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Ultra-precision machining centre for corrective machining of freeform surfaces

Frank Niehaus[1], Stephan Huttenhuis[1], Alex Pisarksi[2]

[1]*Schneider GmbH & Co. KG,* [2]*Schneider Optical Machines Inc.*

f.niehaus@schneider-om.com

Abstract

The UPC 400 enables efficient and accurate machining of freeform surfaces by integrating the fabrication and measurement processes onto a single machine platform. Combining hardware with powerful data handling capabilities allows for corrective machining to achieve high precision freeform surfaces. This paper discusses the corrective machining of spheres that are diamond turned off-axis, requiring the full freeform capability of the machine. Based on the measurement results acquired by integrated optical metrology, a new corrective surface is calculated that compensates for repeatable errors. After corrective machining, a form accuracy of better than ± 0.1 µm was measured with the integrated optical sensor.

Keywords: Ultra-precision machine tool, Freeform machining, Diamond machining, Integrated metrology, error compensation

1. Introduction

Innovative optical systems designed for a wide range of industries such as aerospace, automotive, sensor, LED lighting, and consumer electronics are increasingly using freeform optics [1-3]. Nevertheless, the production of freeform surfaces is challenging and time consuming. Besides the mechanical limits of the machining process, additional limiting errors can result from data conversions and the freeform measurements. These limits are overcome by using an integrated solution which combines machining and full area metrology of freeform surfaces onto a single machine platform and therefore requires only a single NURBS set-point surface for the entire manufacturing process.

Due to integrated metrology, the freeform can be measured directly after machining in one clamping set-up. Afterwards the result can be used without any data conversion for corrective machining. In that way, the highest precision is reached in the shortest time with high reproducibility. This approach is used for the first time by the ultra-precision machining center UPC 400 and will be introduced in this paper.

2. Machine design

The UPC 400, shown in Figure 1, has been designed to efficiently manufacture freeform surfaces up to 400 mm in diameter by integrating fabrication and measurement processes onto a single machine platform. Freeform surfaces can be diamond machined by the UPC 400 using fast tool motion (FTS), slow tool motion or a combination of both. The FTS can achieve high acceleration rates and provides a stroke length of greater than 10 mm. This is currently the longest commercially available stroke length for a fast tool setup and provides the ability to quickly machine highly dynamic freeform surfaces without the use of a time consuming slow tool process.

For optical, non-contact metrology, the UPC 400 uses integrated interferometric or chromatic sensors with measurement frequencies of several kHz and resolutions of < 1 nm. Furthermore, tactile metrology can be integrated to measure steep freeform geometries. The measurement is performed immediately after machining and uses a spiral tool path to scan the freeform surface. This eliminates the need to remove the optic from the machine and enables a final corrective machining process.

The data handling capabilities of the UPC 400 power the machining, metrology, and corrective machining processes. The control allows for the import of NURBS freeform data that is generated in typical optic design software. Thereby losses in data accuracy due to the exchange procedure are completely avoided. The NURBS freeform data from a STEP file then can be directly used to create the subsequent NC programs for both machining and measurement. This further eliminates data conversions between the different process steps that can distort the data. Also, the surface measurement, represented as a point cloud, can be compared to the initial NURBS file to determine the deviation from the prescribed surface. The resulting difference is used to generate a new, error compensation file for corrective machining.

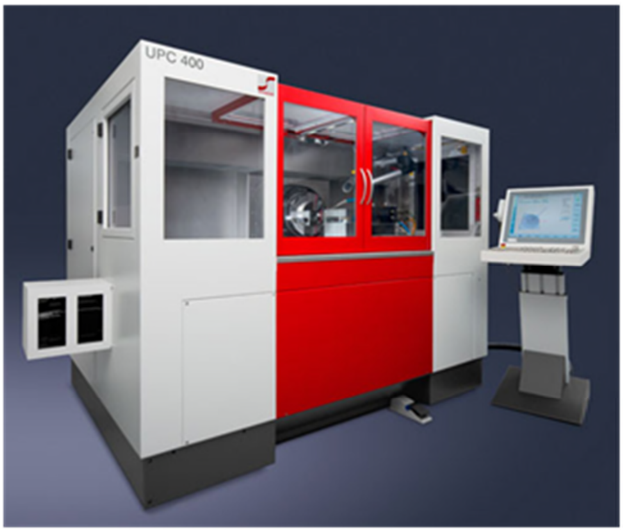

Figure 1. UPC 400 integrates diamond turning, milling, and metrology onto a single machining platform.

3. Machining results

The UPC 400 has demonstrated the ability to fabricate parts to high levels of accuracy. On a 50 mm diameter, spherical aluminum (Al 7075) mirror, the UPC 400 achieved form accuracies better than 60 nm PV (Figure 2, left). The machining took place at 2000 rpm. Furthermore, a surface roughness of about 1 nm Sa can be achieved using nickel-phosphorous materials as shown in Figure 2 (right).

