Chapter 2
Literature Review

In this chapter, a literature survey on the manufacturing processes of hybrid freeform surfaces is presented. Section 2.1 discusses the main principles and the limitations of FTS/SSS diamond turning and other multiple-axis diamond machining techniques. Section 2.2 covers the existing CAD/CAM/CAE technologies employed for the manufacturing of hybrid freeform surfaces, and discusses the needs for the surface generation methodologies to produce an accurate hybrid freeform surface. Lastly, Sect. 2.3 presents the concluding remarks that lead to this dissertation.

2.1 Multiple-Axis Ultraprecision Diamond Machining Techniques

Freeform surfaces play the key role in development of complex optical devices widely used in telecommunication, medical imaging, and surveillance systems. Freeform surfaces also allow freedom for the optics designer to design products with functional, aesthetic, and ergonomic surfaces. Ultraprecision multi-axis freeform machining techniques are often employed for manufacturing freeform surfaces with high degree of accuracy and precision. Diamond turning is one of the ultraprecision machining techniques, which has the advantages like high accuracy and high efficiency. It is often coupled with unique technique known as fast tool/slow slide servo (FTS/SSS) technologies (as shown in Fig. 2.1) for machining a freeform surface with high degree of complexity due to its high resolution and bandwidth. FTS diamond turning integrates a high bandwidth servo unit in an additional W-axis (or superimposed Z-axis) with the existing three axes (X, Z and C-axis) in ultraprecision turning machine [1]. Unlike FTS method, SSS diamond turning uses the existing Z-axis to oscillate the tool. Some of the freeform optical surfaces manufactured by FTS and SSS diamond turning processes are illustrated in Figs. 2.2 and 2.3, respectively.

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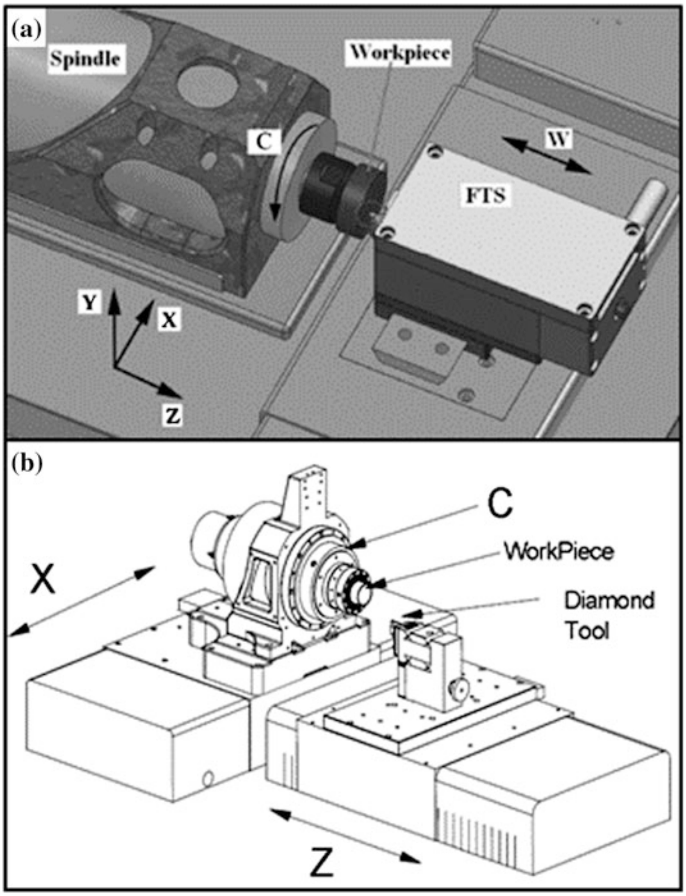

Fig. 2.1 Configurations of ultraprecision lathe machines; **a** fast tool servo and **b** slow slide servo

2.1.1 Fast Tool Servo (FTS)

Fast Tool Servo (FTS) technology plays an important role in machining complex freeform surfaces for the modern optics industry. Hence, FTS diamond turning has been widely employed for fabricating the non-rotational symmetrical surfaces due to its high resolution and bandwidth [1, 7]. Some of the works on FTS, dated back as early as 1980s, Meinel et al. [8] has successfully produced phase corrector plates for wavefront correction, and Luttrell [9] was able to fabricate off-axis conic surfaces and tilted flats with the FTS.

