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Virtual Machining: Capabilities and Challenges of Process Simulations in the Aerospace Industry

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Abstract

Milling processes for the manufacturing of parts for aerospace applications can be influenced by various effects. When machining structural parts with high material removal rates, the stiffness of the machine tool can be a limiting factor because chatter vibrations. Additionally, vibrations of thin-walled structures, e. g., the blades of impellers or turbines, can lead to chatter vibrations and surface location errors. Thermo-mechanical deformations are another cause for violations of given shape tolerances. Geometric physically-based process simulations can be used to analyze milling processes with regard to these effects in order to optimize the process parameters. In this paper, an overview of several applications of a geometric physically-based simulation system for analyzing different effects during milling processes is presented. Depending on the relevant effects, process forces, the dynamic behaviour of the tool-spindle-machine system, vibrations of workpieces and fixture systems, as well as thermo-mechanical deformations are calculated.

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Keywords: Milling, Geometric modeling, Surface

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1. Introduction

In many industrial sectors and especially the aerospace industry, increasingly complex parts have to be manufactured efficiently, while achieving the required surface qualities and reducing the production costs. Milling processes are used to manufacture various components, e. g., impellers or structural parts [1]. Numerous different problems can arise during these machining operations. During the milling of structural parts, process configurations with high material removal rates can lead to chatter vibrations due to the limited stiffness of the milling tools or components of the machine [2]. When manufacturing parts with thin-walled structures, e. g., impeller or turbine blades, the reduced stiffness of these workpiece can cause similar problems. In addition to the process dynamics, the quality of the produced parts can be reduced because of thermo-mechanical effects.

Due to the high complexity of the various effects possibly influencing the result of a milling process and their interactions, the optimization of the processes is a non-trivial task. In many cases, time-consuming and costly run-in processes are required. Geometric physically-based simulation systems [3] provide a flexible and efficient method for analyzing and optimizing milling processes based on a calculation of the geometric engagement situation between the milling tools and the workpieces. At the Institute of Machining Technology (ISF), a geometric physically-based process simulation software is being developed. In this paper, several different applications of this simulation system for analyzing and optimizing different milling processes in order to solve problems which are relevant for the aerospace industry, e. g., workpiece vibrations [4], are presented. While the details of the applications are described in the referenced literature, this paper should give an overview of the recent possibilities of the simulation system for the aerospace industry.

First of all, an overview of the basic modeling approach of the simulation system is given in Section 2. In Section 3, chatter vibrations resulting, e. g., from the dynamic behavior of the machine tool, are analyzed. For simulating the machining of thin-walled impeller blades, the modeling of workpiece vibrations is described in Section 4. The simulation of workpiece deflections resulting from the usage of advanced fixture systems is presented Section 5. The influence of thermo-mechanical deformations on the process result can be analyzed using a hybrid simulation approach as well, which is shown in Section 6. In Section 7, a short conclusion and an outlook on future extensions of the simulation system is given.

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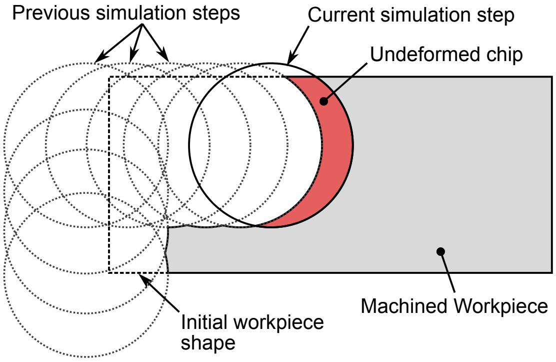


Figure 1: CSG based model of the workpiece shape (cf. [7]).

2. Simulation of machining processes

While several approaches for modeling and simulating machining processes, e. g. analytical approaches [5], exist, a geometric physically-based simulation system provides flexible methods for analyzing milling processes. For this purpose, the milling tools and the workpiece shape have to be modeled. This can be achieved by using the Constructive Solid Geometry (CSG) modeling technique [6] to represent the ideal shape of the rotating tools. In many cases, these shapes comprise simple geometric primitives, e. g., cylinders, spheres, or tori, which are combined using union, difference, and intersection operators. The same modeling technique can be used to represent the shape of the workpieces, which changes during the simulated material removal. This is done by subtracting the CSG model of the rotating milling tools from the initial stock shape, e. g., a simple box or a more complex shape modeled as a triangle mesh, at discrete simulation steps, as shown in Figure 1. Each simulation step corresponds to one feed per tooth. The movement of the tools in relation to the workiece is calculated by interpreting NC programs based on the kinematics of the simulated machine tool. An advantage of this approach is the possibility to optimize the NC programs directly using the simulation results and to run the optimized programs on a real machining center without further conversions.

