Chapter 1
Introduction

Freeform optical surfaces are widely used to reduce wavefront error and sizes as compared to rotational surfaces. Ultraprecision machining techniques such as diamond turning with fast tool/slow slide servo (FTS/SSS) and diamond micromilling techniques are widely employed for machining freeform optical surfaces with ultraprecision accuracy and excellent surface quality.

Over the last several decades, these ultraprecision machining techniques are evolving to meet the demands of ultraprecision accuracy and excellent surface quality of freeform optical surfaces. This evolution in-turn marks the tipping point for the evolution of novel optical designs. These new evolutions have not been fully explored to unleash the hidden potential of freeform optical surfaces. This new field also brings us many new challenges in designing, machining and testing.

This chapter reports the current trends in ultraprecision machining techniques employed for generating hybrid freeform surfaces. Section 1.1 discusses the new era of hybrid freeform surfaces with their functionalities and applications. Section 1.2 highlights a great deal of challenges and machining barriers in this research area to be discussed for optimizing developments of these ultraprecision machining techniques to new higher levels. Section 1.3 gives a list of objectives for contributing the motivation to complete this dissertation. Lastly, Sect. 1.4 presents the organization of this dissertation, which summarizes several areas of improvements in the manufacturing of hybrid freeform surfaces.

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1.1 Hybrid Freeform Surfaces

There is a growing trend of designing freeform optical surfaces with hybrid freeform surfaces [1–7] for non-imaging devices such as solar concentrators and collimators to increase their optical performance, and imaging devices to achieve special imaging effects [7]. Simultaneous multiple surface (SMS) [1–4, 6] is one of the latest designing techniques, which can design N rotationally-symmetric surfaces that, by definition, form sharp images of Nth one-parameter subsets of rays allowing the control of extended sources. This design strategy consists of finding the best configuration of these subsets of rays in phase-space, one that ensures that image-quality specifications will be met by all rays. This gives better control of exit aperture shape without efficiency loss and increases tolerances to source displacement. It would be a challenging task to produce this new generation of freeform surfaces, as illustrated in Figs. 1.1, 1.2, 1.3, 1.4, 1.5 and 1.6, by conventional diamond machining techniques.

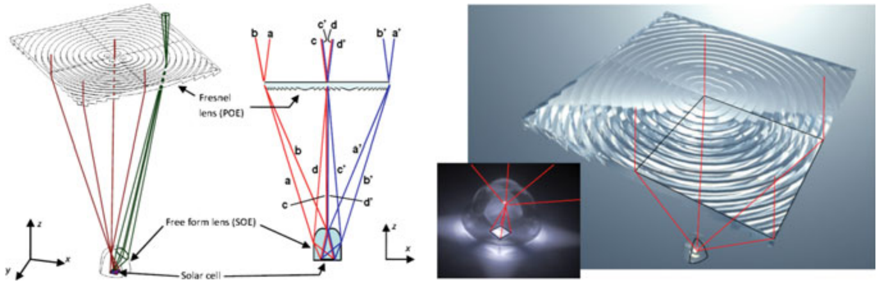

Fig. 1.1 Four-fold Fresnel-Kohler (FK) concentrator [2] schematic diagram (*left*); rendered views (*right*)

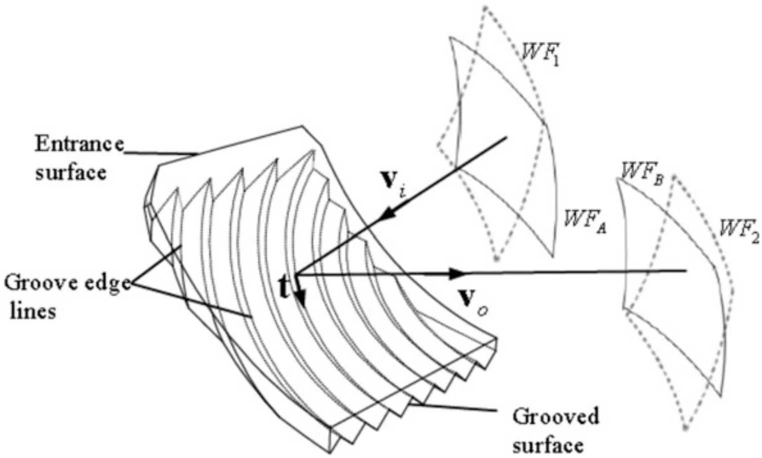

Fig. 1.2 Freeform thin dielectric sheet as a TIR reflector [3]

