euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Manufacturing uncertainty: How reproducible is the depth of cut during diamond turning of OFHC copper?

Junguo Zhao, Claudiu Giusca* and Saurav Goel+

School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, MK43 0AL, UK
*C.Giusca@cranfield.ac.uk *and* +S.Goel@cranfield.ac.uk

Abstract
Single point diamond turning (SPDT) used for micromachining has emerged as an indispensable and high-volume production manufacturing process for shaping and finishing various materials. As a preliminary testbed study, this paper investigates manufacturing uncertainty in SPDT originating from controllable and uncontrollable sources of errors. A Moore Nanotech 350 UPL SPDT machine was employed to perform repeat cutting of step heights on OFHC copper substrate at fine cutting depths in the range of 50 nm to 500 nm. The metrology was performed by a contact stylus profilometer from Taylor Hobson. While a great deal of uncertainty was observed in the results, a stark observation was that the programmed and actual depth of cuts differed less nearer at the centre of rotation of the substrate as opposed to periphery of the substrate demonstrating that the machining achieved least uncertainty nearer to the centre of rotation. A hypothesis is accordingly proposed for achieving more deterministic certainties from SPDT.

Keywords:
Micromachining, diamond turning, OFHC copper, error, uncertainty.

1. Introduction

Image slicer mirrors for Mid-infrared Instrument (MIRI) telescope, Boltzmann sphere, precision textured hydrophobic surfaces and metrology artefacts are just few examples of latest advents in Precision Engineering demonstrated by Cranfield. These state-of-the-art developments in micromachining using diamond turning have pushed the attainable precision positioning in nanometric range. Consequently, whilst micromachining enables to exploit tighter tolerances, it is still somewhat daunting to achieve deterministic nanometric precision accuracies. Establishing uncertainty of a machining system in general and diamond machining in particular is a rudimentary step towards establishing a more predictive capability for error compensation. In this preliminary study, an attempt was made to assess the manufacturing uncertainty during precision SPDT operation. Major motivation of this work stems from a simple research question: whether the tool is likely to yield least uncertainty in a facing cut while entering into the workpiece from the centre and exiting at the periphery or vice-versa? An answer to this question will pave way to suppress machining induced errors.

2. Methodology

Face turning cuts were made on the OFHC copper substrate (Ø74 mm). Copper was judiciously chosen as the workpiece material as it is friendly to diamond machining and avoids the possibility of tool wear, which would have otherwise complexified the error measurements. A newly lapped diamond tool with a nose radius of 0.53 mm, rake angle 0° and clearance angle -10° was used for machining for the entire set of cuts. A single standard tool (non-controlled waviness) was used as supplied by Contour Fine Tooling. Three repeat cuts of four step heights were performed at different radii of the workpiece as shown in Figure 1. In total, four profile measurements at four different places (90° to each other) were made for each cut. Thus, a total of 16 profiles were obtained for each step machined. Overall, 48 data points were obtained from the entire set of machining trials.

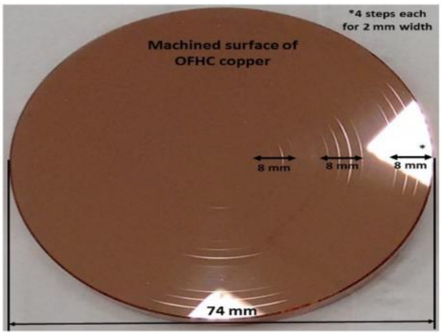

Figure 1. Machined sample

2.1. Machining equipment and process parameters

SPDT trials were performed on an ultra-precision diamond turning machine (Moore Nanotech 350 UPL). This machine tool has a liquid cooled air bearing spindle with aerostatic bearings having motion error of less than 50 nm while its stated driving system resolution is up to 0.034 nm [1]. In this trial study, the sequence of machining followed was from periphery to the centre *i.e*. from edge (first cut) to centre (third cut). A feed rate of 4 mm/min and spindle speed of 2000 RPM were used.

