Design and fabrication of freeform reflector for automotive headlamp

J.B. Jiang, C.F. Cheung, S.To, K.W. Cheng, H. Wang, W.B. Lee
Advanced Optics Manufacturing Centre, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University

Abstract: Modern automotive illumination systems require higher efficiency, safety, and good aesthetic features. The design, fabrication and measurement are critical issues for automotive illumination systems. The non-imaging optical design for the automotive lighting system, which departs from the methods of traditional optical design, is an arisen interdisciplinary field. In order to meet the traffic regulations, unique freeform shapes and geometries should be adopted to create the special legal light pattern. Mean while, high accuracy freeform reflector could not be made by conventional manufacturing process, ultra-precision machining is the method. And the measurement of the freeform surface is also a new area. In this paper, the optical design, fabrication and the measurement of the freeform reflector headlamps are investigated.

Keywords: Automotive lighting system, non-imaging, freeform, ultra-precision machining.

1. Introduction

Currently, dramatic changes are unfolding in automotive lighting technology. Car manufacturers - together with suppliers and legislators - currently aspire to develop the headlights of tomorrow. Freeform headlamp is one of the popular design which offers great flexibility and compactness. The reflector of a freeform headlamp is a freeform surface which cannot be defined by mathematical functions and the design and fabrication of which has always been difficult.

Though the non-imaging ray tracing and the 3D modeling of the lighting system can be undertaken by several market available optical design and freeform generating softwares, such as ASAP[1], TracePro[2], LightTools[3], SPEOS[4], LucidShape[5], ReflectorCAD[6][1], and CATIA[6], Unigraphic[7][7] etc, the designed surfaces can only be fabricated by ultra-precision multi-axis freeform non-conformal machining based on multi-axis raster milling, microgrooving and grinding with submicrometer form accuracy and nanometric surface without subsequent polishing. However, the achievement of functional specifications of the freeform optics still depends largely on the experience of the optical designers and the CNC machine operators through an expensive trial-and-error approach when new freeform optics design is used. The optimal optics design for ensuring good quality depends largely on the functional specifications, machine tolerance and freeform measurement errors. Therefore, a state-of-art design and ultra-precision machining techniques are very important for the adopting the freeform technology into automobile lighting systems.

2. Design of freeform automotive headlamp reflector

The freeform reflector is a new arisen concept that each area of the surface of the reflector is allocated a certain area of the road to illuminate. The surface of the reflector is calculated on the basis of the so-called deflection strategies with the aid of a computer. This results in a so-called "free form" (FF®) instead of a regular shape. The calculation software should be developed individually to calculate and modeling the freeform reflector surface.

With the development of tailored freeform surfaces capable of complying with the stringent demands made on automotive optics, the use of freeform headlamps are moving ever closer within reach. The freeform surfaces allow them to achieve the required hot spot intensity by directing more than 60% of the generated light towards the road and so serve to largely illuminate the available aperture area. Good freeform optics design can significantly reduce the scattering and reflection losses and hence increase the efficiency of illumination.

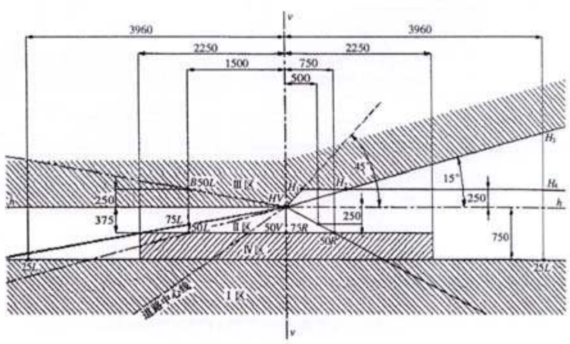


Fig. 1 (Chinese National Standard GB-4599 forward-lighting headlamp beam allocation characteristic)—ECE standard

The design of the freeform reflectors for the automotive head lighting should agree with the international traffic regulations, such as the European ECE standards and the United States SAE standard. The Chinese government also has its own regulation, i.e. the Chinese National Standards GB-4599, shown in Fig.1. It defines such as the flux (lumen), light distribution, light intensity (candela), the measurement methods, and other important issues for the automotive head-lighting. It is derivate from the European ECE standard and is compatible with ECE standard.