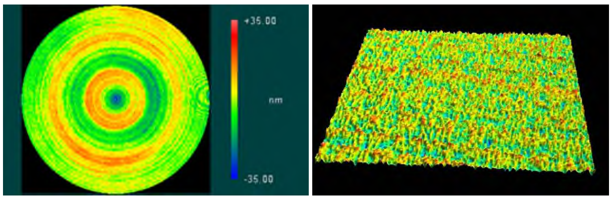

Figure 2. Left: On-axis-sphere R = 100 mm with form accuracy better than 60 nm PV. Right: Surface roughness measurement on nickel-phosphorous material (50x objective: 0.17 x 0.17 mm², Sa = 0.97 nm).

4. Corrective machining results

In order to demonstrate the freeform machining and correction capabilities of the UPC 400, two spherical cavities were machined off-axis (Figure 3). The two opposing spheres are located at a radius of 45 mm. Each sphere has a radius of 100 mm and a depth of about 4 mm. The machining time was 2 hours at a rotational speed of 45 rpm using the slow tool motion of the UPC 400. Given the depth of the cavities, this process time represents a very efficient machining cycle. Nevertheless, the use of the fast tool system enables a 2-3 times higher spindle speed which further reduces the machining time.

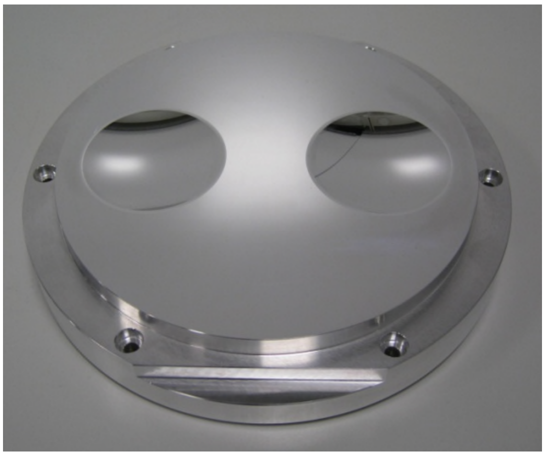

Figure 3. Off-axis-sphere for demonstrating the freeform capabilities of the UPC 400.

Figure 4 (top) shows the form deviation of the off-axis spheres measured by an integrated optical measurement system after the machining step. The result demonstrates the ability of the UPC 400 to machine a freeform surface to submicron level accuracy. The remaining surface figure error of < ± 0.5 µm is low order with minimal mid-spatial frequency errors. The characteristics of this form error indicate also an off-set in the tool height (Y-axis). During corrective machining, these kinds of error can be compensated for and corrected. The resulting specific form deviations of the corrective data file are shown at the bottom of Figure 4. This compensated NURBS surface contains the necessary information to further improve and correct the surface figure error.

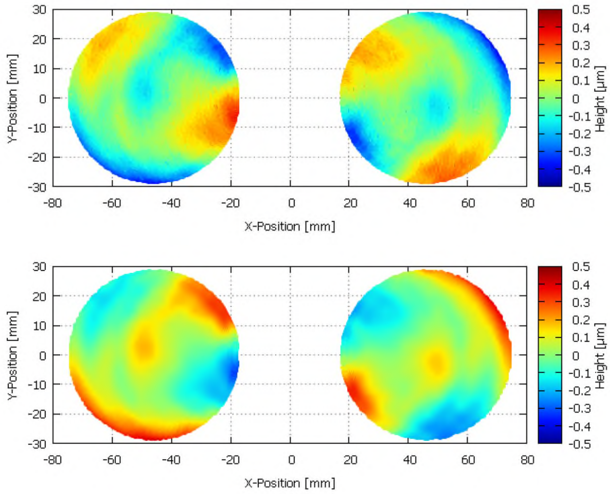

Figure 4. Measured form deviation (top) and specific form deviations of corrective NURBS surface (bottom).

The new surface data is then used for the re-machining using the same machine, tool setup, and process parameters. Figure 5 shows the remaining deviations after re-machining measured by the integrated optical metrology system.

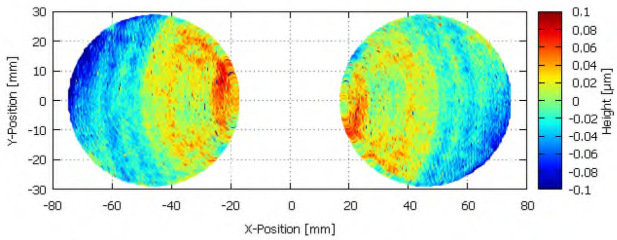

Figure 5. Measurement result after corrective machining.

Values of below ± 0.1 µm can be achieved. These results further demonstrate the accuracy and repeatability of the measurement system and of the UPC 400.

5. Conclusion

By integrating fast and slow tool diamond turning, milling, and metrology along with powerful data handling capabilities, the UPC 400 creates an ideal single machine platform for fabricating freeform surfaces. The highest quality form accuracies in freeform machining are achieved in the shortest process time. The single clamping setup preserves the coordinate system enabling the UPC 400 to correct for repeatable machining errors and achieve highest surface accuracy of < ± 0.1 µm.

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