Unfortunately, most of FTS systems have limited travel of less than 1 mm, which makes it inappropriate for machining freeform surfaces with sag height greater than 1 mm [10]. Hence, there are several works to address this setback by increasing the FTS travel length to fulfill the sag height requirement. Several ways

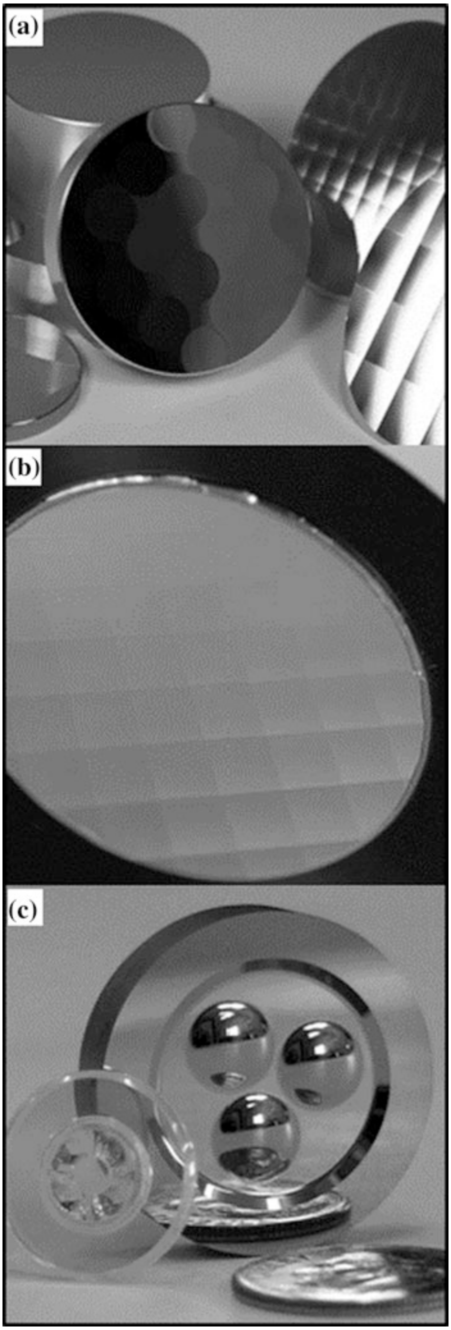

Fig. 2.2 Freeform optical surfaces by FTS process [2]; **a** faceted mirrors, **b** faceted lenses, and **c** aspheric lens array

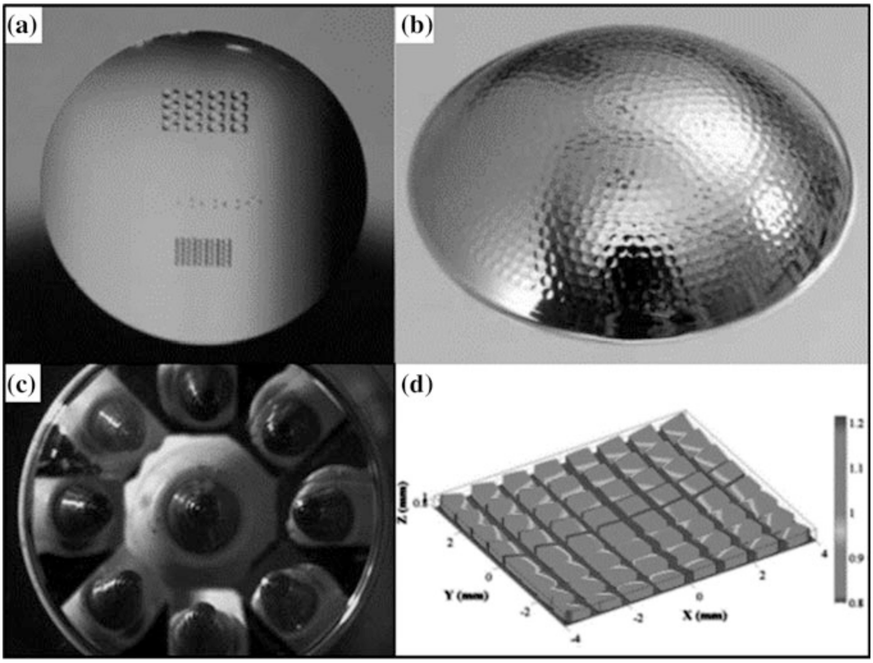

Fig. 2.3 Freeform optical surfaces by SSS process [3–6]; **a** micro Alvarez lens array, **b** artificial compound eye, **c** freeform prismatic lens and **d** 8 × 8 freeform microlens array

of extending the travel of FTS are by using rotary FTS [11] and designing flexure of higher displacement amplification mechanism incorporated with voice coil and/or piezoelectric actuators [12, 13]. Figure 2.4 shows a rotary FTS design that has a travel up to 10 mm with a frequency of 50 Hz. However, it has been reported that there is a large tool position error due to a higher harmonic frequency error during the cutting process.

A long-stroke FTS (LFTS) can also be designed by incorporating with displacement amplification mechanism composed of several levers and hinges, which can be driven by a piezoelectric actuator [12] (Fig. 2.5) or a voice coil [13] (Fig. 2.6).

Although piezoelectric (PZT) actuator may have better resolutions of positioning, it has a resonance due to its low resonant frequency, and a vibration would also induce due to its low stiffness. These would deteriorate the machined surface quality. On the other hand, voice coil actuators are hysteresis-free which can achieve an almost linear current versus force relationship for smaller travels. This is a merit over the PZT actuators which employs a charge control to avoid hysteresis. However, the voice coil FTS usually has a lower frequency. These limitations can be overcome by integrating both PZT and voice coil actuators [14], as illustrated in Fig. 2.7. In this hybrid FTS, a voice coil actuator (VCM) drives a macro-range travel whereas a PZT actuator drive a fine micro-range travel.

