Development of Efficient Milling Technology Using Integrated Process Simulation

R. Neugebauer[1], C. Harzbecker[1], S. Ihlenfeldt[1], C. Hochmuth[1], M. Wabner[1], K. Hoyer[1*]
[1]Fraunhofer Institute for Machine Tools and Forming Technology,
Reichenhainer Str. 88, 09126 Chemnitz, Germany
[*] klaus.hoyer@iwu.fraunhofer.de

Abstract

The aims in machining of dies and moulds are high machining speeds in conjunction with high production accuracy and surface quality. Therefore new strategies in computer-aided manufacturing and advanced control concepts are required. The machine control has to consider the dynamic behaviour of the machine tool, of the drives and the milling tools to adjust the milling path and the feed actually during machining.

The deformation behaviour of the machine tool and the cutting tool are determined. For that purpose finite element simulations were done. The results of the simulations were stored in databases to which the machine control has access.

This control strategy was proved in milling tests. The tests validate the achievement potential of the realised compensation algorithms. Using the same feed rates milling with the new control strategy produce a better surface quality and a smaller geometrical error. Hence, a higher feed rate and higher acceleration may be chosen.

1 INTRODUCTION

The requirements on the machining of dies and moulds are increasing continually. That regards both the contouring accuracy and the surface quality of the machined parts and the total processing time. The primary processing time must be reduced by higher milling velocities. This necessitates high feed rates and high accelerations. Advanced machine tools with powerful drives allow such necessary velocities, accelerations and jerks.

However, caused by the accelerations the moved masses produce not avoidable deformations at the machine tools. This yields dislocations of the engagement of the cutting tools. Deviant from the nominal milling path of the tool center point (TCP) a dynamically changing actual path is realized causing geometrical errors on the surface contour. In addition, caused by the cutting forces in particular long cutting tools are displaces. This leads to modified milling path geometry too.

Both the deviations caused by the machine tool and the cutting tool require an advanced control strategy to compensate these. This compensation must by carried out online during the milling process. Only during the cutting process the real velocities and accelerations may be determined and evaluated. The basics for the compensation are deformation values offline predetermined using finite element method. These values are stored in a database to which the machine control may access.

This integrated process simulation was tested in first milling experiments at a new advanced machine tool. The applicability of the developed control concept could be evidenced. Using the same feed rates milling with the new control strategy produce a smaller geometrical error. Further investigations will be done to improve this control strategy and to make it more powerful.

2 CONTROL STRATEGY

The primary task of computer numerical control systems for machine tools is the command generation. This typically involves several modules inside a CNC:

- An interpreter which translates the part program into an inner data format suitable for the following elaborations.

- A look-ahead function which analyzes the tool path in order to find an optimal feed rate profile according to the axis dynamics and trajectory geometry.
- An interpolator whose role is the trajectory sampling, keeping the tool as close as possible to the planed path and feed rate.
- A kinematics transformation function which applies the inverse kinematics of the controlled machine tool to the interpolator output and generates the reference commands for the axis control.

The developed new control strategy involves the deformation behavior of the machine tool and of the cutting tool into this command generation [1], [2]. Before starting the inverse transformation, the actual position of the tool center point is detected and the actual velocity and acceleration is determined using numerical differentiation. By means of these actual values and the determined machine deformations new nominal values for the next point in the tool path are calculated and used for the axis control. In figure 1 the principal procedure is shown.