The first stage in the design of the automotive headlamp is choosing the light bulb. The High-Intensity-Discharge Lamps (HID), consisting of a broad range of gas discharge lamps, are notable for their high luminous efficacy, good color rendering, and long life. Metal halide lamps have the best combination of the above properties and are considered the most ideal light sources. Recently, there has been an emerging demand to replace the conventional halogen headlamps with the newly introduced small-wattage metal halide HID lamps. In this paper, a Philips HID D2S light bulb is chosen for the low-beam headlamp. The computer modeling and the far field angle light distribution of the bulb is shown in Fig.2

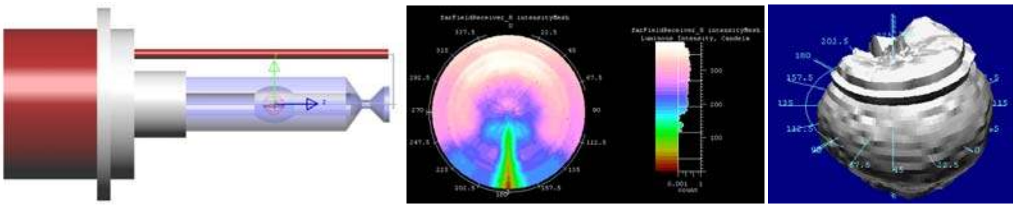


Fig. 2 Computer modeling and the far field angle distribution of the HID D2S light bulb

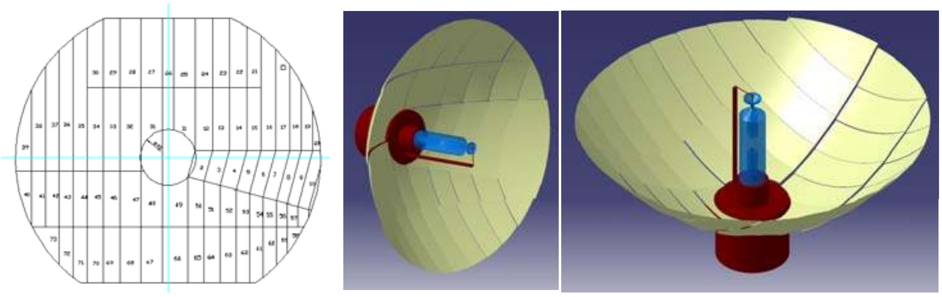


Fig. 3 Segments of the freeform reflector

The design methodology is following the “Edge-Ray Principle”[8]. The reflector is divided into many segments, shown in Fig.3. Each segment creates an individual light aiming region. The light distribution created by different reflector facets combined together form a light pattern meeting the Chinese National Standard GB-4599, which is the forward-lighting headlamp beam allocation characteristic. A C-programmed software is developed by our team in order to calculate the freeform shape according to the “Edge-Ray Principle”. All kind of freeform reflector and optical profile is calculated and then 3D models can be modeled in the Software CATIA. The ray tracing process is performed with a commercial ray tracing software LightTools. The ray tracing , the illuminance map and the light pattern at 25 meter distance away is shown as Fig. 4, Fig.5, and Fig.6. The control of the beam angle of every reflector segment is done very well, as is shown in Fig. 4. In Fig. 5, the cross along the horizontal 0-0 line and the vertical 0-0 line denotes the h-h and v-v lines of GB-4599. The cut-off is very sharp above the h-h line in the left side. And the cut-off along the 15° in the right side is also very sharp. The illuminance map meets the national standard very well.