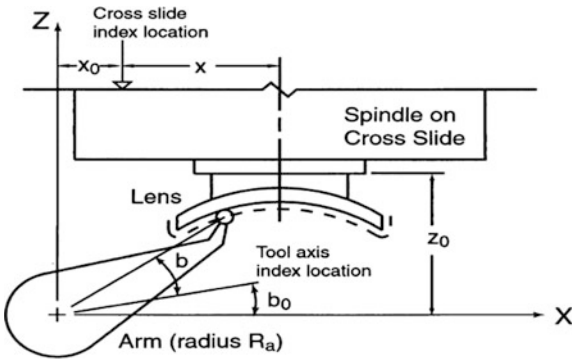

Fig. 2.4 Rotary FTS [11]

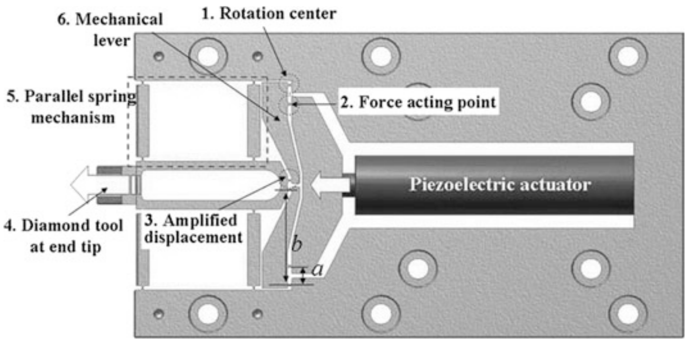

Fig. 2.5 LFTS with PZT actuator [12]

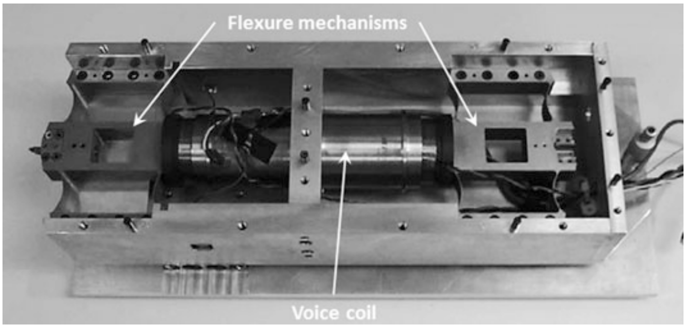

Fig. 2.6 LFTS with voice coil actuator [13]

On the other hand, a fast long range actuator (FLORA) as shown in Fig. 2.8, can also be designed in such a manner that it utilizes an air-bearing slider and linear motors [15]. This FLORA can achieve a travel length up to 4 mm but at relatively low frequency of 20 Hz.

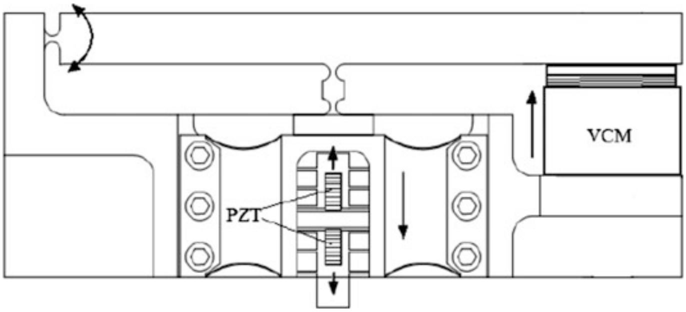

Fig. 2.7 Hybrid PZT and voice coil FTS [14]

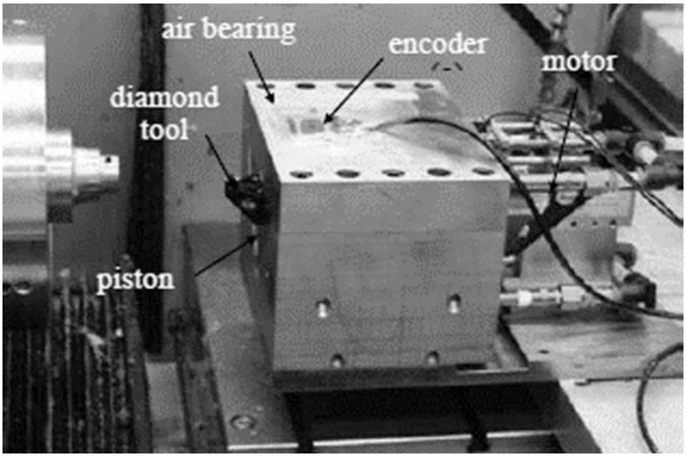

Fig. 2.8 Photographic view of FLORA [14]

From the literature review, it can be concluded that long-stroke FTSs are usually actuated by piezoelectric (PZT) and voice coil actuators [10]. PZT FTSs are usually guided by flexure hinge structures which are more suitable for error compensation. However, piezoelectric FTSs often have a low resonance frequency because of its lever mechanism bringing hysteresis and tracking error. Voice coil FTSs may have longer travels but they have lower frequencies. Hence, the travel and the frequency are two separate performance parameters which cannot be optimized simultaneously for most cases [10].

