Cutting force prediction in micro-milling considering the cutting edge micro-geometry

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Abstract
The micro-milling process is used for a wide range of materials and enables the manufacturing of complex geometries with micro-features. One important factor for the tool life is the cutting force \( F_c \), which depends on the applied technology, process parameters and cutting edge micro-geometry. High cutting forces \( F_c \) can lead to tool breakage in the transition between the shank and the cutting part of cemented carbide end mills. The prediction of cutting forces \( F_c \) in micro-milling processes through cutting force models could potentially decrease the hazard of tool breakage. By including the cutting edge radius \( r_f \) into the prediction model, additional correction factors can be avoided. Therefore, further knowledge about the applicability of those models for the micro-milling process with chip thickness \( h < 0.01 \) mm is needed.

In this investigation, the cutting force model of Kotschenreuther [1], which takes the cutting edge radius \( r_f \) into account, is used for the cutting force prediction in micro-milling. In order to validate this model, an innovative lead free copper alloy CuZn21Si3P is machined. Cemented carbide micro-milling tools with tool diameter \( D = 1 \) mm were used. The manufacturing of different cutting edge radii \( r_f \) was realised with the immersed tumbling process. During milling experiments with a five-axis high precision machine tool the cutting forces \( F_c \) were measured. Cutting forces in a range of \( 6 \) N ≤ \( F_c \) ≤ 26 N were detected. The results show good correlations between the predicted and experimental determined cutting forces \( F_c \). Furthermore, the measured cutting edge radii \( r_f \) show a high influence on the deviation of the measured and predicted cutting forces \( F_c \).

Keywords: micro-milling, innovative micro-geometry, cutting force

1. Introduction
Micro-machining has become increasingly important in recent years, because of the growing demand for components utilizing complex micro-features. In industrial applications, the tool life is one of the key factors for cost-effective micro-machining. This property is influenced by the cutting force \( F_c \), which depends on the technology, the process parameters and the tool geometry. Especially the micro-geometry of the tool edge affects the cutting forces \( F_c \) and is influenced by the proceeding tool wear during the process. Increasing cutting forces \( F_c \) usually lead to tool breakage in transition between the shank and the cutting part of carbide milling tools. Cutting force models according to Kronenberg [2] and Kienzle [3] for predicting the cutting forces \( F_c \) are established in case of conventional machining [4]. The prediction model of Kienzle was extended by Kotschenreuther [4] who reduced all correction factors k on the cutting edge radius \( r_f \). The prediction model is shown in formula 1. The model is influenced by the specific cutting force \( k_c \), the cutting width \( b \), the chip thickness \( h \), the slope value of specific cutting force \( m_c \) and the cutting edge radius \( r_f \). The cutting edge radius \( r_f \) could be determined as the most important influencing factor. The developed model was validated for chip thickness in a range of \( 1 \) µm ≤ \( h \) ≤ 100 µm by turning experiments.

\[
F_{c_{\text{exp}}} = k_c b h^m_{c_{14}} \left( \frac{n m_{c_{14}}}{0.0008442 \text{mm}} \right)
\]

Within the following chapters, the detailed methodological procedure for the validation of the Kotschenreuther [1] prediction model of will be explained. Micro-milling experiments with interrupted cutting for a chip thickness \( h < 0.01 \) mm will be presented and evaluated.