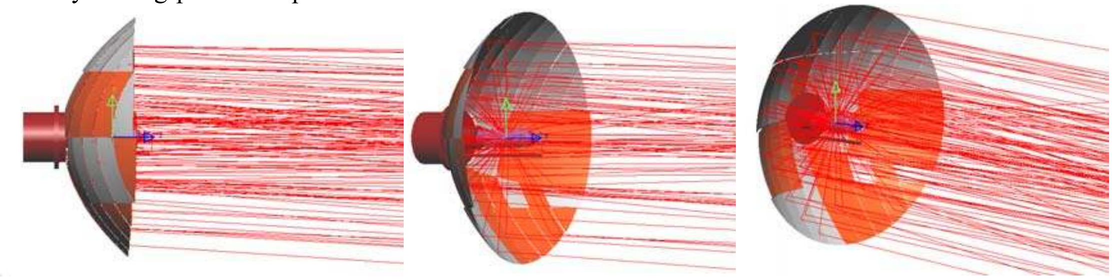


Fig. 4 Ray tracing

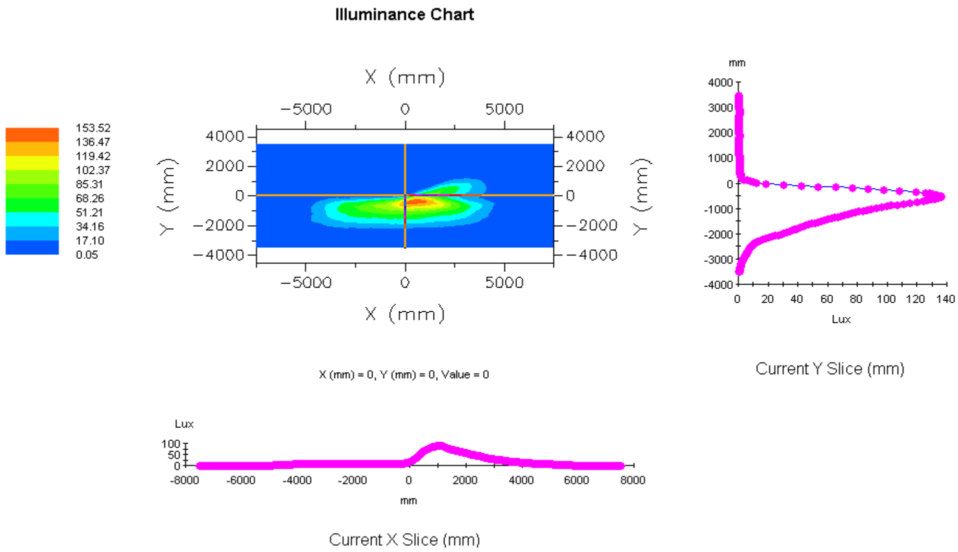


Fig. 5 Illuminance map at 25 meter distance away

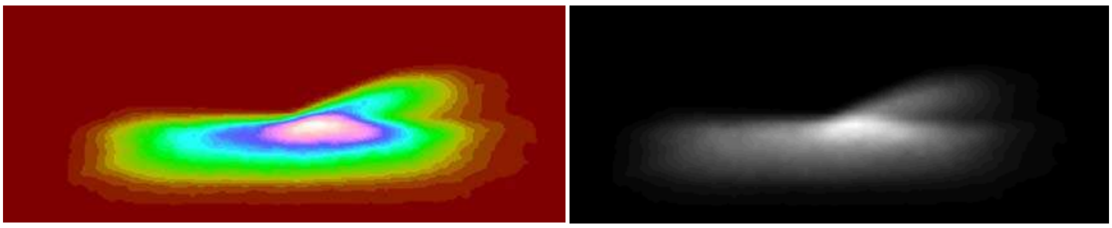


Fig. 6 Light pattern at 25 meter distance away

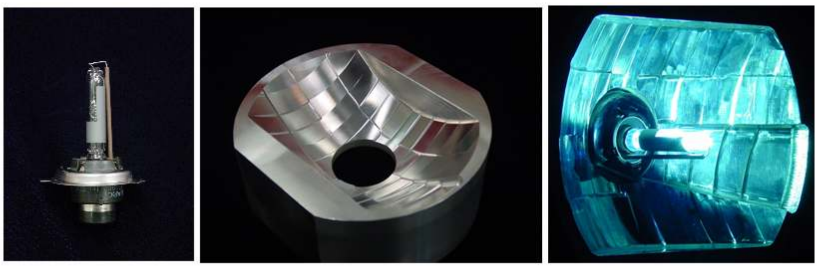


Fig. 7 Pictures of the Philips D2S HID light bulb and the reflector prototype

A prototype is made so that further work can be done, such as the surface roughness measurement, form error measurement, light pattern and light efficiency testing. The pictures of the Philips D2S HID light bulb and the reflector prototype, and the assembled headlamp setup is shown in Fig. 7.