2.2. Step height measurements

Step heights were measured using a profile contact stylus method, Taylor Hobson Form Talysurf Series 2, with semispherical tip of 2 µm radius. Metrology data analysis was performed using TalyMap Gold 4.1. The depth of each step was calculated as the differential height between central 1.6 mm of adjacent plateau as shown in Figure 2. The contribution of the instrument calibration to the step height measurements was estimated to be smaller than 30 nm (k=2) [2].

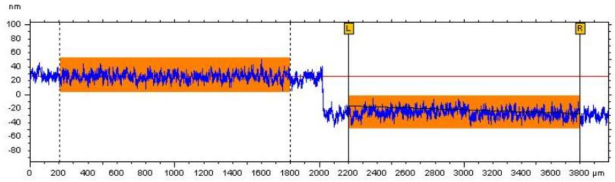

Figure 2. Data analysis on TalyMap Gold 4.1

3. Results and discussions

The surface finish on all terraces was of optical quality, with Ra not exceeding 5.5 nm (roughness cut-off wavelength ratio λc/λs equal to 30 – ISO 3274 [3]).

Table 1 shows the measurement and analysis results of step height information. The same information is illustrated graphically in figure 3.

Table 1. Measurements

Unit: nm		P1	P2	P3	P4	Average	Standard Deviation	Error
1st cut	50nm*	3.19	0.833	1.47	0.97	1.6	1.1	-48.4
	150nm	147	155	156	168	156.5	8.7	6.5
	250nm	231	244	237	233	236.3	5.7	-13.8
	500nm	525	524	527	538	528.5	6.5	28.5
2nd cut	50nm	21.1	32.8	39	31.2	31.0	7.4	-19.0
	150nm	156	163	167	183	167.3	11.4	17.3
	250nm	244	241	245	241	242.8	2.1	-7.3
	500nm	495	497	491	494	494.3	2.5	-5.8
3rd cut	50nm	51.9	42.9	58	47.4	50.1	6.4	0.1
	150nm	156	159	160	161	159.0	2.2	9.0
	250nm	235	239	244	234	238.0	4.5	-12.0
	500nm	505	497	499	500	500.3	3.4	0.3

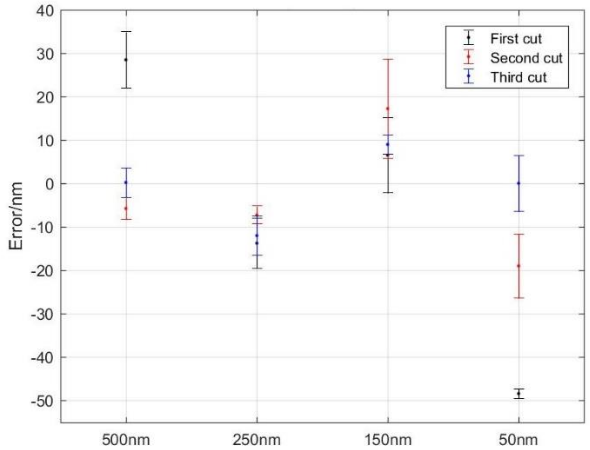

Figure 3. Error map showing programmed vs measured depths. Magnitude of the error bar shows standard deviation for measurements

As evident, all the measurements closer to the centre showed least error (Figure 3). The 50 nm deep cuts showed maximum uncertainty between the three cuts. Quite contradictory for machining systems designed to achieve fine cutting depths of few nanometres in their entire working volume, we noticed that even a cutting depth of 50 nm (of the same order as that of the cutting-edge radius of the tool), showed values of uncertainty that cannot be ignored.

