euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021

www.euspen.eu

Diamond scribing as an alternative to diamond finishing on a high precision milling machine

Marvin Groeb[1], Matthias Fritz[1]

[1]*Kern Microtechnik GmbH, Eschenlohe*

Marvin.groeb@kern-microtechnik.com

Abstract

Cost effective production of high-quality surfaces is in a constant contrast with rising requirements to surface finish. While monocrystalline diamond ball milling is a widely used and well understood superfinishing process, vibration and the inherent nature of an interrupted cut limit the achievable surface quality and process speed. A similar process is the scribing of the surface with a diamond tool. While this process is widely used in diamond turning on ultra-precision machines, form preparation speed and availability of these machines reduces the cost effectiveness of the overall process.

The paper proposes a novel approach of scribing a high-quality surface in nonferrous metal on an industrial milling machine. For this, a series of Taguchi experiments were undertaken to minimize the sample roughness. A survey of the parameters feed rate, angulation of the cutting edge, stepover and depth of cut showed improvements by finetuning both feed rate and stepover. The surface roughness was analysed via bifocal laser microscopy, and the topography with SEM imagery. Chip formation processes were analysed experimentally based on SEM pictures taken. Tool wear was monitored via SEM and EDS analysis. A Ra of ten nanometre was achieved in a very competitive time frame.

Diamond scribing, freeform milling, high precision, surface finishing

1. Introduction

The market for optical elements has been valued at $ 3.6billion in 2012, and has been forecast to reach $ 12.3 billion by 2019 [1]. Rising requirements to the finished surface inevitable lead to higher part cost, as the required machine tool, tooling and process time increase the overall cost dramatically.

Similar to what Moore's law proposed in the semiconductor world, Taniguchi published a development curve for the advancement of machine tool capabilities (see fig. 1) [2], [3]. Taniguchi divides the quality of the machining process into normal, precision and ultra precision. The accuracy of precision milling machines is approaching what used to be reserved for ultra precision milling (UPM) machines, opening possibilities for highly productive surface finishing.

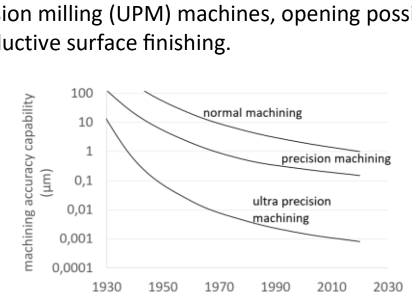

Figure 1: *The machining capabilities of different precision classes, after Taniguchi.*

UPM machining can in theory reduce the cost associated with a finished product, as the higher quality molds require less finishing of the specimen produced [4]. Still, a major cost factor is the UPM machine; often characterized by a low productivity, as well as the need for a separate machine to rough and semi finish the material in preparation for the superfinish. It is generally agreed upon, that the overall efficiency of an ultra-precision finishing machine is low [5].

Modern subtractive super finishing methods can be classified into polishing, grinding and turning or milling. Moreover, chemically or electric assisted processes such as electro rheological fluid assisted polishing are used to produce high quality surfaces [6]. These processes can be, more easily applicable for this paper, divided into a cutting process with geometric defined cutting edge (turning, milling) and those with stochastic material removal processes (grinding, polishing). In the last 20 years, single point diamond turning (SPDT) has been the surface finish process of choice for high form accuracies with a smooth surface, easily visible on the availability of these machines as well as the general research in this field [7], [8], [9], [10]. The use of a small diamond tool on a milling machine is usually described as diamond chisseling, and aims at the creation of high accuracy microstructures [11], [12] or the creation of discontinuous surfaces [13], leaving the productive production of high quality freeform surfaces unresearched.

This paper proposes a novel application of an high precision cnc milling machine, where the process of diamond scribing is used in a highly productive way to create optical shapes. Thereby, surfaces bordering on UPM quality are produced at one order of magnitude faster production times. Moreover, the full process from the raw stock material to the finished part can be handled by a single machine, reducing the total number of machines needed, which holds advantages in the regard of footprint, availability, synchronization and investment cost.

