Investigation of Scaling Effects on Modelling and Simulation of Scaled Milling Processes

K. Weinert, P. Kahnis, W. Koehler

Department of Machining Technology (ISF), Dortmund

Machining three-dimensional structures by micro-milling with high process reliability requires consideration of special difficulties in micro-machining. Occurring scaling effects should be recognized in advance and their influence to the process should be minimized with appropriate methods. The investigations of this project aim at determining scaling effects when scaling the milling process and qualifying an existing milling-simulation, which is successfully used in macro-machining, for micro-machining. The presented paper describes the requirements needed for a scaling of the milling process and presents results of tool investigations, milling experiments and of the simulation of the process.

1 Introduction

Due to the increasing trend towards miniaturization an efficient production of micro parts is more and more important. For the manufacturing of large quantities, forming techniques like injection moulding are well suited. At present the required microstructured moulds are primarily manufactured by EDM or by 2½-dimensional manufacturing methods (e.g. LIGA), which are derived from microelectronics. In recent years, manufacturing moulds by micro-milling became more and more important. This method allows the machining of complex geometries with high surface quality from a broad spectrum of materials. Parts with aspect ratios up to 5:1 and sharp inner edges or steep flanks are well suited to be manufactured by micro milling [1].

2 Current situation

2.1 Problematic Areas in Micro-milling

Micro-milling with smallest cylindrical end mills (e.g. $D < 1$ mm) places high demands on the milling process. One problematic area for example is the low stiffness of the tools. The section modulus of cylindrical bars decreases cubically with decreasing diameter. Therefore, end mills with small diameters have a low ability to compensate forces and torques without failure. Process forces lead to tool deflection and, as a consequence, to a dimensional deviation from the desired contour. In unfavourable conditions this may also lead to tool breakage [2].

A too small depth of cut leads to further problems in micro-milling. When the thickness of cut is smaller than a specific value, the minimum thickness of cut, the material is mainly squeezed between cutting edge and work piece rather than actually machined. This so called "ploughing-process" reduces the surface-quality of the work piece. In this context the increasing radius of the cutting edge caused by tool wear has to be considered. By this the shape of the cutting edge is changed and the chip formation is influenced. Furthermore, the effects on the surface like adhesion or friction have, due to the size of workpiece and tool, more influence on the micro- than on the macro-process. Microstructural details of the workpiece material, like for example inclusions and micro-cracks also should not be disregarded.

2.2 Scaling of the Milling Process

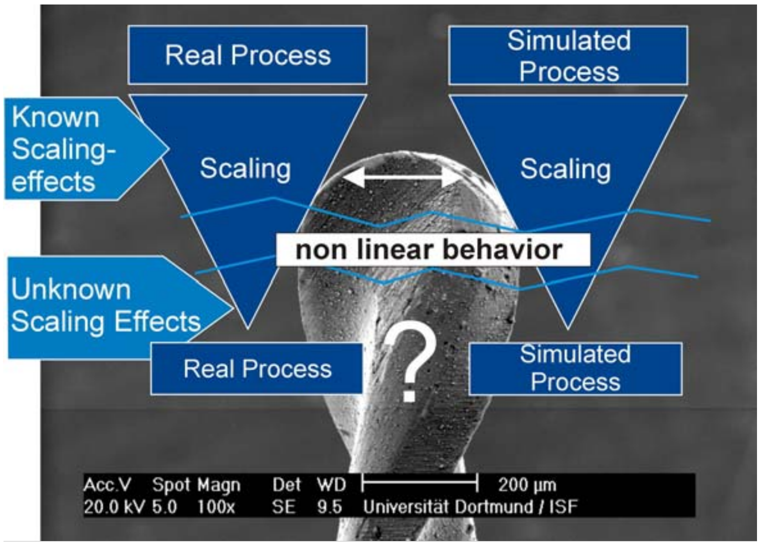

Fig. 1: Analysis of the influence of scaling effects when milling

Starting point of the investigations is the milling process in the macro-range, which is handled in simulation as well as in real application. This process is scaled down step by step until no linear behaviour occurs. Characteristic for this, so called limit of non-linearity is the appearance of scaling effects. That can be for example the "ploughing-process" or a dominating influence of the cutting edge radius. The deflection of the tool is also such a scaling effect. The appearance of this limit can be identified, when results of the simulation don't match the real process, so the model is not valid anymore. Among other, the following forms of mismatch may occur:

- Tool breakage even though the feed rate is adapted.
- Other surface topologies or –structures than predicted can be recognized.
- The simulated work pieces show dimensional variations, form errors or deviation of positions differing from the ones manufactured on a large scale.
- The process cannot be simulated, because the resolution of the model is reached and exceeded.