3. Fabrication of the prototypes of headlamp reflector

For the automotive optics, most of them are non-rotational-symmetrical. Some of the optics are very complex, e.g. the compound TIR&R lens are made up of the refraction parts and the TIR parts. In each part the draft angle is very sharp, it is hard to make in traditional turning and polishing way. Ultra-precision diamond-turning machining can be adopted to manufacture these kind of optics. The headlamp reflectors are combined by many freeform facets. Each has different curvatures in different orientations that cannot be represented by one uniform equation. The whole part is designedin the IGES format. For such kind of freeform reflector, a multi-axis ultra-precision machining technology needs to be developed. This machining technology, based on multi-axis raster milling and grinding, is an enabling technology which provides a solution for machining non-rotational symmetry freeform optical surfaces with sub micrometer form accuracy and nanometric surface. Fig. 8 shows a freeform machine in used in the Advanced Optics Manufacturing Centre of The Hong Kong Polytechnic University. The configuration of raster milling conducted in a 5-axis ultra-precision computer numerical control (CNC) machine is shown in Fig. 9.

Up to now, there are no software packages which are commercially available for the direct programming of NC tool paths based on optical design parameters of freeform optical elements. Therefore, the development of a software package is needed to generate the freeform optics used in the automotive illumination and vehicle lighting. A powerful NC tool path generation software package has been developed for the machining of different kind of the freeform surfaces. Fig. 10 shows the software interface developed by AOMC in the machining of the freeform reflector of automotive headlamp.

Fig. 8 Ultra-precision 5 axis Freeform Machine (Freeform 705G)

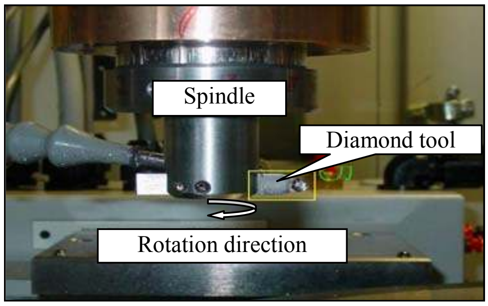


Fig. 9 Ultra-precision raster milling.

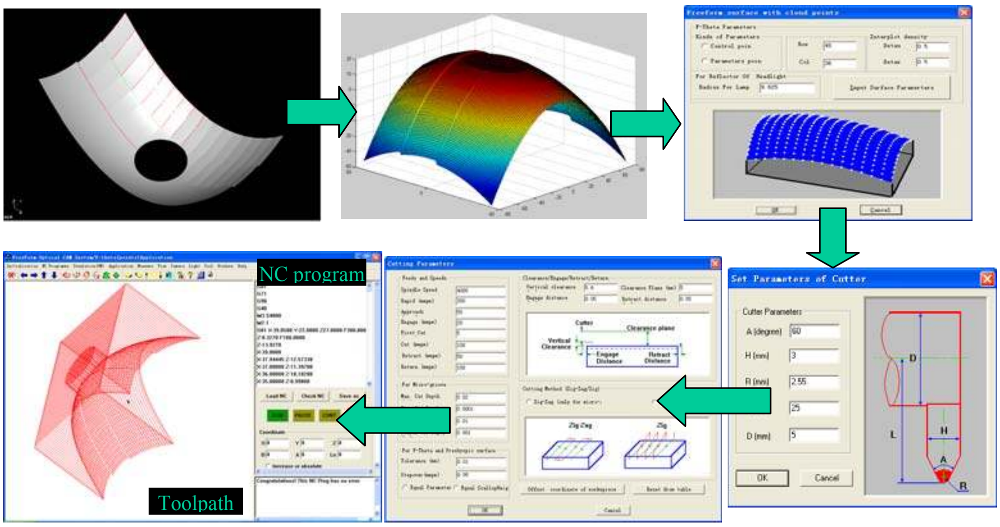
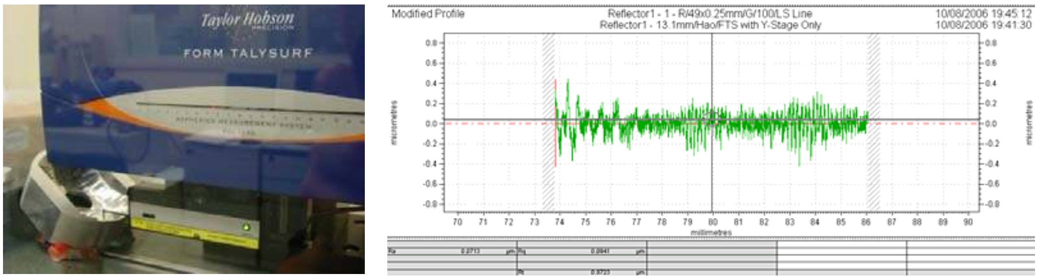