2. Methodology

The milling experiments were performed on a Kern Micro HD precision cnc machining centre. It features micro gap hydrostatic guideways, linear motors and glass scales with nanometric resolution, enabling a positional accuracy well below 1 µm. The machine was equipped with an HSK 40 spindle manufactured by Fischer, having a maximum rotational speed of 42.000 min-1 and a rated power of 15.6 kW.

The sample specimen was held in a vise. The material used is standard cnc quality brass (CW614N, composition CuZn39Pb3, tempered tension free). Roughing and semi finishing was undertaken with a generic DLC coated flat end mill. The used NC code was written in Heidenhain plain text on the TNC 640 control. A contour smoothing cycle of 0.001 mm was active during the operation. The coolant used is a mineral oil (Wilke Wicoil 5045). The monocrystalline diamond ball end mill (6 mm diameter) was produced by Matzdorf. The tool was held in a Regofix PowRgrip toolholder, having a laser measured run out of below 1 µm. Tests were performed in a temperature-controlled environment. If the spindle was rotated, a spindle warm-up period of 5 minutes was completed before cutting, to reduce thermal influences. The work piece temperature was further stabilized by application of the tempered flood coolant for 10 minutes before the experiment. Measurements were taken after the sample was cleaned with isopropyl alcohol. All quantitative measurements were recorded with a confocal laser scanning microscope (CLSM) from Confovis. This enables the recording of areal scans and ISO 25178 conform noncontact measurements of surface roughness. A 50x magnification objective lens was used, and all surfaces recorded as raw 3D data. The data was evaluated in the software MountainsMap, applying ISO 4278 appropriate filtering and selection techniques. First, the sample data is flattened via a least square's algorithm. The upper and lower 0.1 percentile of measurement points are cut off to accord for dust on the sample specimen. A 2D path, zig-zagging along the sample profile, perpendicular to the direction of cut is recorded with a sampling length of at least 4 mm. The waviness is removed with a gaussian filter setting of 0.08 mm. Because the CLSM is proven to be able to return 2D profiles, the R_a instead of S_a values were used, as these are still the more commonly used and better comparable with previous research. Qualitative analysis was done with a Phenom XL scanning electron microscope. Runout of the tool was measured via the built in BLUM LC50 laser.

3. Experimental

In order to accurately examine the performance of the proposed diamond freeform scribing, 3 different experiments (see table 1) were undertaken. By using a Taguchi-based Design of Experiment, a variety of parameters were analysed in two different experiment series. A third series of experiments was undertaken by rotating the tool, giving a base measurement of the performance of diamond freeform milling and enabling a comparison of both surface finish quality and time. The depth of cut (DOC) is here the engagement into the material, whereas the width of cut (WOC) is the spacing between the individual lines.

Table 1: The experiment series with the examined process parameters.

Parameter	Experiment 1	Experiment 2	Experiment 3
Cutting mode	Scribing	Scribing	Milling
Parameter 1	Feed rate	Feed rate	Feed rate
Parameter 2	Angulation	Ap	RPM
Parameter 3	DOC	-	DOC
Parameter 4	WOC	-	WOC

3.1. Process kinematics

While in theory, using the 5 kinematic axis of the machine (2 rotational and 3 linear) and operating the spindle as a 6th actuated axis, every shape could be manufactured; the experiments were conducted by scraping a flat face. The reason for this is the easy programming, reduced amount of noise by fewer moving axis, and the less error-prone optical measurement of the surface quality.

For the scribing experiments, the spindle and tool are oriented in a fixed direction. The workpiece is angulated via B and C axis at 30° relative to the Z axis. A linear movement, starting 10 mm before the sample specimen and ending an equal distance behind it, is executed along the Y-axis of the machine. The tool then lifts up along Z and travels at rapid speed to the starting point while shifting the width of cut along the X axis. For the milling experiments, an identical movement was undertaken, but the tool rotated instead of angulated at a fixed position. Figure 2 shows the schematic view of the tool-workpiece configuration.