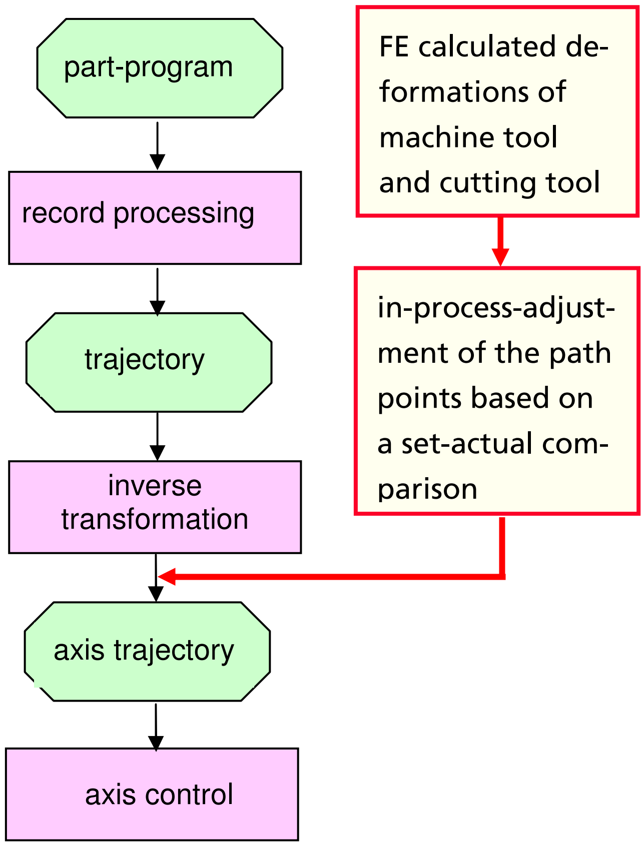

Figure 1: Advanced control strategy.

The deformation of the machine tool is different according to the position of the spindle and the tool. Therefore a matrix with position dependent values c of the mass-weighted elastic compliance is generated based on finite element analysis (see chapter 3). With a position dependent stiffness k_f and an active mass position dependent values c can be calculated as ratio of m_a and k_f by

$$c = \frac{m_a}{k_f} \tag{1}$$

The deformation vector $\vec{d}$ describes the shift of the TCP. It results from the actual acceleration vector $\vec{a}$ according to

$$\vec{d} = c \cdot \vec{a} \, . \tag{2}$$

The position error in milling Δ_{pos} is the superposition of the position error $\Delta_{machine}$ caused by the machine behavior and Δ_{tool} caused by the deflection of the tool.

$$\Delta_{pos} = \Delta_{machine} + \Delta_{tool} \, . \tag{3}$$

The machine caused position error $\Delta_{machine}$ equates to the vector $\vec{d}$ from (2).

3 NUMERICAL INVESTIGATIONS

3.1 Analysis of the machine tool

The finite element analysis of the deformation behavior of the machine tool was carried out for the specific “scissor kinematics” of a new machine concept for tool and die making [3], [4]. A photograph of this new machine tool is shown in figure 2. The Z-carriage, the spindle head, and the tool holding fixture are visible explicitly.

The finite element model of the “scissor kinematics” is shown in figure 3.

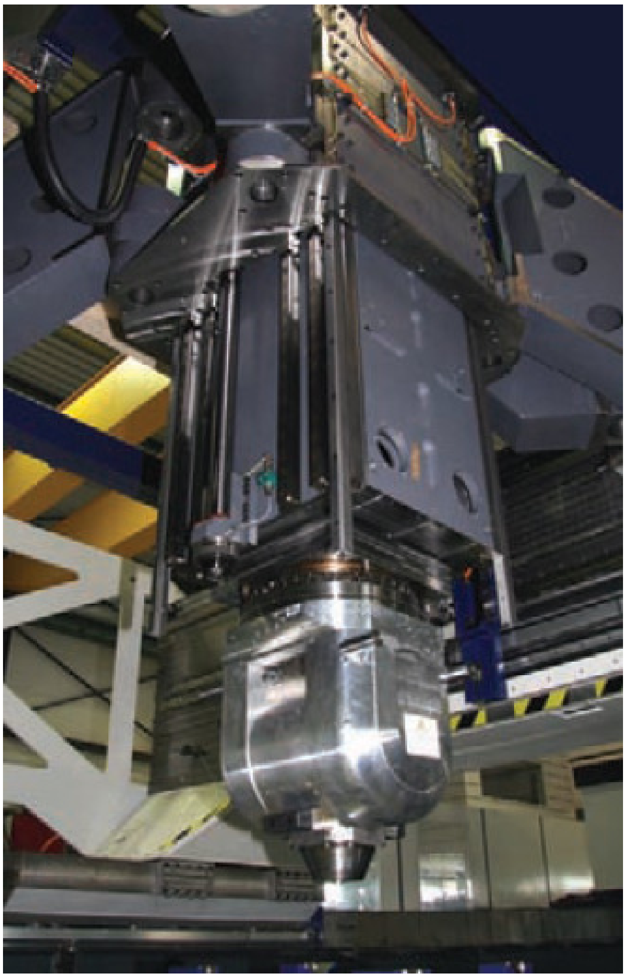

Figure 2: Machine tool with “scissor kinematics”.