2.1.2 *Slow Slide Servo (SSS)*

Slow slide servo (SSS) diamond turning is engineered to address the travel limitation by the FTS system. SSS diamond turning has made its debut appearance in

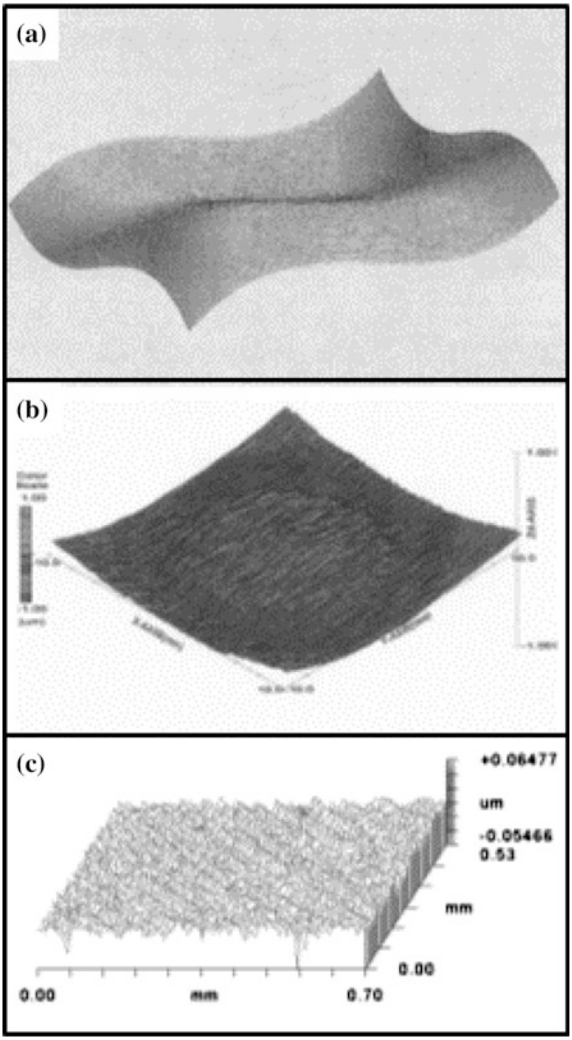

Fig. 2.9 Cubic phase plate; **a** desired surface, **b** form accuracy of 0.263 µm, **c** RMS surface finish <5 nm [16]

2003 [16] and exhibited its distinguished performance to fabricate freeform surfaces, as illustrated in Fig. 2.9, exceeding 1 mm sag height with excellent surface quality and accuracy. This marks the tipping point for the growing interest of this novel ultraprecision machining technique to fabricate freeform optical surfaces with larger sag height. STS technology utilizes the existing diamond turning machine Z-slide for the tool motion by adopting linear motor to replace ball screws. This allows more flexibility in the motion of the slide without damaging the ball screw. It has advantages of fabricating parts with much larger deviation than the FTS. By exploiting its advantages, several works [17–19] have been carried out for the feasibility study of STS diamond turning to fabricate freeform optical surfaces with high accuracy and surface quality.

To the best of the author knowledge, there are very few works reported on SSS technology and this makes it vulnerable to unforeseen barriers in the machining of freeform surfaces. However, there are some issues in this SSS process which have not been addressed. Firstly, SSS process always faces a problem of having high inertial forces due to heavy-weight linear axes, which slows movements of machining axes. This makes it is not suitable for machining freeform surfaces with higher frequency and this results in lowering cutting speeds which would degrade the surface quality. Secondly, SSS is also plagued by thermal drift during the extremely long fabrication time, similar to those traditional fabrication methods such as grinding, polishing, or flycutting.

2.1.3 Other Multiple-Axis Ultraprecision Machining Techniques

Figure 2.10 illustrates and classifies the complexity and scale of different machining processes for generating optical (micro-) structures with respect to their characteristic dimension [20]. Notwithstanding the fact that the multiple-axis ultraprecision machining techniques such as FTS, SSS, diamond milling, etc. have demonstrated their capabilities to fabricate hybrid freeform surfaces, they are still facing the difficulties to fabricate hybrid freeform surfaces with complex curvatures in a single setup. This is due to the increase of complexity associated with the loss

