Angle variation in free form grinding to improve surface roughness

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Abstract. An increasing demand for complex shaped parts requires new methods for increasing the productivity in machining of those parts. The utilization of a 5-axis kinematic in a grinding machine offers high potential for reducing process times as well as improving surface quality. Face grinding is known for producing high quality surfaces but is limited to flat or convex surfaces. The goal of this work is to gain an understanding of the effect of process angles on the surface quality in face grinding. Path planning for free form grinding can be improved by the fitting of the surface curvature of the workpiece to the shape of engagement due to these angles. This paper shows the effect of the yaw angle on the surface roughness for different process parameters. Productivity can be improved by applying higher feed rates while still reducing the surface roughness by selecting optimized yaw angles.

Introduction

The demand of complex products has increased over the last years and will continue to do so in the future. The number of knee replacement surgeries in Germany has risen by about 20 % between 2013 and 2016 [1] and the air traffic is forecasted to increase up to 100 % until 2036 [2]. Knee joint prostheses and aerospace parts (i.e. turbine blades) are machined with grinding processes and possess free-form surfaces in many cases. In order to meet the demand of low production costs, productivity for manufacturing processes needs to be increased for these parts.

Production of complex parts places special demands on the kinematic of the machining process. Additionally, high demands regarding the surface quality and form accuracy arise from the relevant industries (i.e. die and mold industry, aerospace or medical industry) [3, 4]. Fine machining to ensure the needed surface quality is responsible for up to 15 % of the production costs [5]. Currently hard milling, eroding, grinding and polishing are used to reach the required quality [3]. Especially hard milling was established an alternative to grinding and polishing as a finishing operation over the last years [[6]. It is however, limited to certain materials as ceramics and other brittle and hard materials will continue to be difficult to machine by milling [7].

Form grinding is applicable for brittle materials and is able to machine free form surfaces. Currently especially NC form grinding with profiled grinding wheels moving along programmed tool paths is used. Using 5-axis simultaneous machining to control the tool’s path allows the flexible fitting of the grinding wheel to the surface curvature [4, 8, 9, 10, 11].

An established machining strategy is the 3-axis control of toric grinding wheels along parallel tool paths. (see Fig. 1 left). Productivity and form accuracy are closely connected and limited due to the fact that the angle of attack of the grinding wheel changes constantly. This results in changing engagement conditions, process forces, and differing tool displacements. The multipass strategy also keeps the point of contact on the grinding wheel constant throughout the workpiece, which leads to increased local tool wear. Both effects potentially lead to deviations from given form or shape tolerances [12].
This research aims to utilize the angle of attack and yaw angle to increase the productivity of the form grinding process while decreasing the local tool wear. The envisioned strategy uses both angles to fit the tools radius at the point of contact to the curvature of the workpiece (see Fig. 1). Previous investigations regarding the effect of attack angle variations in face and peripheral grinding have shown the great potential for maximizing material removal rates while maintaining the required workpiece quality [4, 9].

**Experimental setup**

The experimental setup for the conducted experiments within this study is shown in Fig. 2. The toric grinding wheel is set above a workpiece made of high-speed steel within a Blohm MC407 grinding machine. The workpiece is mounted on top of two adjusting plates that are used to level the workpiece surface to the grinding wheel. Attack angle as well as a yaw angle are shown in more detail on the right side of the figure. The angles are established by tilting the machine table. The yaw angle (top right) is defined as the angle between the feed rate and cutting speed vector. The indicated tool paths along the workpiece show the direction of the feed rate, while the cutting speed vector follows the circumference of the grinding wheel tangentially from the point of contact. The angle of attack is sometimes referred to as the lead angle (face grinding; $\beta_G = 90^\circ$) or inclination angle (peripheral grinding; $\beta_G = 0^\circ$). In order to conflate both definitions for varying yaw angles $\beta_G = \text{var.}$ the angle of attack in this project is defined as the angle between the surface normal at the point of contact and the grinding wheel’s vertical axis as described by the vector between the contact point and it’s axis of rotation [1].
In the experiments are conducted with a Tyrolit Strato Ultra vitrified grinding wheels with #120 sintered corundum grains under oil coolant which was supplied by the depicted coolant nozzle. The grinding wheel is 350 mm in diameter and has a toric profile with a ring diameter of $r_{tor} = 10$ mm. Each experiment consists of six parallel tool paths spaced 1 mm apart along the width of the workpiece ($W \times L \times H = 25 \times 108 \times 10$ mm). Additionally, preliminary investigations were conducted on a DMG Sauer Ultrasonic 10 (emulsion coolant) with different dimensions ($D = 30$ mm, $r_{tor} = 5$ mm, B91 CBN grains, vitrified bond) to investigate the effect of each yaw angle discretely between $0^\circ < \beta_G < 90^\circ$ (at $v_c = 25$ m/s, $v_f = 500$ mm/min).