In order to use the simulation system for more advanced analyses than the calculation of the geometric material removal, additional models, e. g., for the prediction of process forces or the dynamic behavior of the tools, can be integrated. The calculation of process forces is based on a non-linear empirical force model [8] using the undeformed chip thickness h:

$$f_c = bk_c h_0(\frac{h}{h_0})^{1-m_c}, f_n = bk_n h_0(\frac{h}{h_0})^{1-m_n}, f_t = bk_t h_0(\frac{h}{h_0})^{1-m_t},$$

where b is the width of cut, $h_0 = 1$ mm, and k_c, m_c, k_n, m_c, k_t, m_t are the force model coefficients for calculating the cutting forces f_c, f_n, and f_t in cutting, normal, and tangential direction, respectively. f_n is facing away from spindle axis in radial direction and f_t is perpendicular to f_c and f_n. For obtaining the undeformed chip thickness h, the undeformed chip shape has to be analyzed, which corresponds to the intersection between the workpiece and the CSG model of the tool in the current simulation step. The thickness of this intersection can be analyzed by casting and intersecting rays.

The parameter values of the process force model have to be specified for different workpiece materials and milling tools. Therefore, calibration experiments are required to obtain these values. By measuring the process forces during the calibration experiments and comparing them to forces calculated by simulating the same milling process, the parameter values of the force model can be optimized until the measured and simulated process forces match as closely as possible [9]. Usually, simple slot or flank milling operations are sufficient, but it should be ensured that there are no process vibrations.

In combination with this force model, the described CSG-based model of the tools and the workpieces provides a fast and accurate way for calculating process forces. However, a visualization of the resulting workpiece shape and surface location errors, which could be required to optimize the machining operation, is difficult due to the implicit nature of the modeling technique. Therefore, a multi-scale modeling approach is implemented by extending the CSG model with an additional multi-dexel model [10] of the workpiece shape. The multi-dexel model is cut in addition to the CSG model in each simulation step. By explicitly storing local surface location errors at each dexel, an efficient visualization of the workpiece is possible by coloring the endpoints of the dexels accordingly [11]. The calculation of process forces is still based on the CSG model only.

3. Analysis of process stability

In order to optimize milling processes with respect to vibrations, the dynamic behavior of the tool-spindle-machine-system has to be modeled as well. The dynamic compliance of a tool can be described by frequency response functions (FRFs), which can

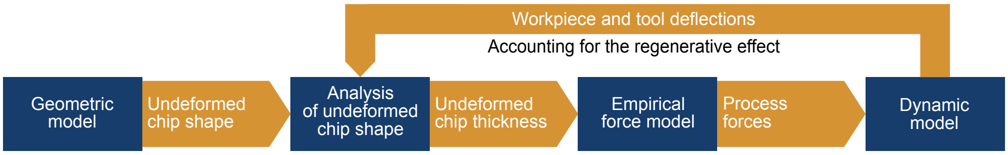


Figure 2: Schematic overview of the simulation system (cf. [7]).

