euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
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Process Stability and Deterministic Behaviour in Milling for Microtextured Surface Generation

P. Azizabadi Farahani[1,2], O. Riemer[1,2] , B. Karpuschewski[1,2]

[1] *Leibniz Institut für Werkstofforientierte Technologien IWT, Laboratory for Precision Machining LFM, Badgasteiner Straße 2, 28359 Bremen, Germany*

[2]*University of Bremen, Germany*

Abstract
This study examines the process stability and deterministic behaviour of producing microtextured surfaces. The demand for precise and reliable microstructuring is increasing across industries, particularly as these surface features contribute to the enhanced functionality and performance of components However, tool wear significantly influences the stability and reproducibility of these textures, as progressive wear alters the cutting conditions and introduces deviations in the surface topography. This study explores how different milling parameters contribute to microtexture variations and their impact on tool wear. In this work, various milling parameters—including milling strategy, line spacing, feed rate, rotational speed, tool inclination (angle and orientation), and tool direction angle—are systematically varied to create a comprehensive range of surface textures. The resulting dataset undergoes exploratory data analysis to assess the precision and reproducibility of the produced microtextures under different parameter settings By examining the key influences on process stability, this study provides insights that could contribute to optimizing milling processes for microstructuring applications. Future work will extend these findings by developing a machine learning model aimed at predicting tool wear based on real-time force measurements, further contributing to the development of more intelligent, adaptive milling systems.

Keywords: Microtexturing, end ball milling, exploratory data analysis

1. Introduction

In the current era of manufacturing, the pursuit of efficiency and performance has prompted the integration of surface engineering techniques, which have led to the substantial enhancement of tool surface properties. A significant advancement in this domain is micro milling, a rapid and adaptable manufacturing process that enables the creation of desired geometries on workpieces and facilitates the simultaneous application of full-surface or locally defined microtextures to the manufactured functional surface [1]. As microtextures assume greater importance across a range of applications [2, 3, 4] the precise machining of microtopographies has become imperative.

However, a significant challenge emerges, particularly in the context of orthogonal ball-end micro milling under unconventional cutting conditions, where tool wear is more prevalent. Tool wear, significantly influenced by the selected milling parameters, can lead to substantial alterations in the 3D topography of the produced microtextures after machining only a few square centimeters of the surface [5, 6]. This deterioration not only affects the quality and functionality of the microtextured surfaces but also compromises the repeatability and reliability of the manufacturing process. Determining and maintaining process stability is therefore essential for ensuring consistent quality in microtexture generation.

An effective method for assessing and optimizing process stability would enable manufacturers to mitigate the adverse effects of tool wear and other process-related variables [7]. Moreover, the wear-induced changes in 3D topography can have a profound impact on the tribological functionality of the surfaces, affecting their performance in applications such as lubrication, adhesion, and wear resistance [8].

These considerations underscore the critical importance of enhancing our comprehension of the interplay between process parameters, tool wear, and the resulting surface characteristics.

2. Materials and Methods

The experimental procedures were conducted on a Kern Micro HD five-axis micro milling machine, characterized by its hydrostatic x-, y-, and z-axes and torque motor-driven rotary axes. This setup, shown in Figure 1a, allowed for a maximum axis velocity of 60 m/min and a spindle rotational capability of up to 42,000 rpm. The milling process was performed using lubrication, where the coolant Zubora 55 M Extra was applied to ensure optimal cutting conditions and reduce tool wear.

As substrates, hardened CrVMo 12-1 steel specimens with a hardness of 65 HRC and a diameter of 45.5 mm were used. The workpiece was mounted on a Kistler dynamometer (type 9256C2) to measure forces during machining. Nine separate islands, each measuring 7 mm × 7 mm × 1 mm, were precisely milled on the faces of the round substrates. A double-edged ball end mill from Mitsubishi (VFR2SBFR0100) with a diameter of 2 mm was utilized for the microtexturing process. The tool was replaced after milling 9 islands, corresponding to one sample.

