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Evaluation of optical functional surfaces on the injection moulding insert by micro milling process

D. Li[1], A. Davoudinejad[1], Y. Zhang[1], F. Regi[1], G. Tosello[1], J. B. Nielsen[2], H. Aanæs[2], J. R. Frisvad[2]

[1]*Technical University of Denmark, Department of Mechanical Engineering, DK-2800 Kgs. Lyngby, Denmark*
[2]*Technical University of Denmark, Department of Applied Mathematics and Computer Sciences, DK-2800 Kgs. Lyngby, Denmark*

Email: dongyli@mek.dtu.dk

Abstract
This study presents the optimization of micro milling process for manufacturing injection moulding inserts with an optical functional surface. The objective is the optimal surface functionality. Micro ridges were used as the microstructures to realize the function to generate contrast between orthogonally textured areas by reflecting light in different directions. In order to maximize the contrast, a sample was machined with the same structures and dimensions, according to a Design of Experiments (DOEs) to optimize the milling parameters by considering the contrast as a response. The contrast was evaluated based on the image processing method. The proper cutting condition was selected in order to obtain machined surface with the highest contrast and the results presented by DOE analysis. The correlations between the cutting parameters, the burrs height, and the function were determined. The contrast was found to be proportional to the spindle speed and feed rate and "oil+air" was considered as the preferred cooling method.

Keywords: optical functional surface, micro milling, optimization, DOE

1. Introduction

The plastic products with micro structured functional surfaces serve the society by many industrial and commercial applications, such as medical components, optical systems, etc. The expected function is to generate contrast under a certain light source by orthogonal textured surfaces with the same microstructures. Injection moulding (IM), the method of mass production of polymer parts with surface textures of micro- and Nano- scale, was used to produce the plastic surfaces. [1] The surface function is highly depend on the surface quality replicated from the moulds. Tool surface quality is affected by the factors in the tooling process, such as the microstructure, burr formation, tool wear, etc. [2, 3] Tooling for injection moulding of the micro structures varies from conventional to emerging ones: milling, lithography, additive manufacturing, etc. [4, 5]. A relatively cheap and short process chain requires the tooling process to be optimized regarding the time and economy costs. Micro milling processes are the down-scaled versions of conventional milling process with the advantages of direct and fast material removal, low cost, low pollution and simple procedure. [6] This paper reports the study on the DOE-based optimization of micro milling parameters with the regard of optical function as well as the relationship between the functionality and the surface quality.

2. Process chain description

2.1. Micro milling experiment

A full factorial Design of experiments (DOEs) [7] was used to consider the impact trend of the milling parameters on the surface functionality to optimize the milling parameters. Regarding the process parameters, four variables and two levels per factor are listed in **Table 1**. To ensure an enough cutting engagement, the depth of cut was set to 20μm. The response variable was the contrast generated by the surfaces. Since the machine might have different accuracy along *X* axis and *Y* axis, the orientation of the textures was considered. 32 square surfaces (3x3 mm2) were machined on one insert with micro-ridges of 5° ridge angle and 50 µm pitch (**Figure 1**).

Table 1. The processing parameters

Factors	Low level	High level
End mill	Φ3mm	Φ4mm
Spindle speed	8500rpm	9600rpm
Cooling/ lubrication	Oil + air	Oil + water
Teeth	4	4
Feed rate	700mm/min	1000mm/min
Feed per tooth	0.021mm/min	0.029mm/min
Width of cut	50µm	
Depth of cut	20µm	

A machining centre (MIKRON HSM 400U LP, 5-axis, control unit: Heidenhain iTNC 530 HSCI) was used to pattern the features on an IM insert. The hyperMILL program was used to generate the code. The tool path is shown in **Figure 1**. The 3x3 mm² square area comprised of 120 micro ridges was defined as a pixel.

