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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_β 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_β 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_β 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 $6\ N \leq F_c \leq 26\ N$ were detected. The results show good correlations between the predicted and experimental determined cutting forces F_c. Furthermore, the measured cutting edge radii r_β 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 progressing 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_β. 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_β. The cutting edge radius r_β could be determined as the most important influencing factor. The developed model was validated for chip thickness in a range of $1\ \mu m \leq h \leq 100\ \mu m$ by turning experiments.

$$F_{c_{exp}} = k_{c_{1.x}}\ b\ h^{1-m_{c_{1.x}}} \left(\frac{r_{\beta_{exp}}}{0.008442\ mm}\right)^{m_{c_{1.x}}} \quad (1)$$

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_β of the major and minor cutting edge, the chipping of the major and minor cutting edge R_s 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_β and to a reduction in chipping of the cutting edge R_s. The workpiece material was a lead-free heavy-duty special brass CuZn21SiP of the company WIELAND-WERKE AG, Ulm, Germany.

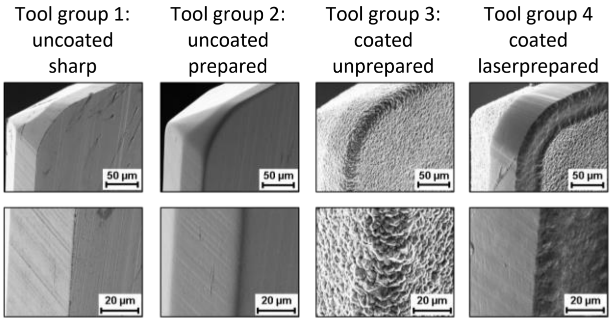

Figure 1. SEM images of tool at an magnification of 500x and 1500x

3. Experimental procedure and evaluation of cutting forces F_c

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.

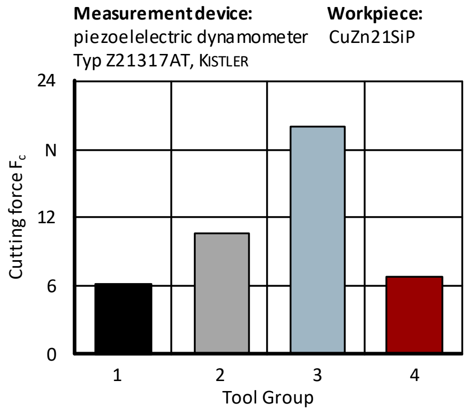

Figure 2. Representation of the influence of cutting edge micro-geometry

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 $k_{c0,5.1}$ 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_β has a strong influence on the slope m_c 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_c and the given x-value represents the constant $k_{c1.1}$, in case of this experiments $k_{c0,5.1}$, for micro-milling.

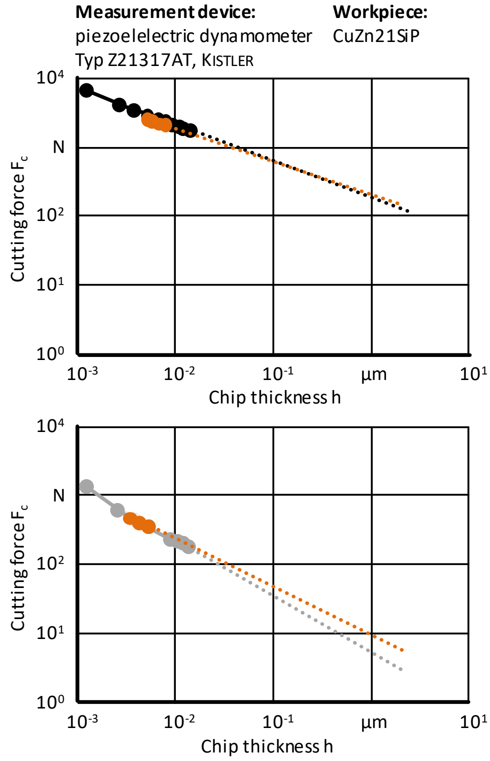

Figure 3. Determined special cutting forces k_c for material CuZn21Si3P in comparison from tool group 1 - 2

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_β of the major and minor cutting edge, the chipping of the major and minor cutting edge R_s and the surface characteristics of the flute.

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