To systematically investigate the influence of milling parameters on surface topography, a partial factorial experimental design (DoE) was employed. This structured approach facilitated the exploration of parameter interactions while optimizing the number of experimental runs. The DoE consisted of 32 runs, where each run was replicated twice over each island row, resulting in a comprehensive collection of 864 individual measurements. For this study we only focusing on evaluating the first row A (A1 – A3).

The DoE in Table 1evaluated five key factors at four levels: line spacing (a_e), feed rate (v_f), rotational speed n, tool inclination angle (α), and tool inclination orientation $\vec{v}$. Furthermore, the milling strategy—comparing up-milling and down-milling—was assessed at two levels. These parameters were carefully chosen to encompass a wide range of machining conditions, enhancing the robustness of the experimental framework.

The tool inclination orientation, as illustrated in Figure 1b, is represented by v. Its quantitative definition is provided in Equation (1), while its qualitative influence on surface characteristics is further elaborated through case differentiation in Equation (2). This comprehensive experimental setup enabled the generation of valuable insights into the production and effects of various microtextured surfaces, significantly contributing to advancements in precision micro milling.

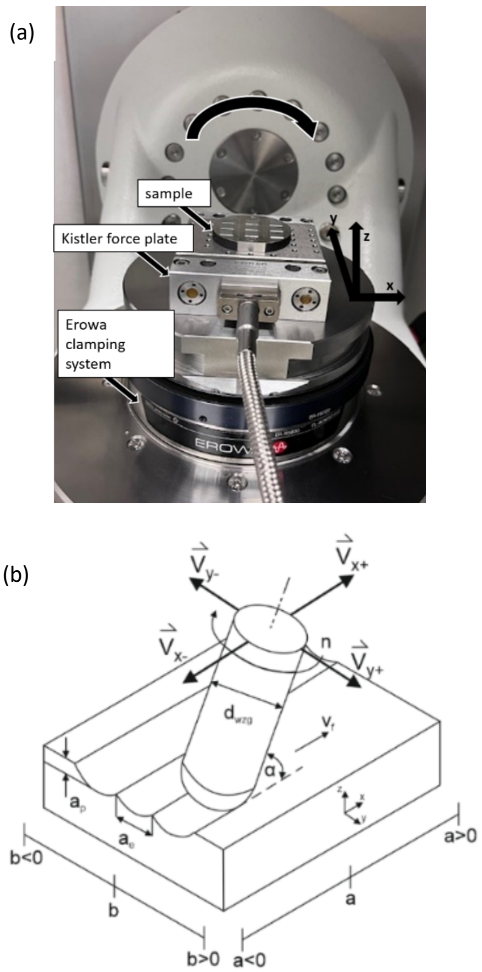

Figure 1. Micro ball-end milling **(a)** Experimental setup **(b)** Process kinematics

$$\vec{v} = a\vec{\imath} + b\vec{\jmath}, \qquad a, b \in \mathbb{R}, \qquad i = [1, 0], \qquad j = [0, 1] \tag{1}$$

$$\vec{v} = \begin{cases} a > 0 \; v_{x+} & in\ feed\ direction \\ a < 0 \; v_{x-} & against\ feed\ direction \\ b > 0 \; v_{y+} & right\ direction \\ b < 0 \; v_{y-} & left\ direction \end{cases} \tag{2}$$

2.2. Material surface charaterization

The surface topography of the machined specimens was characterized using a white-light interferometer (WLI) equipped with a 10× magnification lens. This setup covered a measurement area of 1.65 mm × 1.65 mm, providing a high-

resolution assessment of surface features. A cut-off wavelength (λc) of 0.08 mm was applied to evaluate surface parameters, effectively filtering out long-wavelength components and focusing on the microtextured features generated during milling. For each machined sample, nine measurement fields were defined across the islands, as illustrated in Figure 2. It is important to note that only the first row of each specimen was measured for this study.