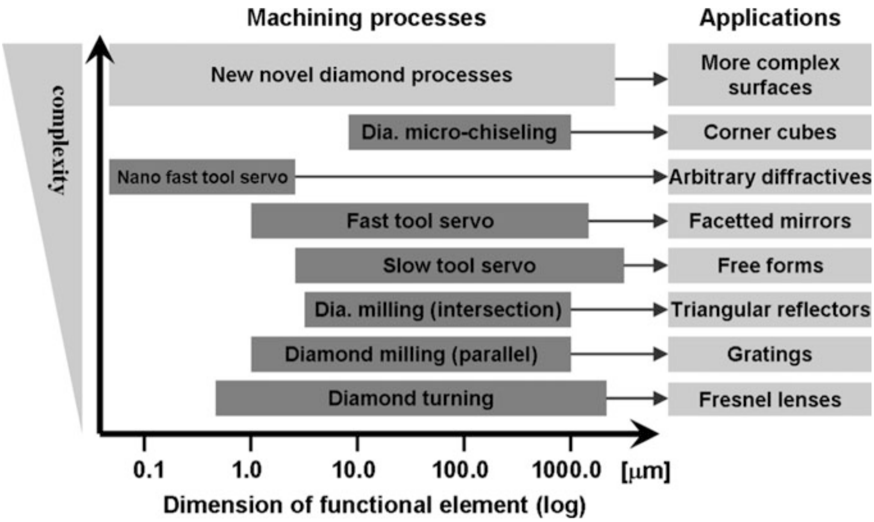

Fig. 2.10 Complexity and dimension of optical (micro-) structures [20]

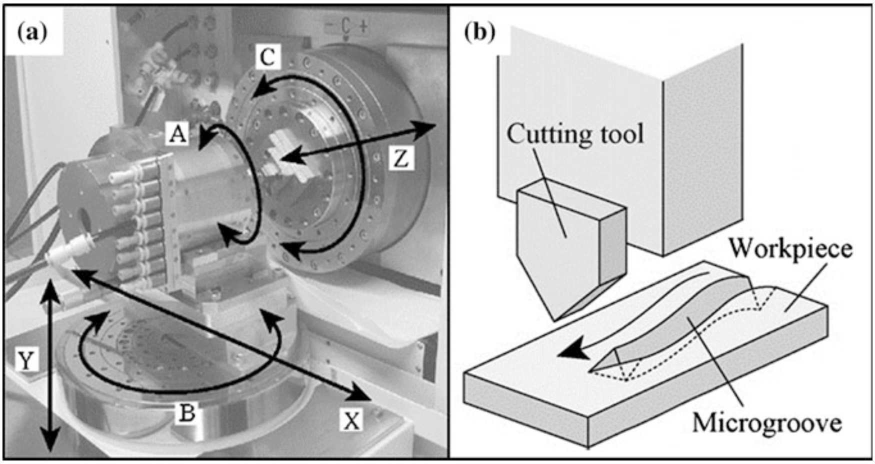

Fig. 2.11 6-axis grooving technique [23]; **a** configuration and **b** cutting a freeform groove

of symmetry of the surface [21]. Hence, it is necessary to increase the number of machining axes for moving a diamond tool to produce a freeform surface [22].

Recently, novel ultraprecision machining techniques have been developed to meet the increasing complexity for freeform surfaces in optical or mechanical applications. Multiple-axis microgrooving [23], as described in Fig. 2.11, is one of the novel techniques exhibiting the capability to fabricate flat-ended freeform microgrooves. Another novel technique is diamond micro-chiseling [24], as shown in Fig. 2.12, which has also demonstrated its capability to fabricate micro retro-reflectors and other micro-optical geometries. In the near future, more novel ultraprecision machining techniques would be begotten from the developments of ultraprecision machine systems offering a great opportunity to unlock the hidden potentials and challenges in the freeform optical surface.

One of the potential multiple-axis techniques is an interesting freeform engraving technique known as Guilloche engraving [25]. Guilloche engravings are widely used in luxury watches and jewelleries, and security features in passports, credit cards, etc. [26, 27]. Guilloche engraving utilizes a rose engine lathe [28], as shown in Fig. 2.13, to engrave a repetitive architectural patterns of intersecting or overlapping spirals [29, 30] in a spirograph manner. Spirograph [31] is a geometric drawing toy that produces mathematical roulette curves of the variety technically known as hypotrochoids and epitrochoids. Notwithstanding the fact that the Guilloche technique has the capability to produce freeform patterns, it is still a tedious and time consuming hand-operated process. Thus, an automated technique is required to replace this hand-operated process.

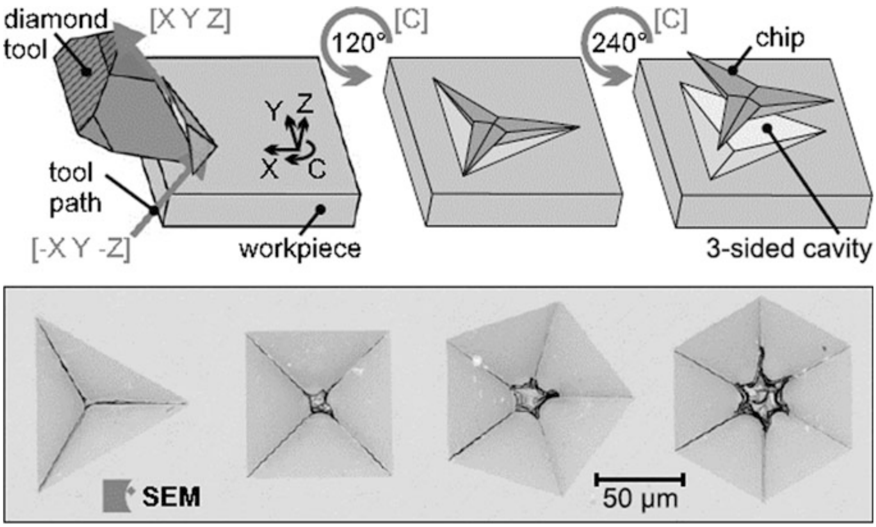

Fig. 2.12 Diamond micro-chiseling technique [24]; (*top*) cutting mechanism and (*bottom*) micro-chiseled prismatic facets