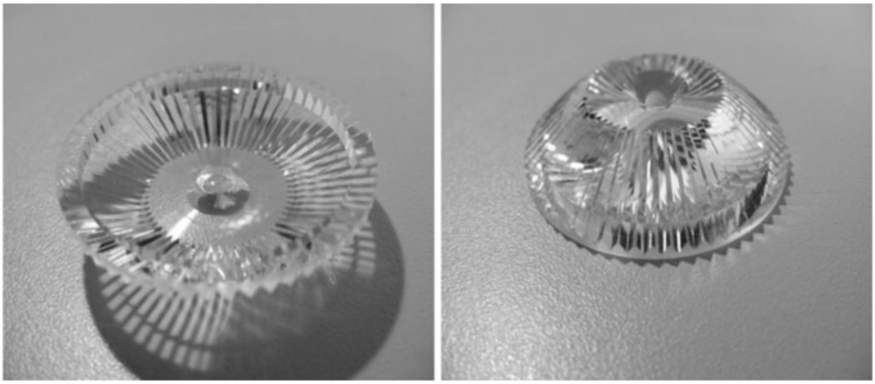

Fig. 1.3 Metal-less TIR RXI collimator [4]

Fig. 1.4 Freeform reflector to eliminate the driver's blind spot effect [5]

Thanks to the state-of-art technologies, these hybrid freeform surfaces can be easily manufactured by multiple-axis diamond machining techniques. Basically, an increasing complexity is often associated with a loss of symmetry of the surface. With an increase in the number of degrees of freedom needed for moving a tool to produce a surface, the number of controllable machine axes will be increased. The applications and principles of these multiple-axis ultraprecision machining processes for the manufacturing of hybrid freeform surfaces are discussed in the next section.

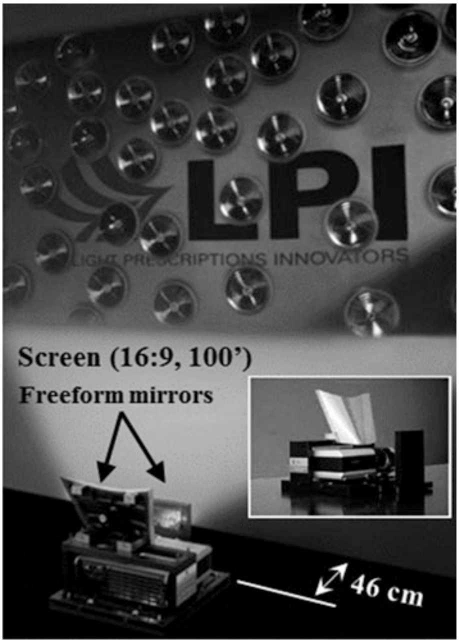

Fig. 1.5 Ultra-short throw projector by LPI [6]

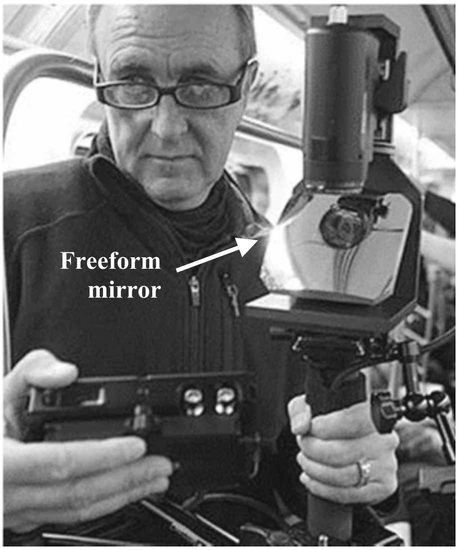

Fig. 1.6 Freeform mirror was used for special movie effect in an Oscar-nominated film, “Sleepless in New York” [7]

1.2 Ultraprecision Machining of Hybrid Freeform Surfaces

Over the past several decades, the diamond machining are evolving into ultraprecision machining techniques [8] which are capable of performing the machining of these freeform surfaces. Four common ultraprecision machining techniques are fast tool servo (FTS), slow slide servo (SSS), raster flycutting and micro-milling. These techniques have exhibited their machining capabilities to produce complex surfaces like lens arrays, bi-conics NURBS defined freeform surfaces, etc.

Figure 1.7 shows a process chain evaluating the feasibility of fabrication methods for freeform surfaces from the design to metrology [9]. This process chain allows a computer-aided manufacturing (CAM) software to generate and modify/correct the tool trajectory with the compensation of surface form error from the metrology process.