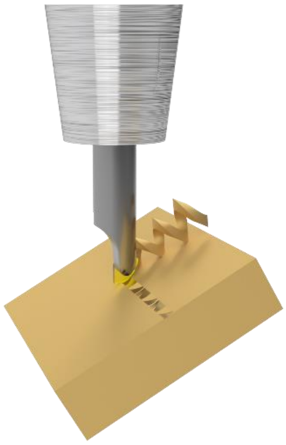

Figure 2: Schematic view of the process kinematics

3.2. Experiment series 1 & 2 – scribing

From a plethora of influencing factors, four parameters have been selected to be evaluated during the first experiment series, as they were judged to have the largest impact and can be most easily influenced on the resulting surface. To act economically and sustainably, a design of experiments approach modelled after Taguchi was used. Table 2 lists the used parameters in the first experiment. In order to quickly sight the influencing parameters and their impact on the result, classic process parameters such as feed rate, depth of cut and width of cut were analysed. Moreover, to see whether an exact angular positioning of the cutting edge has an impact on the surface quality, the cutting-edge angle relative to the material was varied, giving results at positive, negative and neutral rake angles.

Table 2: Parameters and Levels used in the first experiment.

Parameter	Level 1	Level 2	Level 3
F in mm/min	500	1000	1500
Angulation in °	-3	0	3
DOC in µm	2	5	7
WOC in µm	25	50	75

All experiments were conducted in a row, and afterwards batch measured for their respective roughness on a CLSM.

The results are listed in figure 3. The error bars are defined from the general measuring uncertainty of the used CLSM, which has been tested repeatedly to +/- 7 nm. A sample length of > 4 mm was used. Afterwards, the resulting surface roughness was used as a quality parameter for an ANOVA analysis. The analysis was undertaken with the software package "R".[14]

Relating to the brevity of the experimental scope, only first order interactions were analysed. The only significant influencing parameter is the width of cut, having a Pr(>F) of 2.55e-08.

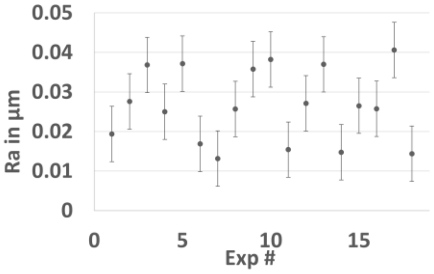

Figure 3: The resulting arithmetic roughness R_a for the first experiment series.

Building on the first experimental series, the parameters feed rate and depth of cut were further analysed, with the goal of possibly separating the influence from the overall noise in the first experiment. Especially the parameter feed rate is of higher interest, as it is not only the relative movement speed of the tool to the material, but in the case of scribing also the cutting speed V_c. In theory, the surface quality can improve with a higher cutting speed. Opposing this effect, the machine frame, movement system and tool deflection increase with higher movement speeds.

Table 3: Parameters and Levels used in the second experiment

Parameter	L1	L2	L3	L4	L5	L6
F in mm/min	250	500	1000	1500	2000	3000
DOC in µm	2	4	6	8	10	12

The tool was kept at a neutral angulation for this experiment. A general width of cut of 25 µm was used for all experiments. Table 3 lists the used levels for the parameters depth of cut and feed rate. All experiments were milled in a row, analysis on a CLSM was undertaken for the specific roughness after the sample was cleaned. The resulting measured arithmetic roughness Ra is shown in figure 4.

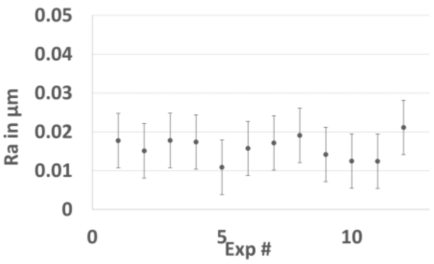

Figure 4: The resulting arithmetic roughness R_a for the second experiment series.

The roughness was used as a quality parameter to conduct an ANOVA. No significant influences on the roughness could be detected.