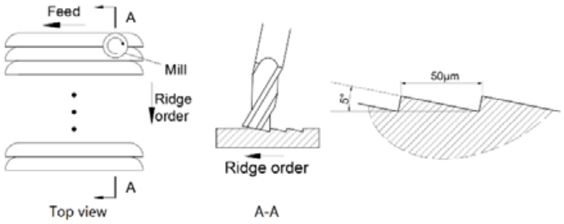

Figure 1. The tool path (left) and the micro ridges (right).

The specifications of the tools used for the experiments is listed in table 2. The insert material was Orvar Supreme (Uddeholm) with hardness of 48~50 HRC by Nitride hardening. The coolant for the "oil+water" was vegetable-based micro-emulsion oil HANGSTERFER'S S-787 and the one for the "oil +air" was NATURAL 77 from IMPIANTI.

Table 2. The specification of the tool.

Parameters	Specification	
Manufacturer	NS	ARNO
Diameter [mm]	4	3
Material	µ grain carbide	Ultra µ granulation
Coating	TiAlN	TiA
Helix angle	45°	30°
Number of flutes	4	4
Overall length [mm]	60	55
Length of cut [mm]	8	3
Shank diameter [mm]	6	6

2.2. Surface evaluation

A 3D laser confocal scanner (Olympus LEXT OLS4100) and an image metrology software SPIP were used to evaluate the burr formation. Each pixel was inspected at three positions from the top left to the bottom right. At each measurement, five ridges were included in the viewing range of 258x 258 μm^2 with 50X magnification. The topography of the surface is illustrated by **Figure 2** where the reflecting part is marked with a white box.

The burr height was measured by analysing the profiles (**Figure 2**). The nominal ridge height was approximately 4.4 µm; the *Z* range of the average profile, where the burr height was omitted, was used to measure the actual height of the ridges. The absolute height (ridge + burrs) was the *Z* range from the 3D height map. The burr height was defined as the difference between the absolute and average height values.

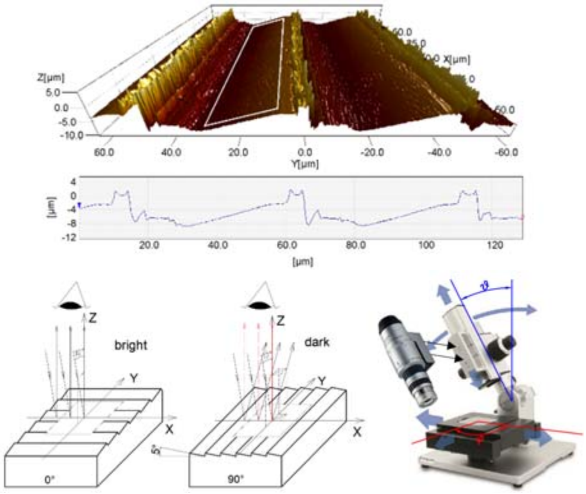

Figure 2. The surface evaluation: surface quality and contrast.

In the contrast evaluation, a digital microscope Hirox rh2000 (**Figure 2**) was employed with the possibility of tilting the objective lens. To simplify the experiment, the surface contrast was measured on the same surface by rotating it by 90°. The reflection of the surface was observed from the microscope over the sample from view angles ((φ, θ); $\varphi \in [0°, 360°], \theta \in [0°, 90°]$) in a semi-spherical range (**Figure 2**). The images captured in these view angles were processed to evaluate the reflectance. The main output, the reflectance radiant exposure $[\mathrm{k} \cdot \mathrm{J}/m^2]$, is measured up to an unknown scale k, and under constant lighting conditions, i.e. intensity and distance to surface, this quantity is proportional to the reflectance of the surface. [8]

In this paper, contrast was defined as the maximum difference between the exposures obtained from a viewing angle (φ, θ) and that from (φ+ 90°, θ) from the viewing angles that used in previous work [8]:

$$\text{Contrast}\,(\varphi,\theta) = \max(|\exp.(\varphi,\theta) - \exp.(\varphi + 90°,\theta)|)\,;$$
$$\text{where: } \varphi \in [0°, 360°], \theta \in [0°, 90°].$$

3. Results and analysis

The contrast distribution among the pixels is illustrated by **Figure 3**. The contrast differed among the pixels machined by different parameters. The contrast of the horizontal pixels was generally higher than that of the vertical ones, which proved the different machining accuracy on *X* and *Y* axis. The discussion will focus on the horizontal pixels. On the horizontal side, the highest contrast was $692\mathrm{k} \cdot \mathrm{J}/m^2$ while the lowest one was $324\mathrm{k} \cdot \mathrm{J}/m^2$.