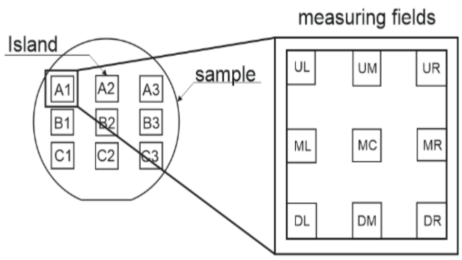

Figure 2. Specimen with microtextured islands A1-C3 and with associated measuring fields

To effectively describe surface features and ensure practical data dependency, this study strategically selects parameters that are both significant and easily measurable. As defined by DIN ISO 25178, the selected topography parameters are categorized into five distinct groups: Height, Functional, Functional Volume, Feature, and Spatial. The details of these parameters are presented in Table 2.

The resulting data was subjected to boxplot analysis to examine the variability and distribution of surface parameters under different milling conditions. The boxplots provided a visual representation of central tendencies, dispersion, and outliers, offering insights into process stability and reproducibility. The experimental design in Table 1 comprised 11 distinct runs, each replicated twice across the defined measurement fields, yielding a comprehensive dataset of 297 individual measurements.

This extensive dataset enabled a detailed statistical analysis of the influence of milling parameters on surface characteristics, identifying trends and anomalies that could inform process optimization. To further elucidate the relationships between the milling parameters and the resulting surface topographies, a Spearman correlation analysis was performed. This non-parametric method quantified the strength and direction of monotonic relationships between variables, providing insights into parameter interdependencies and their relative influence on surface characteristics

Table 1: Design of Experiments for machining parameters for row A

Run	a_e (mm)	v_f (mm/min)	n (1/min)	α (°)	$\vec{v}$
1	0.02	800	20000	0	v_{x_+}
2	0.02	8000	40000	10	v_{y_+}
3	0.035	3900	30000	10	v_{y_+}
4	0.065	1750	25000	10	v_{y_-}
5	0.1	800	20000	10	v_{y_-}
6	0.1	6000	30000	0	v_{x_-}
7	0.02	3250	25000	6,5	v_{x_-}

8	0.035	2100	30000	0	v_{y_+}
9	0.065	1200	30000	6,5	v_{x_+}
10	0.065	5000	25000	3,5	v_{y_+}
11	0.100	2600	20000	3,5	v_{y_-}

Table 2 Selected surface topography parameters from DIN ISO 25178

	Height Parameters	
Sa	Arithmetical mean height	[µm]
	Functional	
Sk	Core height	[µm]
Spk	Reduced peak height	[µm]
Svk	Reduced valley depth	[µm]
	Functional volume Parameters	
Vmp	Peak material volume	[mm³/mm²]
	Feature Parameters	
Spd	Density of peaks	[1/mm²]
S10z	Ten-point height	[µm]
	Spatial Parameters	
Std	Texture direction	[degree]

3. Results

Figure 3 illustrates the arithmetic mean height (Sa) in nanometers for each specimen, with each boxplot representing the distribution of 27 measurements across various machining conditions. Sa values range from 44 nm to 360 nm, reflecting substantial variability in surface topographies. This metric, which expresses the average deviation of height from the mean surface plane, provides a baseline for evaluating machining stability.

While most specimens exhibit a narrow spread in Sa values, indicating stable machining processes under specific parameter settings, a comprehensive analysis of additional topography parameters is essential for a more holistic understanding. However, relying solely on the Sa value for evaluating microtextured surfaces can be misleading. The Sa parameter only provides information about the average surface roughness and does not account for other critical aspects of surface texture.

To obtain a more comprehensive understanding of the surface characteristics, it is necessary to consider feature parameters such as S10z, which represents the mean height difference between the five highest peaks and five lowest valleys, as well as functional parameters like Sk, indicating the core height. These parameters provide deeper insights into the distribution of peaks and valleys, spatial features, and the functional performance of the surface.