3.3. Experiment series 3 – diamond milling

In order to supply a baseline on which to compare the other experiments, a ball milling experiment series was undertaken. A similar experimental design in comparison to the series 1 was undertaken, taking into account the feed rate limitation stemming from the maximum allowable feed per tooth. Table 4 lists the used parameters and levels. The same tool as in the previous experiments was used, holding the surfaces comparable.

Table 4: Parameters and Levels used in the second experiment

Parameter	Level 1	Level 2	Level 3
F in mm/min	250	500	750
RPM in kmin^{-1}	25	27.5	30
DOC in µm	2	5	7
WOC in µm	25	50	75

All experiments were milled in a row, analysis was undertaken after the sample was cleaned on a CLSM for the specific roughness. Figure 5 shows the achieved arithmetic roughness Ra.

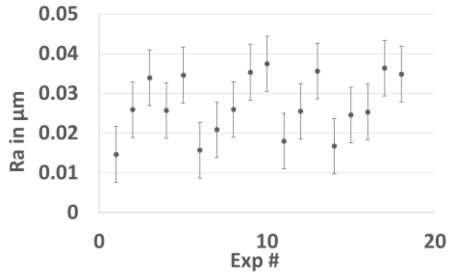

Figure 5: The resulting arithmetic roughness R_a for the third experiment series.

An ANOVA was undertaken by using the roughness as a quality parameter. The width of cut shows a significant influence (Pr(>F) 3.7e-03) on the surface roughness, whereas all other parameters do not reject the null hypothesis.

4. Results & Discussion

The initial parameter survey produced a smooth, glossy surface without visible tool marks. The surface has no discernible higher order surface defects such as orange peel or harmonic vibrations. The measured surface roughness R_a is mainly dependent on the width of cut, the other parameters do not have a significant influence on the surface quality. The measured values vary between R_a 0.013 and 0.04 µm. Correlating the roughness with the theoretic kinematic roughness (R_{th}) of the process parameters and tooling diameter (d) used with equation 1 shows that the achieved surface roughness is close to the theoretical value of 0.017 µm. Moreover, all other parameters do not significantly affect the surface roughness, showing that the process time is mainly limited by the step over. A likely reason why the surface roughness is measured below the theoretical value stems from the low depth of cut, flattening out the peaks of the theoretical, kinematic roughness. The equation of the theoretical roughness is easily derived from a geometric consideration.

$$R_{th} = \frac{d}{2} - \sqrt{\frac{d^2 - woc^2}{4}} \qquad (1)$$

The second experiment series shows a stable process. The parameter variation does not significantly influence the result. Therefore, it can be concluded that especially with productivity in mind, a higher feed rate is preferable. A best-case roughness Ra of 0.011 µm was achieved. Further tests have shown that the surface roughness stays in this stable region, even with higher feed rates, up to the point where machine frame vibrations become visible on the surface.

Figure 6: A diamond milled sample specimen. The vertical lines stem from the division of one piece of stock material into multiple parameter variations.

As a baseline comparative to the undertaken scribing experiments, an experiment series with the spindle in rotation was undertaken. The milled surfaces also exhibit a high gloss. The smooth appearance gets noticeable dimpled with higher feed per tooth. Moreover, a moiré-like pattern can be seen from certain angles, stemming from the phase shift between the tooth entry position of one tool path line to the next. The measured Ra vary between best case 0.014 µm and worst case 0.037 µm. The maximum allowed feed rate to not damage the tool resulted in a significantly slower process than the scribing experiment. The visible reflection is noticeable less crisp to the human eye than the scribed surface. Figure 6 shows a diamond milled sample.

In order to verify the suitability of the process for complex shapes, a convex shape was diamond scribed. As experiment 1 has shown, a small angulation of the diamond edge has no discernible effect on the surface, a freeform convex shape was chosen. Figure 7 shows the result. With a feed rate of 6000 mm/min, a WOC of 0.02 mm and a depth of cut of 5 µm, a competitive Ra of 0.012 µm was reached. The changing angulation of the tool did neither affect the measured roughness nor the qualitative appearance. The surface is regular, smooth and has a very crisp, mirror like reflection.