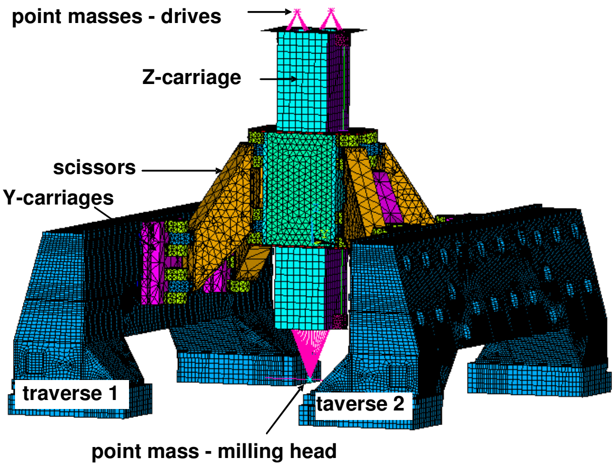

Figure 3: Machine tool “scissor kinematics”.

The deformation behavior due to acceleration forces was analyzed in four different basic load cases I - IV:

I: acceleration in X-direction at the drives of the traverses.

II: opposite acceleration in Y-direction at the drives of the Y-carriage.

III: similar acceleration in Y-direction at the drives of the Y-carriage.

IV: acceleration in Z-direction at the drives of the Z-carriage.

Two of these load cases and the calculated deformations are shown in the figures 4 and 5.

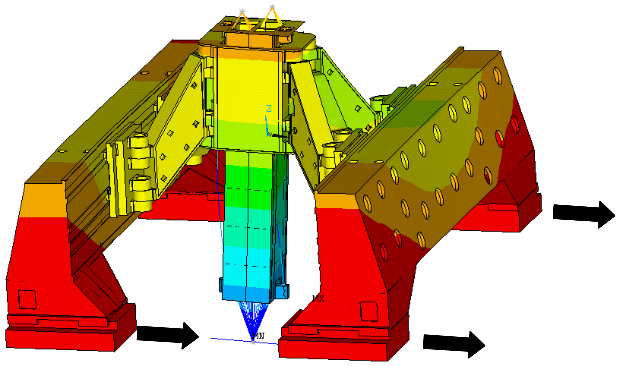

Figure 4: Load case I: acceleration in X-direction at the drives of the traverses.

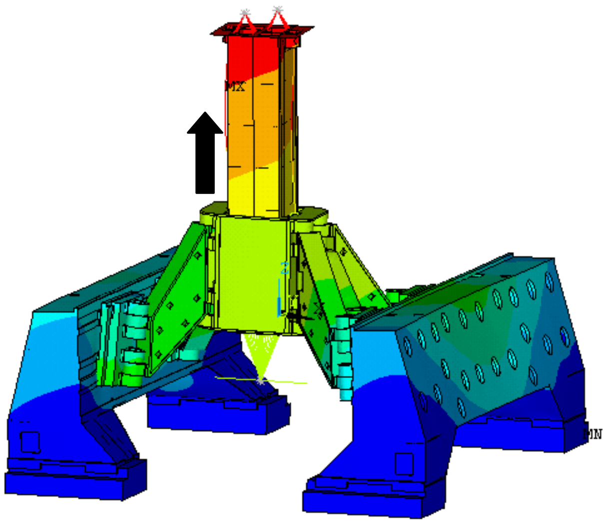

Figure 5: Load case IV: acceleration in Z-direction at the drives of the Z-carriage.