When using CBN grains, smaller grain sizes are used to achieve the same surface roughness. This is based on the fact that corundum grains break more easily, resulting in a constant renewal of cutting edges. A corundum grain breaks several times before leaving the bond, resulting in smaller cutting edges than its nominal mesh size, while a CBN grain exhibits less tendency of grain breakage. For the same chip thickness and therefore same surface roughness at equal cutting conditions a smaller CBN grain needs to be selected.

The process parameters for the investigations with the larger grinding wheels were kept at a constant cutting speed of $v_c = 25$ m/s while varying the feed ($v_f = 250, 500, 750$ mm/min). Each experiment started with one pass along all six paths across the workpiece with no depth of cut followed by an increase of the depth of cut by 25 µm until the total depth of cut of 100 µm is reached. This process ensures constant engagements along the last passes before measuring the surface roughness with regard to DIN 4768. The surface roughness was measured practically with a sample length of $\lambda = 5.6$ mm perpendicular to the feed rate in three places along the tool paths which were averaged mathematically. The grinding wheel was dressed by a diamond profile roller with a dressing depth of cut of $a_{cd} = 20$ µm after each individual experiment to ensure constant initial conditions.

Theoretical background

In order to understand the surface development on a microscopic level, Fig. 3 illustrates the relationship between surface roughness and process parameters schematically. The abrasive layer of the grinding wheel is reduced to a single protruding grain, which is further simplified by a triangle (top left). The single grain cuts grooves into the workpiece at each tool revolution (bottom left). The parallel distance between grooves changes with the ratio of feed rate to cutting speed. The distance between the grooves a can be calculated with eq. 1 and was verified by microscopic images of ground surfaces from the investigations (bottom right).
If the distance \(a = a_{\text{crit}}\) between grooves matches the width of a grain engagement (groove) \(b\), the surface roughness is highest. Reducing the distance between grooves improves the surface roughness as the grooves overlap, levelling each other partially with every revolution (center).

\[
a = \cos(90^\circ - \beta_G) \cdot \pi \cdot D \cdot v_f / (v_c \cdot 60).
\]  

(Eq. 1)

The variation of the yaw angle changes the width of engagement \(b\) by rotating the protruding grain along its path of engagement. For a simplified grain model, a roof shape is shown in the upper right corner of Fig. 3. Veering this grain causes the shape of the resulting groove to vary from a triangle to a trapezoid (right). This changes the interrelation shown previously between the groove distance \(a\) and the groove’s width \(b\) on the resulting surface roughness.

Fig. 3: Surface roughness development on microscopic scale

Results & discussion

The improvement of the surface roughness between peripheral and face grinding is widely known [13]. After the preliminary experiments with the smaller CBN mounted point revealed an unexpected increase in surface roughness between \(15^\circ < \beta_G < 20^\circ\) after an initial decrease between \(0^\circ < \beta_G < 15^\circ\), ten discrete yaw angles were selected for the experiments with the larger grinding wheel.