3.1. Error sources

Various errors sources that may emerge during diamond turning operations were alluded in the past [4]. These factors can be divided into controllable and uncontrollable factors, and a list of these is also highlighted in Figure 4. One can further dwell on this by analysing further the causes of these error sources, which will be one of the objectives of the follow-on work. In general though, it is widely agreed that the machining parameters (controlled inputs such as feed, depth of cut and spindle speed) and tool geometry are prevalent controlled factors [4]. There are, however, various uncontrollable factors hat stems from the local plastic contact between the cutting tool and the workpiece, which, in turn, are influenced by materials microstructure as well as hard inclusions in the substrate [5]. These factors are jointly influenced by the contact stiffness and frame compliance mechanism for both machine structure loop and sample material both in static and dynamic mode. Spindle run outs are also escalated as potential problems leading to asynchronous error, which adds to chatter and vibrations despite utmost care taken in mounting the tool and workpiece on diamond turning machine. They couple further with the thermal gradients and jointly all these factors could build up to large uncertainties at shallow machined depths.

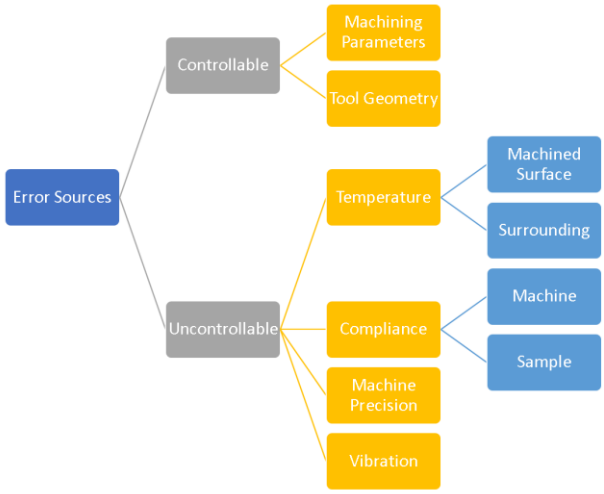

Figure 4. Possible error sources during SPDT

4. Conclusions

1) In all the SPDT machining trials made, a good surface quality with Ra not exceeding 5.5 nm was obtained.
2) It was observed that the machining uncertainty is least nearer to the centre of rotation as opposed to periphery of rotation. This observation supports a hypothesis made earlier by another group that the cutting speed at the centre is nearly zero. Thus, the impact on the tool is least whilst the tool enters into the workpiece at the centre as opposed to an impact on the tool if it enters from the periphery of the workpiece.
3) Despite aging (Moore Nanotech at Cranfield is 16 years old) and various other contributors resulting in the differences between programmed and measured depth of cuts, the SPDT machine provided stable machining accuracies at cutting depths above 50 nm even at distances far from the centre of rotation.

Acknowledgement

This work was done in the Centre for Doctoral Training (CDT) in Ultra-Precision at Cranfield University which is supported by the RCUK via Grant No.: EP/K503241/1. Authors are grateful to the help of Mr Alan Heaume as well as technical discussion with Mr Gavin Chapman from Moore Nanotech System LLC.

References

[1] S. Goel, X. Luo, P. Comley, R. L. Reuben, and A. Cox, “Brittle–ductile transition during diamond turning of single crystal silicon carbide,” *Int. J. Mach. Tools Manuf.*, vol. 65, pp. 15–21, 2013.

[2] C. Giusca and R. Leach, “Calibration of the metrological characteristics of contact stylus instruments." Measurement Good Practice Guide (GPG 129),” 2013.

[3] I. O. for Standardization, *Geometrical Product Specifications (GPS)--surface Texture: Profile Method--nominal Characteristics of Contact (stylus) Instruments*. ISO, 1996.

[4] V. Mishra, N. Khatri, K. Nand, K. Singh, and R. V. Sarepaka, “Experimental investigation on uncontrollable parameters for surface finish during diamond turning,” *Mater. Manuf. Process.*, vol. 30, no. 2, pp. 232–240, 2015.

[5] A. Sharma, D. Datta, and R. Balasubramaniam, “An investigation of tool and hard particle interaction in nanoscale cutting of copper beryllium,” *Comput. Mater. Sci.*, vol. 145, pp. 208–223, 2018.

Manufacturing uncertainty: How reproducible is the depth of cut during turning of OFHC copper?

Zhao, Junguo

2018-06