The analysis strategy includes the following steps:

- Determination of the elastic compliance for a normalized acceleration value of 1.0 m/s^2 at different positions in the working space for each of the four loads.
- The outcomes of this are normalized elastic compliance matrices.
- The total elastic compliance may be calculated by superposition of the acting load cases and by multiplying with the actual acceleration values.
- Further values for elastic compliance are determined by interpolation.

The results of the numerical simulations were summarized in elastic compliance matrices.
The elastic compliance of the machine tool is mainly influenced by the position of the Z-carriage which may be moved 1,800 mm.

To exemplify this for the load case I the displacement of the tool center point (TCP) for different positions of the Z-carriage for a fixed X-Y-position are shown in table 1. The Z-value represents the move of the Z-carriage downwards, measured at the TCP.
The displacements of the TCP are about three and a half times greater if the Z-carriage is in its lowest position.

Z-carriage position downwards [mm]	displacement of the TCP [µm]
0	37.7
450	50.2
900	67.1
1350	81.1
1800	130.0

Table 1: Displacement of TCP for different Z-carriage positions in load case I (see fig. 4)

3.2 Analysis of cutting tools

The deflection of different milling tools was determined by finite element analysis too. The deflection depends on the acting cutting forces and the stiffness of the tool. In particular long and lean milling tools may be pushed aside during cutting significantly. In figure 6 the model of a milling tool with clamping unit and the calculated deflection are shown.

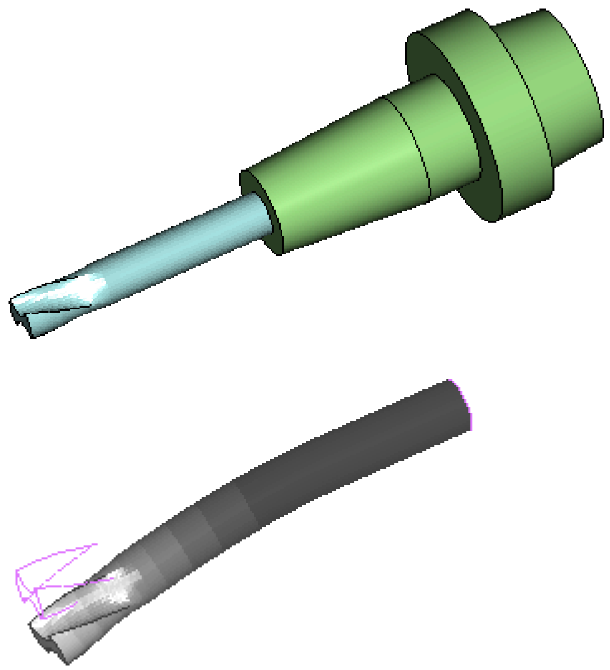

Figure 6: Model and deflection of a milling tool.

The magnitude of the deflection may reach values up to millimeters. For example, a milling cutter with a diameter of the shank of 16 mm and a free length of 150 mm reaches a deflection of 1.48 µm/N if the cutting force is acting under an angle of 36 ° - see figure 7.
Therefore, at cutting forces F_c of about 700 N the tool is deflected about one millimeter.

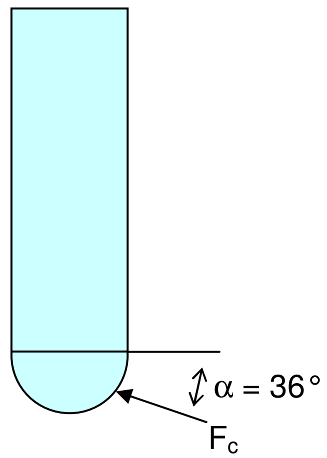

Figure 7: Cutting force acting at a milling tool.

The acting cutting forces depend on the actual cross-sectional area of the cut A which is the product of the width of cut b and thickness of cut h ($A = b \cdot h$) and the specific cutting force k_c. The values of k_c for different materials are collected in specific cutting handbooks. The cross-sectional area A will be determined during the cutting process based on data in the CNC program.

