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Form error in diamond turning

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ABSTRACT

The main feature of ultraprecision, single point diamond turning (SPDT) is its ability to produce high quality surface finishes on the order of nanometers while meeting tight form tolerances on the order of micrometers. This capability allows for the production of optical devices with minimum post-processing operations. The issue of form error is critical since it may severely compromise the performance of the designed optical system. Tool-workpiece relative vibration is a major cause of this error. In this article, the authors have demonstrated that imbalance of the spindle is a major cause of form error which eventually leads to a structured error called "spindle star" that appears as straight concentric spokes radiating out from the center of the part. The formation of a spindle star pattern can be explained using Campbell's rotordynamics analysis. This analysis explains how assisted air-hammering instability and cross-coupling effect of the air-bearing spindle can contribute to spindle star. This experimental approach used force and accelerometer data with the help of modal analysis to conclude that spindle star is a synchronous error and is a function of rotational frequency of the spindle and its harmonics. The integer harmonic from the Campbell's waterfall diagram predicts the number of spokes in the spindle star. It was also observed that the height of the spindle star undulations increases with higher rotational speed. It was also observed that cutting material and tool geometry has no influence on the spindle star formation; rather this is an inherent characteristic of air-bearing journals. Finally, the analysis was successfully validated by changing the natural frequency of the spindle by adding mass.

1. Introduction

Ultra precision, single point diamond turning (SPDT) is a tool based machining technology to produce high quality surface finishes on the order of nanometers while meeting tight form tolerances on the order of micrometers. The purpose of improving the surface finish in diamond turned surfaces is to reduce the cost of rotationally-symmetric optical components by reducing or eliminating costly manual polishing and lapping. In the diamond turning process, the proper combination of good workpiece quality, sharp and controlled waviness tools, and a high quality positioning system will create a part with high accuracy and optical surface quality. It is generally agreed that surface finish in SPDT is primarily affected by four factors [1,2] which are: tool geometry (nose radius, machining parameters), relative vibrations between tool-workpiece, material properties and microstructure, and tool cutting edge quality. Among these factors, form error is generated from the undulations between the "relative vibrations between tool-workpiece" and may become a part of the surface roughness measurement. This issue is extremely critical if the error is structured and regular in pattern as it severely compromises the designed optical system performance.

Many articles have reported on the relative vibration between the tool and workpiece and their effect on surface roughness. Off line and in process metrologies have also been performed to develop new technologies to compensate for such errors; however, the source and characteristics of these errors have not been fully developed. In this article, the authors have summarized their observations on spindle star formation on a diamond turned flat workpiece surface using rotordynamic analysis and assisted air-hammer instability of the air-bearing spindle. The observations explain the formation of structured undulations which have been consistently observed on the machined surface of parts. This article also explains how to predict the expected number of undulation spokes from a given air-bearing spindle system and provides recommendations for minimizing their formation.

One of the pioneering works on relative tool-workpiece vibration was done by Takasu et al. [3] who assumed that a simple harmonic motion with small amplitude and low frequency exists between the tool and the workpiece. He presented equations

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describing the resulting pattern in the feed direction by considering the effect of vibration on surface roughness, specifically as it concerns the interplay between the tool nose radiuses. His analysis for fly-cutting was further adopted by Fawcett [4] who also measured the relative tool/workpiece vibrations (not during cutting) in the in-feed direction with a capacitive gage to develop a fast-low-amplitude tool servo to compensate for such errors during turning. These equations [3] are in turn used by Cheung and Lee [5–7] with a capacitive displacement probe between the tool and the spindle in predicting values of peak–valley surface roughness, R_t, and mean arithmetic roughness, R_a, and on comparing predicted values with those measured on ultraprecision machined workpieces. In their works [6,7] the surface roughness evaluation length used was 0.5 mm. Since such vibrations can be large enough to be considered as part of the form error, the authors of this article believe that this small evaluation length may result in a misrepresentation of the surface finish. In their work, Cheung and Lee [6] also concluded that material crystallography induced vibration is another major factor contributing to the generation of surface roughness, in addition to the tool feed rate, the spindle rotational speed, the tool geometry, the material properties, as well as the relative tool-work vibration, which have been previously studied. The possibility of chatter in diamond turning has been ruled out by them [7] since the depth of cut in ultraprecision machining is usually in the range of a few to several tens of micrometers and the chatter vibration induced by the regenerative effect seldom occurs as it is generally developed under heavy-duty cutting. However, some high frequency marks (12 kHz to 14 kHz) on the cutting force signal and surface roughness profile have recently been reported in the cutting direction which is believed to be from the tool-tip vibration [8] during SPDT. Nevertheless, none of these articles explain the source of the error motion, except in the case of tool-tip vibration which is not a focus of this article.

