Experimental analysis of cutting forces in actuated face milling of micro patterns

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Abstract

This article presents an experimental analysis of cutting forces in fast tool servo-based face milling of micro structures. These structures can be used as a binary information carrier [1]. For a proper process design on a wide range of materials, knowledge of the cutting forces is necessary. The analysis was conducted on the materials Al7075, AISI 4042 and TiAl6V4. The investigated parameters are cutting speed, feed, depth of cut, variable depth of cut change and frequency of change. The experiments were conducted according to a full-factorial design using two levels for all parameters and with the tool in full engagement. The used tool system is based on a piezoelectric actuator, enabling tool tip deflections up to 4.5 kHz with an amplitude of 30 μm. A precise linkage to the angular spindle position allows adjusting the deflection over the width of the rotatory tool tip movement. In analogy to the information carrying micro patterns, sinusoidal structures are generated in the engagement range from 45 to 135 degrees angular tool tip position. In order to minimize possible superimposed vibrations of the dynamometer and amplitude gains of high frequency force signals, a filter is used. The filter is based on an inverse function of the force measurement transfer behavior system with mounted specimen. The effects are evaluated on the mean values of the extracted force signals between 45 and 135 degrees engagement range and compared to the effects of machining without variable depth of cut.

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Peer-review under responsibility of the Organizing Committee of SysInt 2014.

Keywords: Fast tool servo; micro patterns; highly dynamic force measurement

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1. Introduction

The Collaborative Research Centre (CRC) 653, sponsored by the German Research Foundation (DFG), researches innovative component properties and concepts for their manufacturing and implementation in production engineering processes. One of the CRC’s visions is the inherent storage of significant component information, such as production date, process parameters, process forces or even production drawings on the component itself [1]. In addition, these advanced properties provide an excellent basis to protect the component against plagiarism. The machining of defined micro patterns into the component surface during a finishing operation offers a promising possibility to store binary information (Figure 1). In [2] this approach was successfully performed with a specially designed piezo-electric milling tool capable of axial tool tip deflections up to 4.5 kHz with an amplitude up to 30 μm. Aiming to refine this method for industrial use, knowledge of cutting forces during machining of the micro patterns is essential. With this information the design of new tools and processes for different materials is possible. The force measurements are carried out in order to analyze the influence of excitation frequency and amplitude on cutting force components under different process conditions. So far detailed force measurements with fast tool servos hadn’t been carried out [3,4,5] due to problems with dynamic effects of the dynamometer while using high excitation frequencies. This Paper uses an inverse filter technique [6] primarily used in force measurements for micro milling, to extend the measurable frequency range of a dynamometer.

The aim is to derive universal correlations for the interpretation of structuring processes which can be used to improve the mechanical design of tools. The materials Ti6Al4V, Al7075 and AISI4042 are machined with variation of the parameters excitation frequency, amplitude, cutting speed, feed and depth of cut.

![Fig. 1. Machined micro patterns for information storage on the component surface [2].](image)
2. Test Setup

The tests are carried out on a HELLER MCi16 milling centre. The structures are generated by using a piezo-actuator driven milling tool as also used in [1]. The tool is controlled by a real-time computer system. The control system receives the current angular position of the spindle and creates a sinusoidal deflection signal in a specified engagement area of the cutting edge. The process forces are measured in three directions with the Kistler MiniDyn C2 dynamometer. The transmission behavior, which is necessary for filtering of the force measurement data, of the measuring platform with mounted workpiece was defined by the impulse hammer method. The test setup is shown in Figure 2.

The tool head consists of a 20 mm face milling head with one insert. The flank face of the cutting edge is prepared in the form of a bar so that a constant chip thickness during machining of the structures in dependency of the structure depth can be maintained (Figure 3). The cutting edge was prepared by grinding.