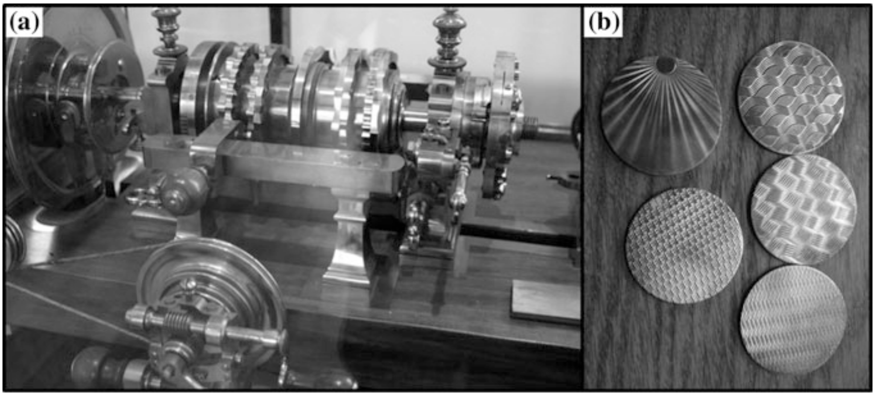

Fig. 2.13 **a** Rose engine lathe [28] and **b** Guilloche patterns [29]

2.2 State-of-Art CAD/CAM/CAE Technologies

2.2.1 CAD/CAM Technology for Surface Generation

It is commonly to employ a computer-aided design (CAD) software (SolidWorks, etc.) to design the hybrid freeform surfaces for optical applications, instead using of traditional and tedious mathematical approaches. CAD software solutions provide not only designing solutions but also simulation analysis solutions with an aid of computer-aided engineering (CAE) technology [32]. These CAD models could be further utilized for post-processing into tool path by CAM software. However, there are common shortcomings for conventional CAM software solutions which make them unsuitable for generating tool path on freeform surfaces, which are of resolution ranges of 10 nm in the CAM systems and lack of post-processing system to support FTS/SSS processes [33]. This 10 nm resolution range not only is large as compared to ultraprecision applications (<1 nm), but also often causes large shape deviations and poor surface roughness on the fabricated freeform surface. Hence, customized CAM software is deemed necessary for providing suitable post-processor with adequate accuracy in generating tool path for FTS/SSS diamond turning.

Although there are available commercial software solutions such as DIFFSYS [34] and NanoCAM 2D/3D [35] for FTS/SSS diamond turning, they are still very costly and their methodologies for generating accurate surfaces with optimized process parameters are executed in the black box. Hence, there is still a room for improvement on the optimization of process parameters to achieve good surface quality and accuracy. Manufactures have been searching for solutions to sustain their competitive advantage in mass producing products at the shortest time to market and at a most economical cost. Hence, these drive the need for an alternative and economical option of generating accurate tool trajectory for FTS/SSS diamond turning and other multiple-axis machining processes.

Fortunately, the resolution ranges found in most commercial CAD software solutions are generally finer than those in CAM systems. This advantage could be further exploited for generating tool trajectory on freeform surfaces by employing the Visual Basic application programming interface (API). This marks the tipping point for growing attention on integration of API and CAD software for reverse engineering methodologies [36]. However, according to author's knowledge, there is no implementation of API approach to generate accurate spiral tool trajectories for the FTS and SSS process.

2.2.2 Surface Accuracy and Error Compensation Approaches

The new era of ultraprecision machining technologies for freeform optics requires the advancement of design and testing for innovative optical function and improved optical performance [37]. Although a mirror surface is necessary for a good optical performance of freeform surfaces, the surface accuracy is a dominant factor for the overall optical performance. Figure 2.14 clearly explains that a freeform surface with good accuracy would guide the lights to the designed paths accurately. Otherwise, the lights would be diverted away from the designated paths. Hence, much research work has been conducted in the area of surface generation with ultraprecise surface accuracy for freeform optics. Over the past decades, much