On this account it is necessary to identify the scaling factor until which the so far known processes and simulation methods are valid and usable. At the same time the actually occurring conditions are determined by experimental investigations in order to improve the simulation model by integrating these results. Furthermore, these experiments can point out further, until now unknown, scaling effects.

First of all investigations are made on a process which is relatively easy to monitor. This process is scaled down step by step. For this purpose, straight paths are milled and the process forces are recorded. Starting with D = 2 mm, the tool diameter is reduced step by step to 0.2 mm, which is a total factor of 10. According to this the engagement parameters like the depth of cut, lateral engagement and feed per tooth are also linearly scaled at constant cutting speed.

3 Results

3.1 Comparison of the Tools

In Fig. 2 pictures made in a scanning electron microscope (SEM) of tools which are used in the investigations are shown. Above all, the pictures show differences regarding the tool-geometry. Related to the tool diameter the ground shape of the tools with larger diameter is more accurate. The SEM-pictures allow to recognize deviations from the ideal contour especially on small tools (0.2/0.4 mm). Relative to the diameter the smallest tool also shows a more jagged cutting edge. In this diameter range the size of the cemented carbide grains has more effects on the cutting edge. Furthermore, the radius of the cutting edge in relation to the diameter is larger at the smaller tools. Due to the minimum grain size of the cemented carbide and the thickness of the coating the cutting edge radius cannot be reduced in the same way as the tool diameter. These scaling effects, which can be noticed by investigating the tools will influence the behaviour of the process when scaling the tool diameter.

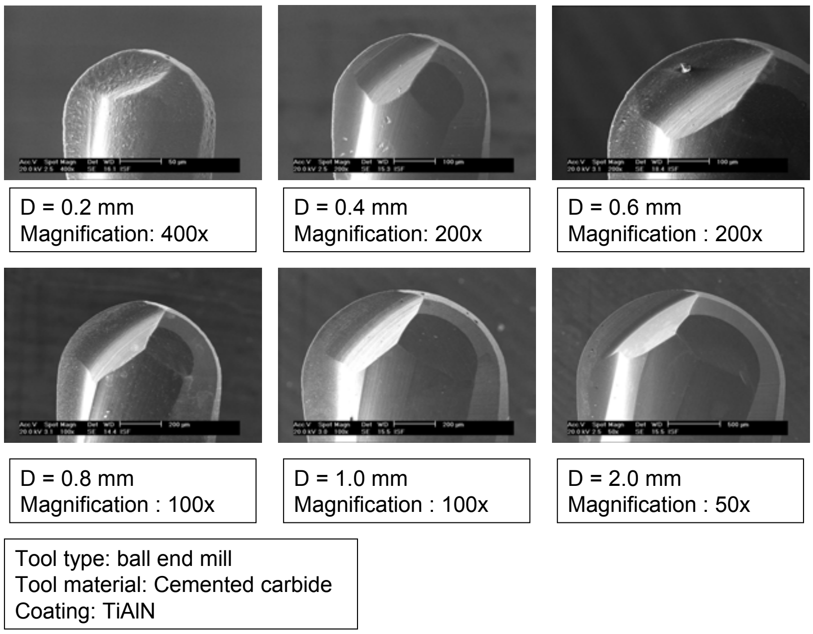

Fig. 2: SEM-pictures of the tools

3.2 Tool Wear

The evaluation of the process and the determination of scaling effects are made in a first step by the comparison of the process forces. For this purpose, simple paths were milled with a length of 30 mm. The parameters depth of cut, lateral engagement and feed per tooth are adapted to the tool diameter at constant cutting speed, i.e. they are scaled linear. The arising process forces were measured with a 3-component-dynamometer.