Bittner [9] simulated all possible sources of error while diamond turning diffractive optical elements. His simulations covered not only physical errors from decentering of the tool with respect to the center of rotation and tilting of the machine slide relative to the spindle, but also periodic errors like variable shift between tool and spindle, periodic structures formed due to thermal effects, and tool wear and vibration of the axis of rotation which produces a spindle star pattern on the part. Kim and Kim [10] analyzed and compensated the thermal growth spindle error in real time using a fast tool servo along with a capacitive displacement sensor and were able to bring the form error down to 0.1 μm in a 100 mm diameter specimen. Finally, vibrations of the spindle perpendicular to the workpiece can result in azimuthal ripples on the surface forming the spindle star pattern. Again, according to Juergens et al. [11], spindle star can be caused by imbalance of the workpiece on the machine and a properly designed spindle generally produces little or no spindle star. The size and location of the air bearing orifice can cause axial oscillations of the spindle; however, newer spindles all have continuous air slots based on the use of porous bearing materials. The use of these designs has greatly reduced this source of error but they remain a significant source of workpiece quality issues as product specifications have tightened. It is difficult to see further reductions in the spindle star form error through spindle balancing as it is impossible to make a part without error and compensation for imbalance is often done out of the error plane on the body of the vacuum chuck. Torque ripple from the motor can also cause vibration. It has been observed that parts produced from current study and off-the-shelf components produced from other machines all suffer from spindle star error. Fig. 1 shows optical metrology of a diamond turned copper workpiece showing a star pattern radially spreading outward from the center as observed in this study. Fig. 1 has a field of view of 30 mm × 24 mm.

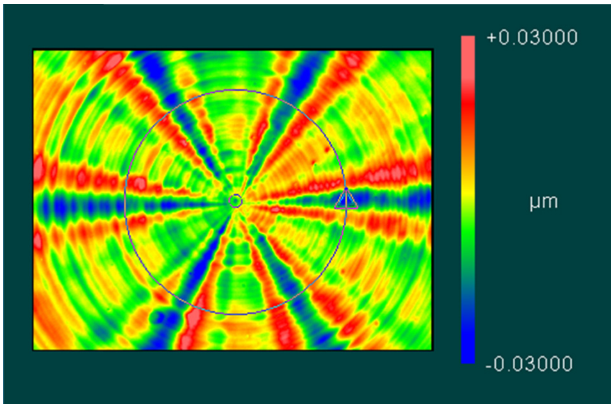

Fig. 1. Spindle star formation on a diamond turned copper workpiece.

Khanfir et al. [12] in 2005 has also observed the spindle star and stated that the error is due to resultant facial and radial motion of the machine spindle. By using a spindle with active magnetic bearings, Khanfir et al. was able to filter out the fifth harmonic vibration of the spindle, eliminating the five lobed spindle star, and leaving a surface with a seven lobed spindle star pattern instead. Although the vibration amplitude decreased when the active magnetic bearings were applied, the pattern continues to exist. A similar observation on spindle star was also made by Zhang et al. [13] in 2012. They developed a mathematical model with five degrees of freedom of an aerostatic spindle and analyzed how its movements affect the surface topography in spindle star formation of a machined surface in SPDT. Zhang et al. [13] also observed that the operating speed has a significant role on how that imbalance will act and the moving point contact of the tool-workpiece can also trigger an imbalance. It is very important to know what may cause the spindle star form error since each machine may operate at different spindle speeds. However, both these articles [9,11] addressed the source of such error as coming from the spindle axial motion due to the imbalance in the air-bearing spindle system.

The spindle star error is a form error that results in a wavy surface in which the peaks and valleys form straight, radial spokes on the surface of the workpiece. These straight, radial spokes are constant across the surface and are not dependent on machine position. Although the spindle star pattern is not visible to the naked eye, the structured form error can be amplified in an optical system which causes imaging problems.

In air bearing spindles, motion error is often characterized by 3 features: eccentricity, higher order synchronous motion, and asynchronous motion errors. Synchronous vibration is defined as a vibration that is equal to an integer multiple of the rotating frequency. Asynchronous vibration is defined as a vibration which is at a frequency that is other than an integer multiple of the rotational frequency. In other words, when the disturbance frequency is a harmonic of spindle rotating frequency, it is termed as synchronous error motion and when the disturbance frequency is independent of spindle rotating frequency it is termed as asynchronous error motion. Basic eccentricities in motion error can be addressed by proper bearing alignment and balancing; however, reducing synchronous and asynchronous motion requires a combination of attention to air flows and bearing geometry. One of the major factors in ensuring low asynchronous motion error is an air supply that is free from pressure pulses and contaminants [14]. Improvements in manufacturing methods have had an important effect on motion error and have enabled errors to be reduced from about 200 nm down to 50 nm [14,15] over the last twenty years. Further improvements are needed as tolerances continue to tighten. To meet these challenges, our understanding of the