and mild metal [1−3]. This study deals with the optimization of (1) parallel grinding condition of the WC mold to fabricate aspheric glass lenses for a camera phone module with respect to surface roughness (Ra) and (2) molding conditions with regard to the form accuracy (PV) of the molded lens. Finally, we investigated how to transcribe the form and texture of mold surface into the molded lens surface under an optimum in among the designed conditions. In addition, the bearing ratio analysis is employed to bring out further indications about transcription properties of the roughness of the mold surface.

2. Experiments

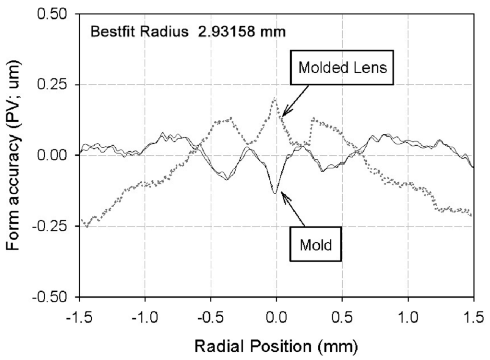
Four process parameters, depth of cut, feed rate, work speed, and wheel speed, were selected with two levels of experimentation to optimize a grinding condition. Many investigations have revealed that these parameters significantly affect the roughness (Ra) of ground surface [4]. A dummy WC was parallel-ground under various conditions to be drawn by full factorial design. The molded lens studied was pressed in two step and then slow−cooled from molding temperature to rapid cooling point. Five process parameters were employed for fractional factorial design; Step1−pressing force, Step2−pressing time, Pressing force on the slow cooling process, Rapid cooling point, and Slow cooling rate.

3. Result and discussion

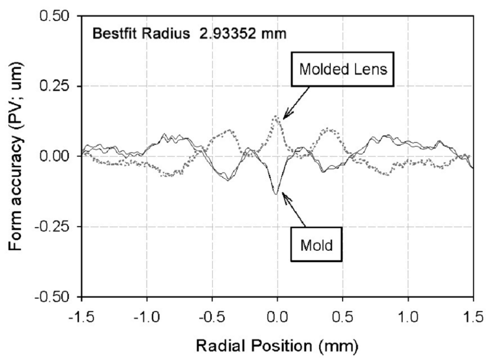
Two-way fractional ANOVA and *P*-value (significance level) were used to check the significance of the effects on the form accuracy (PV) of aspheric surface of the molded lens.

Pareto chart, main effect plot, and interaction plot show that the factors of depth of cut, *A*, and feed rate, *B*, are highly significant, whereas other individual factors and all interactions slightly affect the surface roughness (Ra). Depth of cut and feed rate are significant operative variable, inducing the deepest variations in the surface roughness (Ra) of ground WC. When the values of depth of cut and feed rate are reduced, the roughness of ground WC is also decreased. Using the best combination to obtain a low surface roughness (Ra) value, the mold for aspheric glass lens molding was fabricated.

In case of glass lens molding process, pareto chart points out that four main factors except for step2−pressing time was highly significant on the form accuracy (PV) of the molded lens. The slow cooling rate represents the most significant variable, inducing the deepest variations in the form accuracy (PV) of the molded lens, whereas the parameters of pressing process had comparatively little effect on the form accuracy (PV). The form accuracy (PV) of the molded lens on the best combination condition was 0.23 um as a mean value and the standard deviation is less than 0.01 um. This result suggests that the experimental condition has a reliable reproducibility for our system. It is given in Fig. 1 that the form deviation profile between the mold and lens molded under the worst condition and the optimum condition. Due to the contraction of glass on the cooling process, the radius of the molded lens is decreased as compared with the radius of the mold. The more the radius is decreased, the more the form of the lens deviates from that of the mold.



(a)



(b)

Fig. 1 Form deviation profile between the mold and lens under the worst condition (a) and the optimum condition (b).

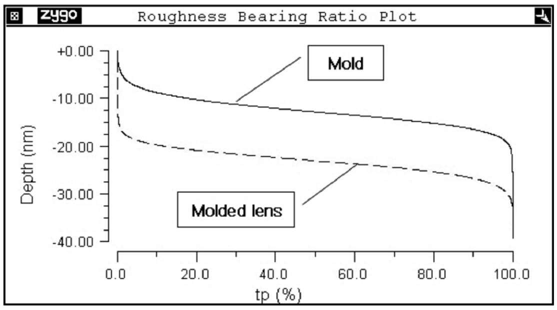


Fig. 2 Bearing ratio curve of the mold and the molded lens.

Percentage transcription ratio is calculated as the ratio of the form accuracy (PV) between the mold and the molded lens and it is around 85.4% on the optimum condition. The 3-D surface roughness (Ra) of the mold and the molded lens were 3.97 nm and 4.22 nm, respectively. However, because surface roughness (Ra) does not tell the whole story about a surface, bearing ratio analysis was employed to investigate more detailed information of surface roughness. Figure 2 indicates bearing ratio curves of the mold and the molded lens.

4. Conclusions

- The roughness (Ra) of ground tungsten carbide (WC) surface is sensitively decreased with reduction of depth of cut and feed rate value.
- To improve the form accuracy (PV) of the molded lens, the slow cooling rate has to be considered as the most significant variable.
- The best combinations of factors for the optimum condition are as follows:

  (For WC grinding)

  All factors are at their low level.

  (For glass lens molding)

  Step 1 pressing force : level "−1"
  Step 2 pressing time : level "−1"
  Slow cooling−pressing force : level "+1"
  Rapid cooling point : level "−1"
  Slow cooling rate : level "−1"
- The lens molded under the optimum pressing condition show 85.4% of transcription ratio. This value is sufficient for fabrication of the precision optical component for our system.
- The bearing ratio analysis shows that the surface roughness of the molded lens is caused by all the section (Peak, Valley, and Core section) of the mold and, especially, peak and core section of the mold strongly affects on the roughness of the molded lens.

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