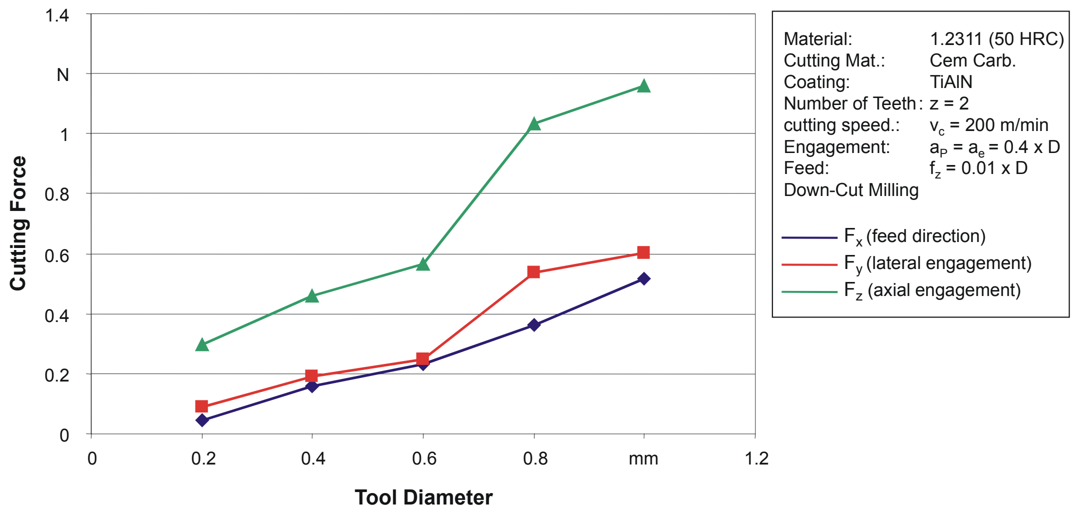

Fig. 3: Process forces subject to tool diameter

Fig. 3 shows the averaged progression of the process forces subject to the used tool diameter. At each path, the average value of the forces of three mills with a milling distance of 300 mm, is displayed. Between the tool diameters 0.2 and 0.6 mm an approximately linear behaviour of the forces occurs. After 0.6 mm the y- and z-values are clearly above the previous ones. In consequence of the volume of the machined material an more exponential progression is expected. To what extent size effects are responsible for this behaviour has to be analysed in further investigations.

In addition to the determination of the process forces at selected parameter combinations wear investigations with a longer milling path were made. Apart from the evaluation of tool life these investigations are used to exclude a possible influence of premature wear on the milling forces.

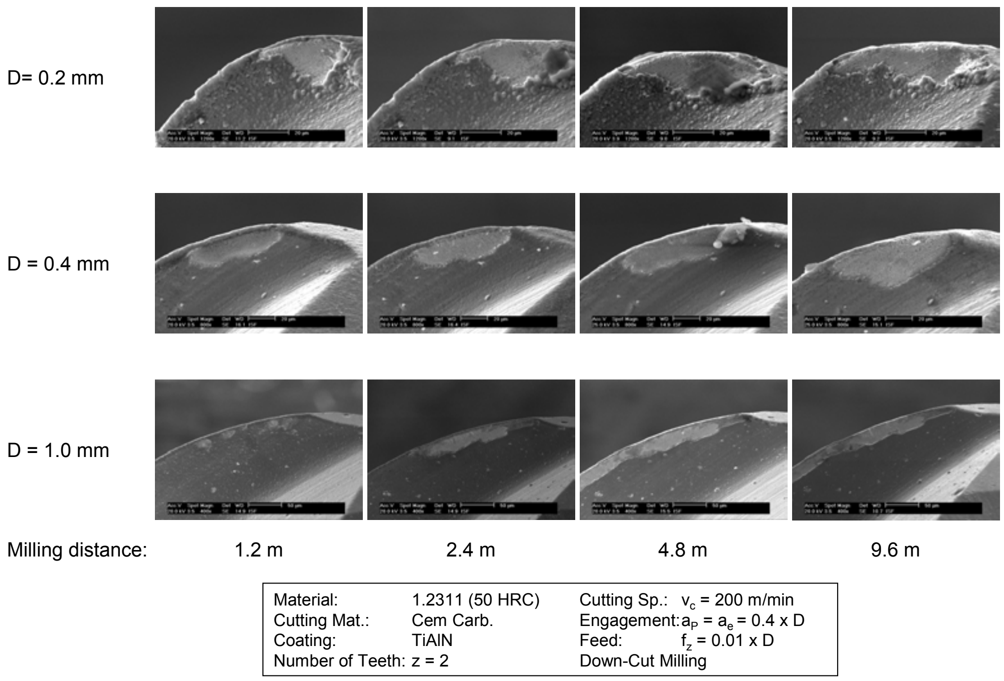

Fig. 4: Development of wear at different tool diameters

The evaluation of wear took place on the basis force measurements, as well as by the analysis of the width of wear mark by use of a scanning electron microscope. Fig. 4 shows the development of wear subject to the milled distance at different tool diameters. As expected, the mill with D = 1.0 mm showed the lowests wear. Apart from a flaking of the coating, after 9.6 m milling distance no further wear can be detected. In contrast to this, at the smallest tool an almost complete removal of the cuttig edge can be recognized after the same machining length. But it should be considered that in relation to the tool diameter the fivefold length was machined with this tool compared with the large one. However, even when comparing related milling distances (2.4 m with a 0.2 mm mill correspond 4.8 m with a 0.4 and 12 m with a 1.0 mm mill) the small mill shows higher wear than the other mills.