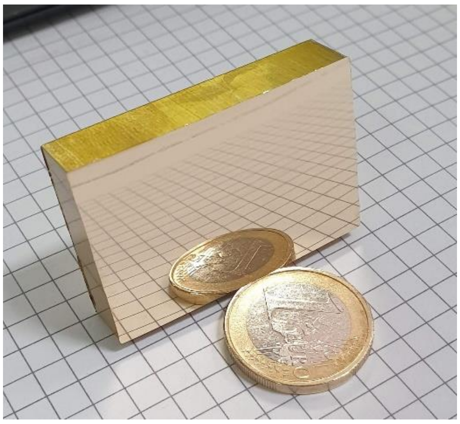
Figure 7: The finished freeform convex sample. The curvature is r = 1 m.

5. Conclusion

The proposed diamond scribing process is able to produce nanometric surface roughness approaching the single digit range. Experiments have shown a stable and robust process that can produce surface qualities of Ra = 0.01 µm.

The resulting finishing speed is a magnitude faster than traditional diamond milling, with no visible surface defects. Tool wear and process limitations should be further researched. The authors see promise in:

1. Operating the spindle as a 6th, actuated axis to allow for full freedom of geometry.
2. A simplified CAM solution could be developed, as traditional CAM software does not contain a "scribing" mode.
3. The limits of the process should be explored, for example the maximum viable feed rate.

References

[1] Study:, Optical Components: Market shares, strategies, and Forecasts, Worldwide, 2013 - 2019, Technical Report, Winter Green Research, Lexington, Massachusetts, 2013.

[2] P. Shore, P. Morantz, Ultra-precision: enabling our future, Phil.Trans. R. Soc. **370** (2012) 3993–4014

[3] N. Taniguchi, Current status in, and future trends of, ultraprecision machining and ultrafine materials processing, CIRP Annals 32 (1983) 573 – 582.

[4] F. Schneider, J. Das, B. Kirsch, B. Linke, J. C. Aurich, Sustainability in ultra precision and micro machining: A review, International Journal of Precision Engineering and Manufacturing-Green Technology **6** (2019) 601–610.

[5] Z. Zhang, J. Yan, T. Kuriyagawa, Manufacturing technologies toward extreme precision, Journal of extreme Manufacturing **1** (2019) 022001.

[6] K. Shan, P. Zhou, J. Cai, R. Kang, K. Shi, D. Guo, Electrogenerated chemical polishing of copper, Precision Engineering **39** (2014).

[7] Z. Dong, S. Zhang, Z. Xiong, X. Rao, A generalized dynamic model for spindle vibration influencing surface topography in different ultra-precision machining processes, The International Journal of Advanced Manufacturing Technology **96** (2018) 2471–2478.

[8] Y. He, P. Zou, W.-L. Zhu, K. F. Ehmann, Ultrasonic elliptical vibration cutting of hard materials: simulation and experimental study, The International Journal of Advanced Manufacturing Technology **91** (2017) 363–374.

[9] F.-J. Shiou, A. Asmare, Ultra precision surface finishing processes, International Journal of Automation Technology **13** (2019) 174–184.

[10] M. A. Rahman, M. R. Amrun, M. Rahman, A. S. Kumar, Variation of surface generation mechanisms in ultra-precision machining due to relative tool sharpness (rts) and material properties, International Journal of Machine Tools and Manufacture **115** (2017) 15–28.

[11] T. Moriya, K. Nakamoto et al., Creation of V-shaped microgrooves with flat-ends by 6-axis control ultraprecision machining, CIRP Annals – Manufacturing Technology 59 (2010) p. 61-66

[12] E. Brinksmeier, R. Gläbe, L. Schönemann, Diamond Micro Chiseling of large-scale retroreflective arrays, Precision Engineering 36 (2012) p. 650-657

[13] E. Brinksmeier, L. Schönemann, Generation of discontinuous microstructures by Diamond Micro Chiseling CIRP Annals, Manufacturing Technology 63 (2014) p. 49-52

[14] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2017.