4 IMPLEMENTATION

The implementation of the control strategy using the results of the finite element calculations was done in several steps. The first step contained the generation and the storage of database tables of the calculated stiffness and elastic compliance of the machine tool and of specific deflection values of different tool types.

The second step includes the programming of the code as part of the control code of the milling tool and the testing of the procedures outside of the milling tool. These tests were done in simulations at a personal computer and in experiments at a drive test equipment (figure 8).

Figure 8: Drive test equipment.

During these tests suitable values for low-pass and mean-value filters were determined and embedded into the code.

At the third step, the code was implemented into the machine control of the machining tool “scissor kinematics” and the real milling tests were prepared.

5 EXPERIMENTAL VERIFICATION

The experimental verification was done using a specific inspection part for NC machining, the so-called “rippled surface” [4]. A test part with the surface contour to mill and the milling direction (arrow) is shown in figure 9.

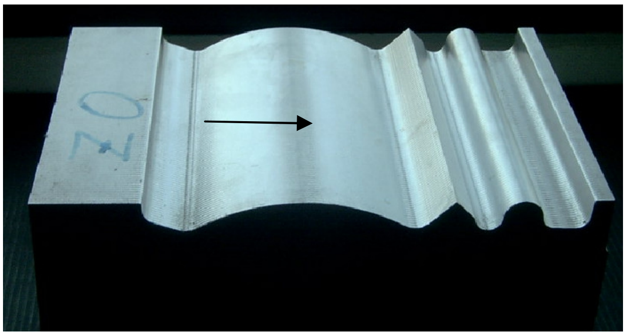

Figure 9: Surface contour of the test part.

The milling experiments were carried out with different milling parameters (e.g. feed f) and different maximum values for the accelerations and the jerks. A solid carbide ball nose end miller with a diameter of 12 mm was used. Because this milling cutter was clamped in our experiments with a short free tool length the compensation algorithm for the machine deformations was tested only. Future experiments with longer cutting tools and the compensation of the cutting tool deflection errors are scheduled.

There were done tests with feed rates of 5,000 and 7,500 mm/min and with maximum accelerations of 0.7 and 1.25 m/s² and maximum jolts of 5 and 10 m/s³ respectively.
The tests were done with three different positions (Z-highs) of the workpiece in the working chamber of the machine tool (see figure 10). In position 1 the Z-carriage is driven out in maximum depth.

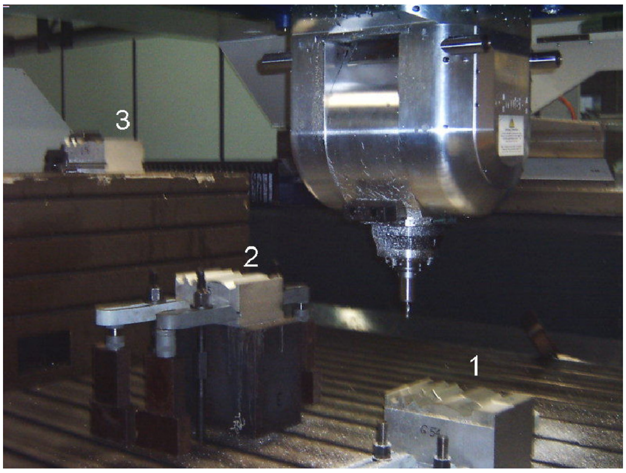

Figure 10: Three different highs of the workpiece

All the present tests had shown that the milling *with* the compensation of machine deformation errors based on described method may cause verifiable better surface contour accuracy.

Two examples shall demonstrate this. The two detail positions 1 and 2 of the “rippled surface” marked in figure 11 are the evaluated segments in detail of the contour.

Figure 11: Segments of surface contour.

At the left segment 1 the actual contour in milling *without* the compensation has a significant dint downwards (fig 12 - mark ①). This is due a deflection error of the Z-carriage caused by its mass inertia during acceleration into X-direction (feed direction). The acceleration a_X in X-direction reached here defined maximum values of 0.7 m/s² and 1.25 m/s² respectively.
Switching the compensation algorithm *on* the actual contour is much more closed to the nominal contour. The contour error caused by the acceleration and the jerk is reduced substantially. Because all the milling and control parameters were unchanged this better behavior is caused by the compensation algorithm only. The actual contours with an amplification factor of 250 are shown in figure 12.