Fig. 10 Tool path generation of the freeform optics

4. Surface Measurements of the headlamp reflector

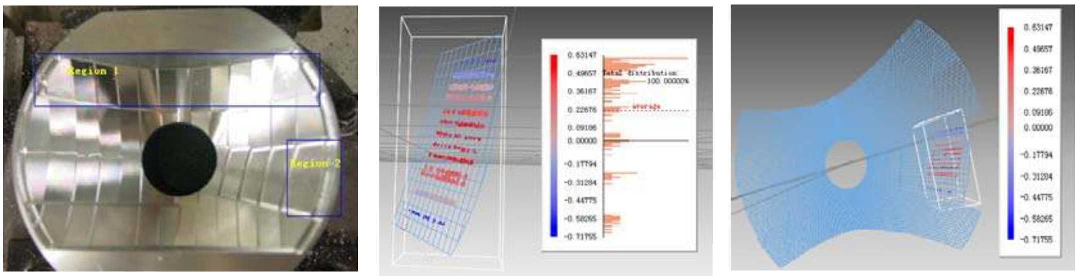
The surface roughness of the reflector has been measured on the aspheric measurement system Form Talysurf PGI 1240, shown in Fig. 11 (a), and the result is obtained as in Fig. 11 (b). In general, Ra is 71.3 nm, Rt is 0.8723 um, and Rq is 0.0941 um. Because the optics design of headlamp reflector employs the sculptured surface, in which the entire reflector surface is made up with small freeform patches and gaps between them, it would be impossible to measure the entire surface with the stylus of Talysurf. Thus, the surface roughness is evaluated on separated surface patches without taking the gaps into consideration. Moreover, it is also impossible to use Wyko optical profiling system to measure the concave surface with great depth.

The form accuracy of the reflector prototype has been tested on a laser CMM Smartscope Flash 300 with the precision of 0.5 um. About 1100 points on surface are sampled in regions 1 and 2 on surface. Then the points exported in the CMM machine format are transformed into (X, Y, Z) format to form a “shell” which is further used to compare with the design “surface”. In Fig.12 (a), the points in Region 2 are used to compare with the design surface in the corresponding region. First the shell in region 2 is registered with the surface in region 2. Then the comparison shows the distribution chart on the left part in Fig. 12(b). The average deviation lies at 0.2276 mm, with the maximum of 0.63147 mm. The corresponding perspective view is shown in Fig. 12(c).



(a) (b)

Fig. 11 (a) Surface measurement on Talysurf, (b) Surface Roughness Result



(a) (b) (c)

Fig. 12 (a) Reflector surface, (b) Deviation Distribution, (c) Perspective view

5. Conclusion

In this paper, the optical design, fabrication and the measurement of the freeform reflector headlamps are investigated. The design of the freeform reflectors for the automotive head lighting should agree with the international traffic regulations, such as EU-ECE, US-SAE or Chinese national standards. To create the special light pattern, the design of the freeform reflector is following the "Edge-ray principle". The reflector is divided into segments. Each segment creates an individual light aiming region. The combined light pattern meets the Chinese National Standard GB-4599 very well. In order to manufacture the freeform reflector, the raster milling conducted in a 5-axis ultra-precision computer numerical control (CNC) machine is used. A powerful NC tool path generation software package has been developed for the machining of different kind of the freeform surfaces. The surface roughness and the form error measurement are carried out on Talysurf and a laser CMM Smartscope Flash 300. Good results are achieved.

References:

[1] http://www.breault.com/
[2] http://www.lambdares.com/
[3] http://www.opticalres.com/
[4] http://www.optisworks.com/
[5] http://www.lucidshape.com/
[6] http://www.3ds.com/
[7] http://www.uni-graphic.com/
[8] Harald Ries, Ari Rabl, Edge-ray principle of nonimaging optics, J. Opt. Soc. Am. 11(10), October 1994/A, 2627-2632.

Contact info:

Dr. Sandy To
Assistant professor
Advanced Optics Manufacturing Centre, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University
Hung Hom Kowloon Hong Kong
Phone: 852-2766 6576 Fax: 852-2764 7657
Email: mfsto@inet.polyu.edu.hk
Website: http://www.aomc.hk/