3. Test Execution

In accordance with the structuring processes, the sinusoidal structures are generated in face milling with one insert and an engagement angle of the milling head of 45° to 135°. The sinusoidal excitation signal has the advantage that it cannot be influenced qualitatively by the transmission behavior (LTI system) of the tool. Only amplitude and phase can be influenced. This can be predicted by an existing transmission model and is taken into account during test interpretation. In order to prevent overlapping of structures, they are generated only every 10th revolution. The tests are run according to a full factorial two-stage test approach. The examined variables are varied with the values indicated in Table 1 for all three materials used.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$f_{struc}$ [Hz]</th>
<th>$a_{struc}$ [μm]</th>
<th>$f$ [mm]</th>
<th>$v_c$ [m/min]</th>
<th>$a_p$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>500</td>
<td>8</td>
<td>0.02</td>
<td>41</td>
<td>0.1</td>
</tr>
<tr>
<td>+</td>
<td>1500</td>
<td>17</td>
<td>0.07</td>
<td>82</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The conditions of the machining process during structuring, the form of the structure and the prepared cutting edge are shown in Figure 3.
4. Processing of Measurement Data

Before evaluating the results of the measurements, the recorded forces are cleansed up from the falsifying self-oscillation of the dynamometer by means of an inverse filtering method [6]. In order to determine how the structuring is influencing the cutting forces, the average differences of force progression at one revolution with and without structuring in the engagement area of structuring are used. In the following those forces are called structuring forces $F_{struc}$. This is carried out for the force components $F_c$, $F_{cN}$ and $F_z$. A statistical statement can be made by averaging the structuring forces over 10 machining operations. A schematic diagram of processing the data is shown in Figure 4.
5. Results of the Cutting Force Measurement

Figure 5 displays exemplary the process forces while machining Al7075. It can be seen that the sinusoidal structuring force is clearly visible in the cutting and passive forces. The structuring force progressions are symmetric concerning their gradient and descent. As a conclusion, no measurable influence of the changing shear zone can be given.

![Exemplary force progressions during structuring.](image)

The effects of the average structuring forces were determined according to a statistical evaluation and provide information about an average change in force depending on the examined parameters (Figure 6).

The evaluation shows that significant effects on cutting and passive forces exist at a 99% confidence interval depending on structuring amplitude and partially on feed. Especially the effect of the structuring amplitude shows a double to triple average increase in force compared to the superior effects.

Since the reciprocal effects of the investigated parameters are below a 95% threshold, they are not displayed in Figure 6. Neither the structuring frequency nor the resulting different effective speed at the cutting edge have an influence on the structuring forces.
The relatively high increase of the structuring force regarding the total depth of cut is primarily related to the rapid increase of the chip thickness to the full width of the bar at the cutting edge. As well as the change in chip width dependent on the excitation signal.

In Figure 7 the average cutting forces of all measurements dependent on depth of profile are plotted and confirm that there are no dependencies of the structuring forces on feed and cutting depth. The evaluation by using averaged values is allowed in this case due to a low scatter of the measurement values of 1 – 2 N. It has to be noted that the structuring forces in face milling operations are independent from regular machining conditions. The total forces while structuring result from the named conclusions as it follows:

\[ F_{i,\text{total}} = F_{i,\text{regular}} + k_{i,\text{struc}} \cdot a_{\text{struc}}(S(\varphi)) \quad \text{with } i = c, z \]  

Thereby \( F_{i,\text{regular}} \) represents the cutting forces without structuring. The constant \( k_{i,\text{struc}} \) is the gradient coefficient, which is calculated as a product of the specific cutting force constant and an equivalent chip thickness. The structuring depth depends on the deflection signal \( S(\varphi) \) which is dependent on the engagement angle \( \varphi \).

The linearity of the increase of structuring force results from the independency of the specific cutting force constant from chip width [7] and the rapid increase of the chip thickness to a static value of the whole structuring. This is verified by the constant amplitude of the structuring forces throughout the whole engagement area (Figure 5).
6. Summary

In conclusion it can be stated that the structuring forces necessary for machining of information carrying structures are largely dependent on the structuring amplitude and the macro geometry of the cutting edge. The results indicate that the structuring frequency and cutting speed do not affect the process forces. The structuring forces can be expressed by a linear behavior with a defined increase factor for the whole engagement area.

Since structuring increases the process forces significantly, precision errors may occur in the structuring depth to be attained if tools are not designed with sufficient stiffness. Therefore, structuring tools have to be sufficiently stiff in design and application, especially when machining steels like AISI4042.

Acknowledgements

The presented investigations were undertaken with support of the German Research Foundation (DFG) within the Collaborative Research Centre (CRC) 653 “Gentelligent Components in their Lifecycle“. The authors would like to thank the DFG for its financial and organizational support of this project.

References


Fig. 7. Dependency of cutting force on depth of profile during structuring on the example of Al7075.