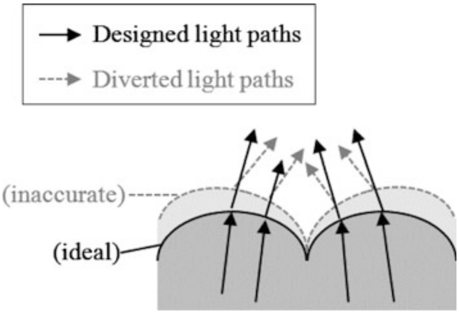

Fig. 2.14 Effect of surface accuracy on the optical performance

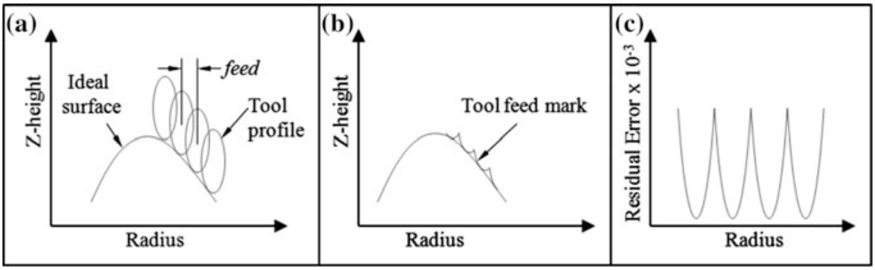

Fig. 2.15 Cutting residual error of a machined freeform surface; **a** Tool profiles on ideal surface, **b** resulted tool feed marks on machined surface, and **c** resulted cutting residual errors due to the errors from feed marks

research has been conducted on the surface generation methods, machine dynamics, error analysis and methodologies for error compensation.

In the FTS/SSS processes, there are two different types of surface errors, namely cutting residual and cutting linearization errors. The cutting residual error, as described in Fig. 2.15, is the formation of tool marks on the surface along the feed direction [38–42]. Kong et al. [38] and Yu et al. [40] have studied and successfully developed their models for predicting this residual error in the FTS/SSS processes. They also conclude that the residual error dominates the errors by the tool nose radius and feedrate, and is analogous to surface roughness. Thus, a proper selection of feedrate and tool nose radius should be developed for machining accurate freeform surfaces.

In contrast, cutting linearization error, as illustrated in Fig. 2.16 is the Peak-to-Valley error (PV_{err}) between the ideal surface profile and the linear tool trajectory in the spiral cutting direction. This PV_{err} depends mainly on the cutting distance between the two corresponding points in the cutting direction. It has been reported that the best profile accuracy results can be achieved by the spline interpolation method in the DiffSys software [43, 44]. However, the details for selecting cutting parameters in the spline interpolation method were not reported.

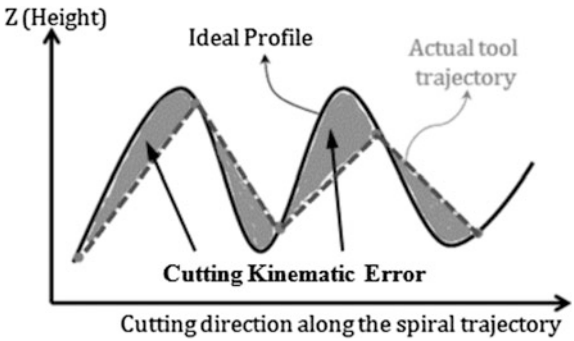

Fig. 2.16 Cutting linearization error of a machined freeform surface

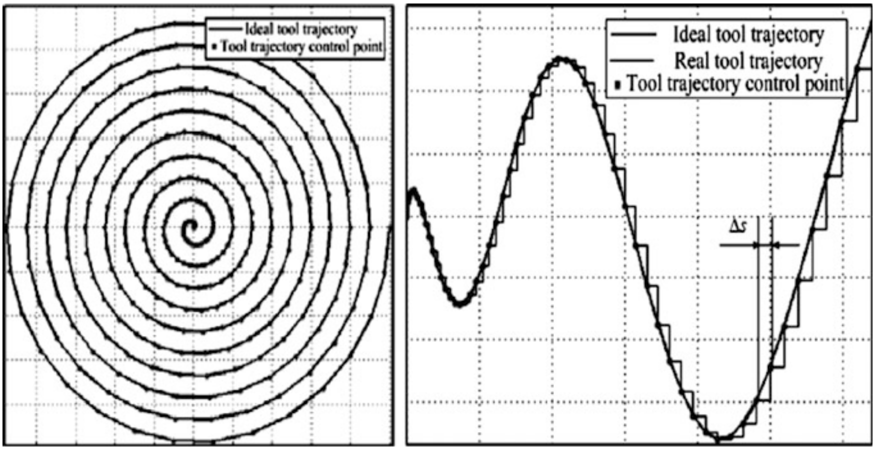

Fig. 2.17 Tool trajectory by constant angle method [45]

Zhou et al. [45] have conducted a comparison studies on surface quality of machined surface based on constant-angle and constant arc-length methods, as illustrated in Figs. 2.17 and 2.18, respectively. When the constant-angle method is employed, the surface quality of outer regions is reported to be worse than that of central regions due to arc-lengths between the corresponding points on outer regions are sparser than those on central regions. Whereas the constant arc-length method shares the same number of cutting points as constant-angle method, the machined surface error is constant.

It has been also reported that the selection of critical incremental arc-lengths plays an important role in achieving accurate ultraprecision freeform surfaces [46]. Notwithstanding the fact that the constant arc-length method demonstrated its capability for better overall profile accuracy, only sinusoidal wave grid (SWG) profiles were served as case studies. It still remains unknown whether the constant arc-length method is also an ideal method for other profiles as well.