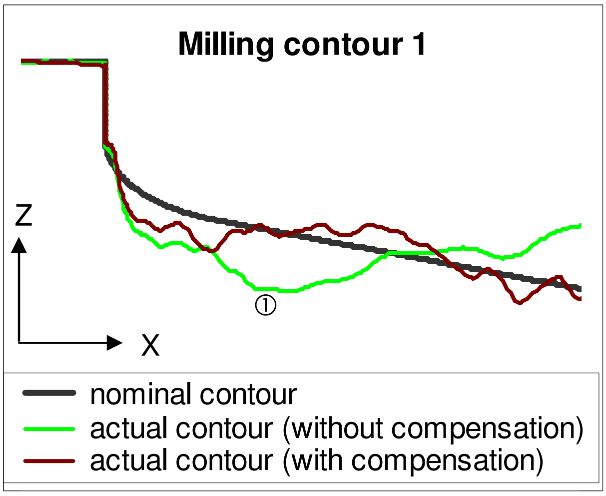

Figure 12: Milled contours at segment 1 (amplified with factor 250).

The real deviation in this section has a maximum amount of 17.6 µm in milling without compensation and of 9.9 µm in milling *with* compensation. This is a reduction of the maximum difference to the nominal contour of about 44 %.
At the segment 2 the contour milled with compensation is essentially closer to the nominal contour - see figure 13. The contour curves in figure 13 are amplified with factor 250 again.
This segment of the contour is characterized by a constant feed rate in X-direction (therefore a zero-acceleration a_X) and a nearly constant nonzero-acceleration a_Z in Z-direction of about 0.15 m/s². Due to this Z-acceleration the actual contour in milling with compensation switched *off* lies above the nominal contour.
Switching the compensation *on* this offset is reduced totally. The remaining differences are again essentially contouring errors caused by the drives and oscillation errors of the machine.

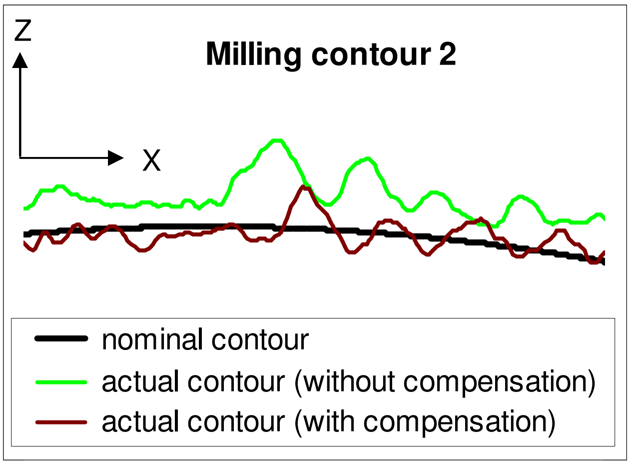

Figure 13: Milled contours at segment 2 (amplified with factor 250).

The real deviation in this section has a maximum amount of 15.0 µm in milling without compensation and of 8.1 µm in milling *with* compensation. This is again a amount of reduction of about 45 %.

These two detailed examples demonstrate the achievable improvement using the online compensation based on the integrated process simulation under utilization of extensive numerical simulations.

6 CONCLUSION

The integrated process simulation is an indicated way to develop and to establish efficient milling technologies in machining of dies and moulds with high machining speeds. The inclusion of numerical simulation results for the machine tool and cutting tool behavior into the machine control strategy is a suitable way to an effective compensation of milling errors caused by static and dynamic deformations of machine and tool.
First results of the investigations encourage for a continuation of this way. The contour error caused by the acceleration forces of the machine tool could be reduced almost to the half partially.
In further steps the compensation algorithms shall be improved using different filters and smoothing algorithms.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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