Figure 4 shows the S10z values, representing the mean height difference between the five highest peaks and five lowest valleys within the measurement area. These values range from 481 nm to 3820 nm, showing a distribution similar to Sa values.

Additionally, the core height (Sk) parameter in Figure 5 exhibits a consistent distribution across specimens, indicating that most textures were generated with high reproducibility over the entire volume. This consistency underscores the reliability of the machining processes in maintaining uniform surface characteristics under controlled conditions.

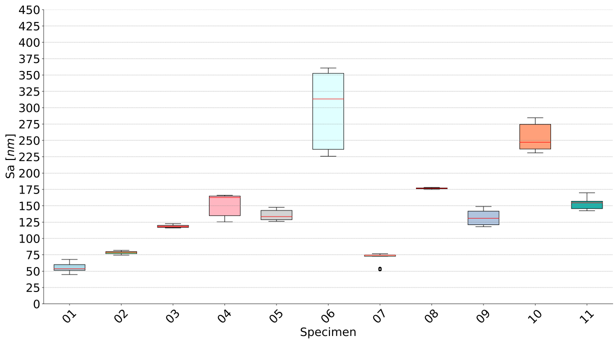

Figure 3. Boxplots for Sa distribution

Specimens 6 and 10 stand out due to their significantly larger spreads in Sa, Sk, and S10z values, indicating increased variability in surface topographies. Specimen 6, in particular, exhibits the highest S10z values and the largest variability. Analyzing its machining parameters in Table 1 reveals the combination of the highest feed rate (v_f), the largest line-spacing (a_e), and the lowest tool inclination angle (α).

The correlation heatmap in Figure 6 highlights the dominant influence of line-spacing (a_e) on surface roughness parameters. Larger line-spacing increases gaps between tool paths, amplifying height variations due to the spherical geometry of the ball-end mill and reduced overlap between passes. Conversely, smaller line-spacing enhances path overlap, leading to smoother, more homogeneous surfaces.

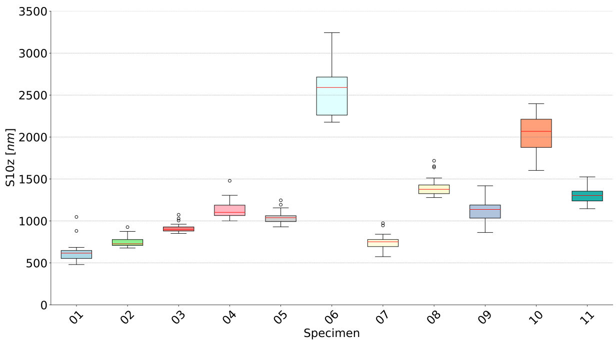

Figure 4. Boxplots for S10z distribution

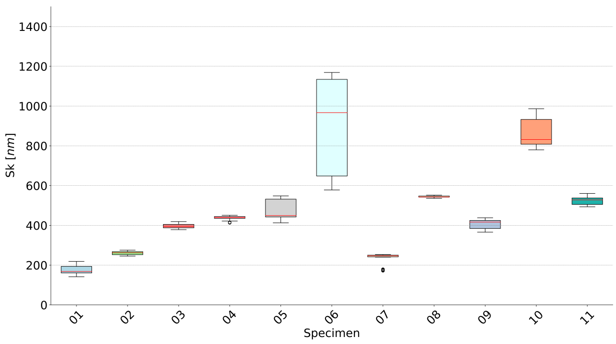

Figure 5. Boxplots for Sk distribution

Similarly, the feed rate (v_f) also plays a critical role in determining surface topography. Higher feed rates generally correlate positively with increased surface roughness metrics, excluding Spd, which exhibits a negative correlation, as shown in Figure 6. Elevated feed rates introduce wider spacing between tool engagements, creating pronounced ridges and wave-like surface patterns. Additionally, reduced overlap in material removal amplifies irregularities, while higher dynamic forces and potential tool vibrations exacerbate non-uniform features.