2. Experimental methodology
In order to generate extensive knowledge about the influence of the tool micro-geometry on the cutting force \( F_c \), it is necessary to understand the cutting process. First, the cutting edge micro-geometries of the prepared tools are extensively analysed in a test-preparatory step. After the practical experiment, the cutting forces \( F_c \) were analysed. This study includes two series of experiments, which are repeated three times. The influence of wear can be eliminated because of the possibility to use a new tool every experimental setting. The first series of experiments includes a variation of the process parameters feed per tooth \( f_z \), depth of cut \( a_p \) and spindle speed \( n \). In a second series of experiments, only the process parameter feed per tooth \( f_z \) has been varied. Thereby, only the mean chip thickness \( h \) changes. As a starting point for the parameter variation, the process parameters recommended by the manufacturer of the tools were used. The cutting force \( F_c \) were measured with the piezoelectric dynamometer Kistler type Z21317AT from Kistler Instrument AG, Winterthur, Switzerland. Solid carbide milling tools from ZECHA Hartmetall Werkzeugfabrikation GmbH, Königsbach-Stein, Germany, were used. To achieve different cutting edge micro-geometries, tools with identical macro-geometry were prepared differently. The tools are prepared by coating, lapping and laser preparation, as shown in figure 1. Prior to the experiments, the cutting edge radii \( r_f \) of the major and minor cutting edge, the chipping of the major and minor cutting edge \( R_c \) and the surface characteristics of the
flutes are measured. It was possible to achieve significantly different tool micro-geometries. A preparation of the uncoated milling tools leads to a slight increase in the cutting edge radii $r_b$ and to a reduction in chipping of the cutting edge $R_c$. The workpiece material was a lead-free heavy-duty special brass CuZn21SiP of the company WIELAND-WERKE AG, Ulm, Germany.

The experiments were carried out on the five-axis high precision machine tool PFM 4024-5D from the company PRIMACON GmbH, Peißenberg, Germany. Within the experiments, slot milling over a length $l = 10$ mm was used. For the evaluation of the cutting forces $F_c$, the piezoelectric dynamometer was applied. The results were analysed with the software MATLAB and a correspondingly developed program for the calculation of real cutting forces $F_c$. Subsequently, the determined cutting forces $F_c$ in the cartesian coordinate system were converted via the transformation matrix in a polar coordinate system related to the tool. The evaluation of the cutting forces $F_c$ has shown that the variation of cutting edge micro-geometry has significantly affects, as is shown in figure 2. In addition to the analysis of the cutting forces $F_c$, Kienzle’s linear relationship between the cutting force $F_c$ and the depth of cut $a_p$ in the area of micro-machining could be demonstrated.

Due to the minimised scope of the experiments and the nonlinear influence of the chip thickness $h$, only the main value of the specific cutting force $k_{0.5.1}$ can be determined. The quotient of the cutting force $F_c$ and the chip cross section $A$ is plotted over the chip thickness $h$ in a double logarithmic coordinate system to calculate this value.

Figure 3 shows the grades of both test series for the material CuZn21Si3P. It is recognisable that the cutting edge radius $r_b$ has a strong influence on the slope $m_1$ of the compensatory degrees.

The straight lines reflect the relationship to the Kienzle’s cutting force model. The given exponent consequently corresponds to the slope of the specific cutting force $k$ and the given x-value represents the constant $k_{0.5.1}$, in case of this experiments $k_{0.5.1}$ for micro-milling.

![Image](image-url)

**Figure 1.** SEM images of tool at an magnification of 500x and 1500x

**Figure 2.** Representation of the influence of cutting edge micro-geometry

**Figure 3.** Determined special cutting forces $k_c$ for material CuZn21Si3P in comparison from tool group 1 - 2

**4. Conclusion**

In this paper, the experimental methodology and the evaluation of cutting force prediction in micro-milling, considering the tool micro-geometry, are presented. As a result, the linear relationship between the cutting forces $F_c$ and the depth of cut $a_p$ can be detected in micro-milling. Additionally the results show a good correlation between the predicted and experimental determined cutting forces $F_c$. The results are a first step of detailed understanding of the influence of cutting edge micro-geometry at micro-milling tools. It is necessary to extend the experiments in future investigations, to get more comprehensive results of the different parts of cutting edge micro-geometry. This includes the cutting edge radius $r_b$ of the major and minor cutting edge, the chipping of the major and minor cutting edge $R_c$ and the surface characteristics of the flute.

**References**