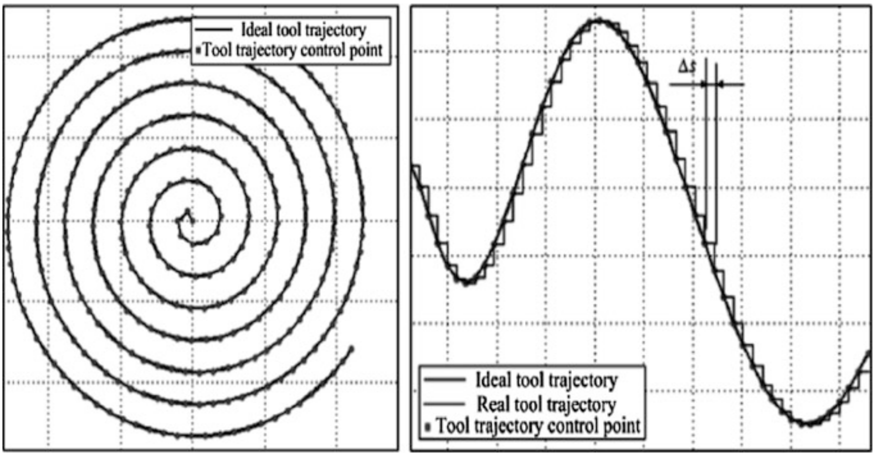

Fig. 2.18 Tool trajectory by constant arc-length method [45]

2.3 Concluding Remarks

From the literature review, it can be concluded there are four main loopholes which are necessary to be addressed for the seamless manufacturing of freeform surfaces with good quality and accuracy. They are highlighted as below:

(i) Limitations of FTS and SSS processes

The limited travel length of fast tool servo (FTS) system is not suitable for machining freeform surfaces with larger sag heights. The travel length has to be increased by employing either piezoelectric and/or voice coil actuators. Although piezoelectric FTSs are more suitable for error compensation, they often have a low resonance frequency because of the lever mechanism. This lever mechanism also brings hysteresis and tracking error from the lever bending. On the other hand, voice coil FTSs may have longer travel than piezoelectric FTSs but they have lower bandwidth than other FTSs.

Although the slow slide servo (SSS) process may have much longer travel length than FTS process, the major limitation of SSS is having a low bandwidth system due to the heavily-weighted machine slides. This low bandwidth makes SSS process not suitable for machining freeform surfaces with higher frequency asymmetries. It also limits the cutting speed to low spindle speeds which would bring the possibility of degrading the surface finish. Furthermore, the low spindle speed may lead to thermal drifts as the fabrication time of the freeform surface increases.

Both of the travel and the bandwidth are two separate performance parameters which cannot be optimized simultaneously in most cases. Hence, a study for optimization of FTS and SSS process is necessary to obtain both optimal travel and bandwidth for the machining of hybrid freeform surfaces.

(ii) Machining barriers in the machining of complex freeform surfaces

Although FTS and SSS diamond turning can produce complex three dimensional structures, higher degrees of freeform optical surfaces such as Fresnel lens arrays are yet to be achieved in a single setup. This is due to the increase of complexity associated with a loss of symmetry of the surface. Hence, it is necessary to increase the number of machining axes (degrees of freedom) for moving a diamond tool overcoming the loss of symmetries to produce a freeform surface. Few novel ultra-precision diamond machining techniques have been begotten from the developments of ultraprecision machines to fulfil a great deal of demands for generating highly complex freeform optical surfaces.

However, these machining techniques are suitable for only a handful of freeform surfaces and may require several setups which would lead to accumulation of setting errors resulting inaccurate ultraprecision freeform surfaces. Thus, a novel multiple-axis ultraprecision machining technique is necessary to minimize the number of setups for producing accurate ultraprecision hybrid freeform surfaces.

(iii) Cutting linearization errors

Cutting linearization error is the profile error (PV_{err}) between the ideal surface profile and the linear tool trajectory in the spiral cutting direction. This inherited error should not be ignored as it would sequentially accumulate those errors from the machine dynamics, etc., resulting larger errors or poorer profile accuracy. Cutting linearization error usually depends on the machinist's skills and experience, and it often analyzes during post-machining stages. Hence, it is not reliable to depend on highly skill labour and not cost effective to analyze in post-machining stages. Therefore, it is necessary to develop a model to analyze the cutting linearization error for generating accurate ultraprecision freeform surfaces in the FTS and SSS processes.

(iv) Comprehensive CAD/CAM system for machining of hybrid freeform surfaces

Most of commercial CAM software solutions (SolidCAM, Unigraphics, etc.) are presently unable to support fast tool/slow slide servo (FTS/SSS) diamond turning of freeform surface due to the difference in the coordinating systems. Hence, a special CAM post-processor is required to generate the spiral tool trajectory in the FTS/SSS diamond turning. However, these special CAM software solutions are very expensive. Manufactures have been searching for solutions to sustain their competitive advantage in mass producing products at the shortest time to market and at a most economical cost. Hence, these drive the needs for an alternative and economical option of generating accurate tool trajectory for FTS/SSS diamond turning of freeform surfaces.

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