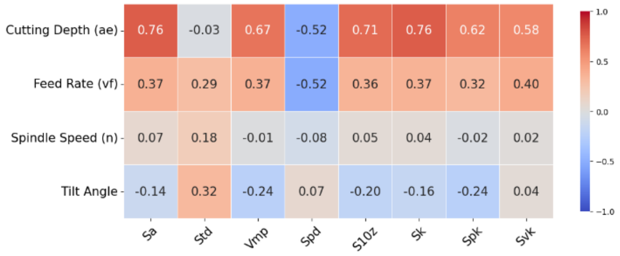

Figure 6. Spearman correlation heatmap between milling parameters and surface topography metrics

A closer examination of specimens 6 and 10 suggests that their variability arises from non-linear interactions among machining parameters, such as feed rate, rotational speed, and tool inclination. These interactions potentially induce localized changes in cutting forces, thermal conditions, or tool dynamics, which lead to less predictable surface features. External influences, including tool vibrations, spindle runout, and inconsistent coolant application, further complicate the outcomes.

This unpredictability appears closely tied to the condition of the cutting tools. Qualitative SEM analysis of tools 1, 6, and 10, as shown in Figure 6, reveals pronounced wear on the sixth and tenth tool compared to tool one.

The accelerated wear observed on tool 6 and 10, likely caused by its machining conditions—higher feed rates and larger line-spacing—offers a plausible explanation for the increased variability in specimens 6 and 10. This relationship highlights the critical interplay between tool wear and surface irregularities, emphasizing the importance of controlled wear to maintain consistent machining outcomes.

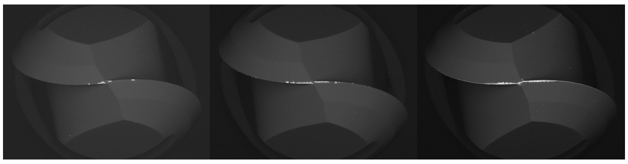

Figure 7. SEM Images of ball end mill 1,6 and 10

4. Summary and Conclusions

The results of this study underline the critical need for a controlled machining environment to reduce external disturbances and improve process stability. The variability observed in surface topography metrics highlights the inherent complexity of achieving consistent results in microstructuring. The Design of Experiments (DoE) approach provided valuable insights into parameter interactions, but the inconsistencies observed in certain specimens emphasize the intricate nature of these mechanisms.

To address these challenges, future efforts should prioritize advanced methodologies. For the application of machine learning, it is essential to collect and integrate process data, both historical and real-time. Combining these with machine learning frameworks can enhance process precision and ensure the reliable generation of microtextured surfaces with tailored properties. Optimizing machining parameters is essential for stable and reproducible results.

Among the investigated parameters, line spacing (a_e) proved to have the strongest influence, followed by feed rate (v_f) and tool inclination angle (α). Effectively balancing these factors can significantly improve surface quality while minimizing variability.

Future work will extend these findings by developing a machine learning model aimed at predicting tool wear based on real-time force measurements, further contributing to the development of more intelligent, adaptive milling systems.

Analyzing the relationships between process forces and tool wear can provide a better understanding of the effects of milling parameters on microtexture and potentially on their reproducibility. This can inform the development of adaptive control strategies that adjust machining parameters in real-time to maintain optimal conditions.

In summary, the study highlights the importance of a controlled machining environment, the potential of integrating process data for machine learning, and the need for data-driven approaches in achieving consistent and high-quality microstructuring.

Acknowledgements
Funding: This work is supported by the German Research Foundation (DFG) under Grant No. KA 1006/34-1, Project No. 500273939
Conflicts of Interest: The authors declare no conflict of interest

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