3.3 Simulation

The simulation for prediction of cutting forces is based on an analysis of the engagement conditions of the tool. For this, tool and workpiece are modelled by Constructive Solid Geometries (CSG) and are intersected with each other. With an incremental intersection the simulation is able to calculate the exact volume of actual machined material at any time of the process. The determined shapes of the machined material are very accurate and are used to calculate the arising cutting forces by means of the Kienzle-equation, calibrated by measured forces [3].

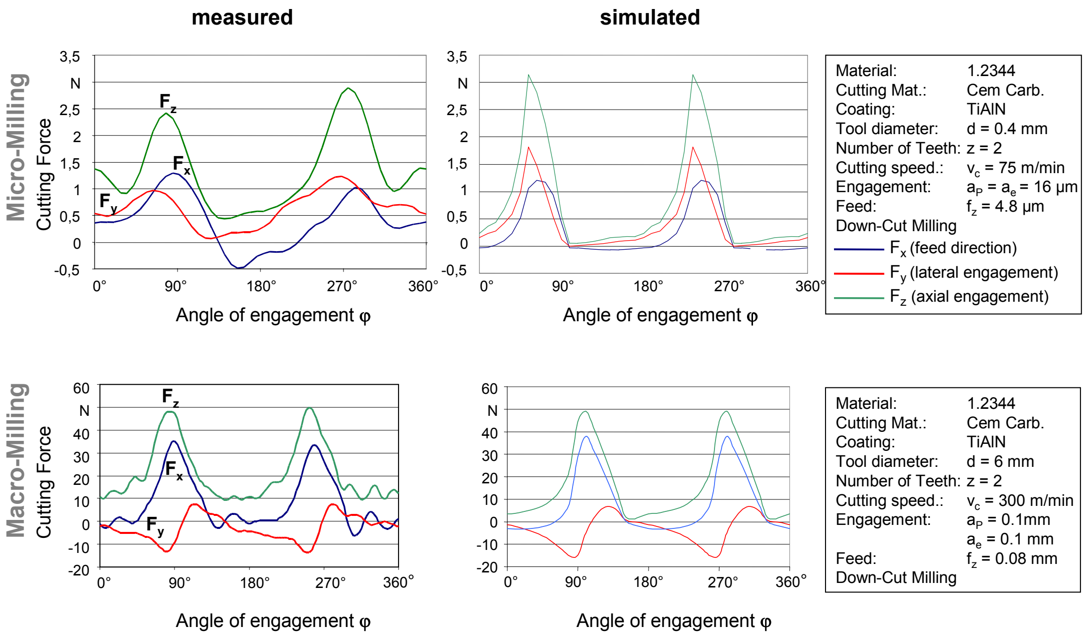

Fig. 5: Measured and Simulated Force Progression in Macro- and Micro-milling

Fig. 5 shows the progression of the cutting force for one tool revolution when milling with a 0.4 mm and a 6 mm mill. The components of measured cutting forces in micro-milling show a similar progression as the respective forces in macro milling. For the macro-process with a tool diameter of 6 mm the simulated forces match the measured progression well. However, it becomes evident that the simulation of the force progression in micro milling is only partly successful. Only the progression of the force in feed direction shows a similar behaviour. An explanation could be occurring vibrations, asymmetric cutting edges of the small tools or increasing ploughing effects due to a rounded cutting edge. Therefore, a precise simulation of the force progression needs further investigations regarding occurring scaling effects.

4 Conclusion

The presented paper describes investigations on a scaling of the milling process using ball end mills. Tool diameter and, dependant on this, feed, lateral engagement and depth of cut were scaled. Investigations on the used tools showed differences regarding e.g. the geometry of the different tool diameters. The analysis of cutting force as well as the investigations on tool wear indicate the existence of scaling effects. First results of the simulation show, that these occurring scaling effects should be considered to achieve an exact match of the modeled process with the simulation.

5 References

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