The result of both sets of experiments are shown in Fig. 4. Even though the tool diameter varies from \(D_1 = 350\) mm to \(D_2 = 30\) mm, grain size and type are different, both resulting surface roughness graphs show similarities in their trends. For visual comparability, both tools are shown on the right side. After an initial decrease in surface quality, the roughness increases temporarily before decreasing again. In case of the smaller CBN tool, the surface roughness drops to about the same amount that it increased before and remains mostly constant for \(30^\circ < \beta_G < 80^\circ\). With the larger tool the surface roughness decreases constantly towards its global minimum at \(\beta_G = 90^\circ\). The absolute values of the surface roughness especially close to the local roughness maximum are comparable, which was the aim of these investigations.
To investigate the surface roughness increase in more detail, the process parameters were varied in experiments with the larger grinding wheel at ten discrete yaw angles. Fig. 5 shows the influence of a changing feed rate on the surface roughness and the calculated groove distance $a$ for each parameter combination. Moreover, the critical value of the groove distance $a_{\text{crit}}$, where highest roughness is expected, is shown. In this case the feed rate was changed from $v_f = 250$ mm/min to $v_f = 500$ mm/min and $v_f = 750$ mm/min. Changing feed rates alter the contact conditions between the tool and the workpiece. An increase in feed rate, with otherwise unchanged process parameters, generally increases surface roughness as the chip thickness increases. This effect can be seen when raising the feed rate from $v_f = 250$ mm/min to $v_f = 500$ mm/min. The surface roughness increases over a wide range of yaw angles ($0^\circ < \beta_G < 50^\circ$) and the aforementioned local roughness maximum appears at yaw angles around $\beta_G = 20^\circ$.

Similar effects occur, when increasing the feed rate from $v_f = 500$ mm/min to $v_f = 750$ mm/min. It results in an increasing chip thickness and therefore reduced surface quality. The graph (see Fig. 5) shows the increased surface roughness for yaw angles $7^\circ < \beta_G < 15^\circ$ and for $\beta_G > 50^\circ$. However, the
local roughness maximum is shifted toward a smaller angle ($\beta_G = 15^\circ$) and for a large range of yaw angles ($0^\circ < \beta_G < 7^\circ$ and $20^\circ < \beta_G < 50^\circ$) the higher feed rate results in a lower surface roughness. This contradicts the correlation between chip thickness and surface quality as the surface roughness should be higher for all process angles at the higher feed rate.

It also becomes apparent in Fig. 5 that the local roughness maximum is influenced by the cutting speed to feed rate ratio. With constant cutting speed, a variation of the feed rate influences the roughness significantly (Fig. 5). The local roughness maximum can be shifted to varying yaw angles or avoided almost entirely.

Following the theoretical background specified earlier, the correlation between surface roughness and process parameters can be explained by the parallel groove distance in relation to the grain dimensions. The calculated groove distance $a$ is also shown in Fig. 5 (grey graphs) for the three sets of process parameters. When cross-referencing the yaw angle for the local roughness maxima with the groove distance $a$ of each set of process parameters (red lines), it becomes apparent that all maxima appear around similar groove distances. This groove distance closely matches the grain size of the grinding wheel at about $a_{\text{crit}} \approx 135 \mu m$, proving the introduced mechanism for surface development on a microscopic scale. The simplification introduced in Fig. 3 therefore leads to a better understanding of ground surfaces development and influences of the yaw angle on the surface roughness. Due to the statistical distribution of grains, this theory is not applicable for other grinding tools. Further investigations will show it’s scope of application for the design of future grinding processes. Experiments with varying grain sizes will be carried out to validate the theoretical background.

Summary

The utilization of the yaw angle in grinding processes has a high potential to increase the surface quality while reducing the process times. Characteristic combinations of cutting speed and feed rate for different grinding wheels can be applied with respecting yaw angles to increase the feed rate by 50 % while simultaneously reducing the average surface roughness by 20 %. Certain yaw angles are to be avoided for each set of process parameters for surface roughness increases where the parallel distance between ground grooves correlates with the grinding wheel’s grain size. At these process parameters, the resulting surface quality decreases drastically due to the fact that grooves are no longer overlapping. This understanding enables the complex path planning for the grinding of free form surfaces for improved process times as well as surface qualities.

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