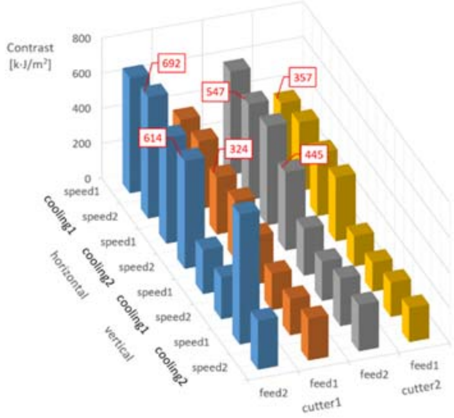

Figure 3. The contrast distribution among the pixels

The highest and lowest contrast and the burr height of the corresponding pixels are shown in **Figure 4**. Some of the pixels had the contrast in between. As the burr height increased, the contrast decreased. There is seemingly a linear relation between the burr height and the contrast of the machined surface. The images above the bars show the corresponding pixel topography under LEXT (top view), which illustrates the burrs formation along with the height.

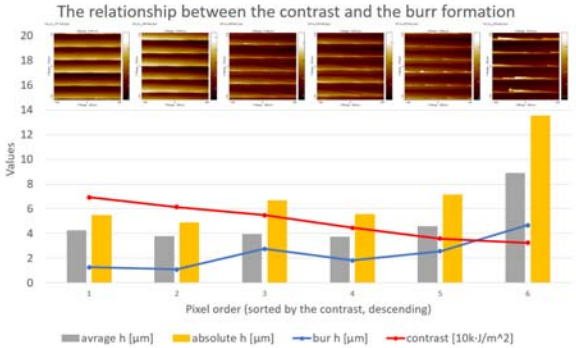

Figure 4. The contrast decreased as the burr heights increased.

The contrast values are used as the response of the DOE to evaluate the influence of the parameters on the functionality of the surfaces. As shown in **Figure 5**, the cooling condition and the feed rate affected the contrast significantly: "oil+air" and higher feed rate were preferred. Even the diameter and the spindle speed had less influence on the contrast generation of the surfaces, a bigger diameter and higher spindle speed were positive regarding the surface function.

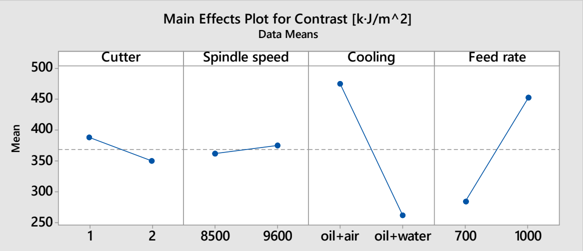

Figure 5. The impact of parameters on the surface contrast.

4. Conclusions

In this study, the functionality and the burr formation of micro-ridges machined using micro milling process, with different parameters, were investigated. The correlations between the functionality and the burr height and milling parameters were determined. Results suggested that the micro-ridges were able to generate detectable contrast and that coated carbide end mills were capable of manufacturing those surfaces. Some specified conclusions can be drawn as follows:

1. The optical functionality was linearly decreasing with the burr height. Future work will be dedicated to burr reduction or removing after machining.
2. The DOE suggestion for better contrast generation of the milling parameters were: the diameter of the cutter 3mm, the spindle speed 9600 rpm, the cooling condition “oil + air” and the feed rate 1000 mm/min. That would give more suggestions for future study on micro milling in terms of the optical function of surfaces.

5. Acknowledgement

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