FTS diamond turning has been widely employed for fabricating the non-rotational symmetrical surfaces due to its high resolution and bandwidth [10]. Although SSS technique has a longer travel length up to several millimeters, its limited bandwidth restricts the speed of Z-axis (in the tool trajectory) for machining a complex freeform surface [11]. When raster flycutting is employed, there are several shortcomings to overcome such as relatively long and difficult setup and restriction of tool swing diameter [11]. Lastly, micro milling method requires overcoming of inherent static and dynamic limitations in the ultra-precision machine system and material removal rate is much lower than the turning process [11]. Therefore, FTS and SSS diamond turning is often employed for machining freeform surfaces [11]. In order to machine a hybrid freeform surface with large sag height, we need to have an ultraprecision machine which has the capability to machine at a larger depth and a system to generate accurate NC codes quickly and easily.

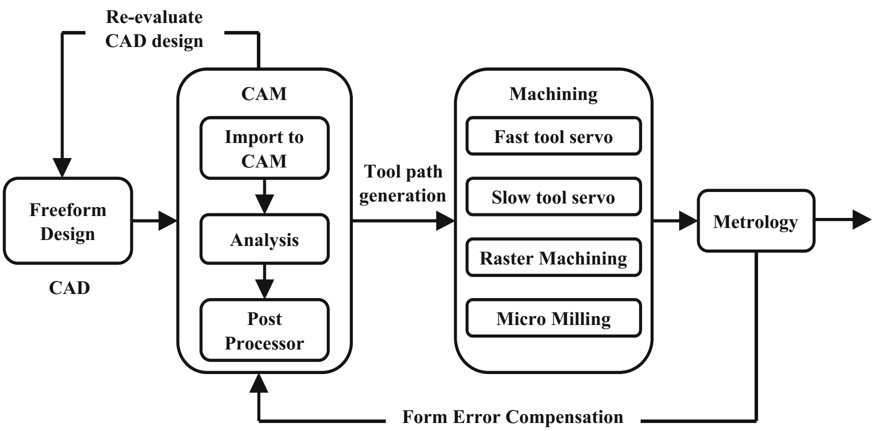

Fig. 1.7 Process chain for the fabrication of freeform surfaces [9]

1.3 Main Objectives of This Dissertation

This dissertation aims to achieve a seamless manufacturing of hybrid freeform surface with good surface quality and accuracy using the diamond turning process. The main objectives are to be fulfilled, as follows:

i. To address the limited stroke distances and bandwidths for the FTS and SSS technologies in generating hybrid freeform surface with large curvature depths;
ii. To address the difficulties in machining complex hybrid freeform surfaces which cannot be machined by FTS and SSS processes;
iii. To conduct a process optimization of machining hybrid freeform surfaces in generating accurate tool trajectory control points with ultraprecise surface accuracy;
iv. To address the need for an alternative and economical option of specialized CAD/CAM system in generating accurate complex hybrid freeform surfaces for FTS/SSS and other multiple-axis diamond turning processes.

1.4 Organization of This Dissertation

This dissertation discusses several areas of improvement for diamond turning of hybrid freeform surfaces in the following chapters:

- Chapter 2 presents a literature survey which has been conducted on the studies of the manufacturing of hybrid freeform surfaces. A list of literature loopholes are also highlighted for this dissertation.
- Chapter 3 introduces an alternative method of surface generation for FTS/SSS diamond turning of freeform surface directly from computer-aided design (CAD) software with an integration of application programming interface (API).
- Chapter 4 discusses the hybrid FTS/SSS process with a novel tool trajectory generation technique by means of several layers of tool trajectory to overcome the short FTS travel length and low bandwidth of SSS system.
- Chapter 5 discusses a novel automated Guilloche machining technique (AGMT), offering capabilities to produce of complex freeform surfaces such Fresnel lens which cannot be machined by FTS/SSS diamond turning.
- Chapter 6 discusses a novel surface analytical model which evaluates the cutting linearization errors in the FTS/SSS diamond turning process. The accuracy of machined freeform surface can be pre-evaluated with the derived novel surface analytical model before machining stage.
- Chapter 7 discusses the integration and implementation of developed methodologies in the developed CAD/CAM system. This integration shall plan and

conduct the manufacture of hybrid freeform surface within the multiple-axis diamond turning process.

- Lastly, Chap. 8 highlights the conclusions of this dissertation and recommends some future works to be done.

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