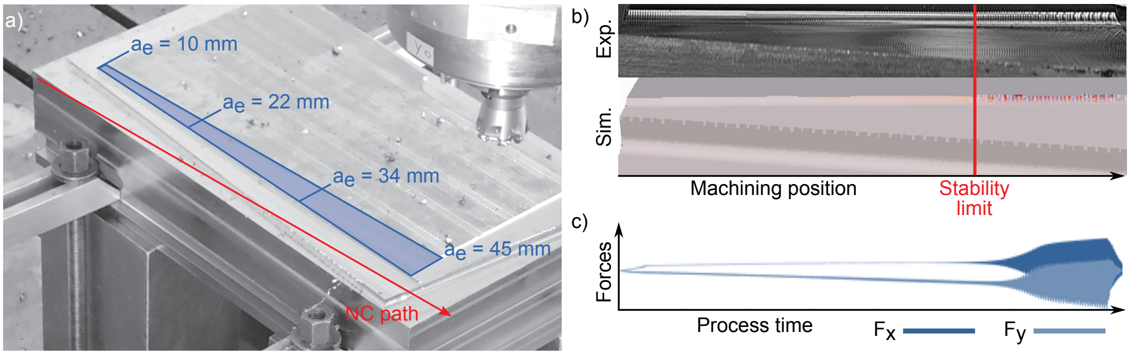


Figure 3: Comparison of simulated and experimental surface location errors resulting from machine tool vibrations (cf. [17]).

be measured using impact hammer tests or electro-magnetic shakers [12]. These frequency response functions are represented using uncoupled models of damped harmonic oscillators, which are described by their eigenfrequency, modal mass, and damping coefficient. Each oscillator corresponds to one eigenmode. During the simulation of a milling process, the calculated process forces are used as excitation of the oscillators in each simulation step. The deflection of the tool is calculated as the superposition of the resulting deflections of the oscillator models. In order to account for different dynamic compliances in x-, y- and z-direction, every direction is modeled separately. By taking the deflections of the tool into account when calculating the undeformed chip thicknesses using the CSG model, the regenerative effect is modeled and, thus, chatter vibrations can be predicted. A schematic overview of the steps required for simulating the process dynamics is shown in Figure 2.

The deflections of the tool are simulated as displacements of their respective models. The influence of the tool holder, the spindle, or components of the machine tool itself are not modeled explicitly. However, by measuring the dynamic compliance of the tools in the spindle, the resulting frequency response functions are influenced by all relevant components. When machining large structural parts using comparatively stiff tools, chatter vibrations can be caused by the compliance of the structure of the machine tool. In contrast to the tools, the dynamic behavior changes when the axes of the machine move [13,14]. In order to take this account in the simulation, the FRFs of the tool are measured in different poses, where the kinematic configurations of the machine are different [15].

An examplary milling process showing chatter vibrations caused by the compliance of components of the machine is shown in Figure 3. Using a medium-scale machining center, a workpiece (1.2312 steel) was machined with a toroidal cutter with seven cutting edges, a diameter of $d = 52\,\mathrm{mm}$, and a corner radius of $c_r = 5\,\mathrm{mm}$. The spindle speed and feed velocity were $a_p =$ mm, $n = 1225\,\mathrm{min}^{-1}$, and $v_f = 1715\,\mathrm{mm\,min}^{-1}$ respectively. The radial depth of cut a_e was increased from 10 mm to 45 mm throughout the process using an upmilling strategy. To parameterize the simulation system, the dynamic compliance of the tool was measured in a different pose at the same positions as used during the milling process. The resulting FRFs, which comprise the dynamic behavior of the tool, the spindle, and the machine, were used to define the oscillator-based model of the system. The parameter values of the oscillators can be found using evolutionary optimization methods for fitting the FRF of the oscillator model to the measured FRF [16]. A comparison of the surface of the machined workpiece and the surface location errors resulting from the process simulation is shown in Figure 3b. Figure 3c shows the simulated process forces. At about two thirds of the process, chatter marks are clearly visible in the experiment and the simulation. At this point of time, the process forces become significantly higher and unstable. Concluding from the agreement of the simulation results with the experiments, the presented simulation system is capable of predicting the stability of milling processes, which can by limited by the dynamic compliance of the machine tool, and resulting surface location errors.

The optimization of machining processes is a major application of the presented simulation system. Figure 4 shows a pocket workpiece with multiple steps, where chatter marks are present in the corners, resulting from an increased engagement angle and higher cutting forces. Corresponding to the visible chatter marks, the process simulation predicts high surface location errors in the corners as well, so the unstable process section could be identified. In order to optimize the process, different process parameter values, e. g., for spindle speed or depth of cut, can be chosen. However, conducting experiments for evaluating different process parameter values is time consuming and expensive. Therefore, simulations can be used to improve the parameter values. In the presented example, the axial depth of cut was decreased from 4.5 mm to 1.125 mm, leading to stable process conditions even in the corners. Applying the optimized parameters to the process, no chatter marks are visible anymore.

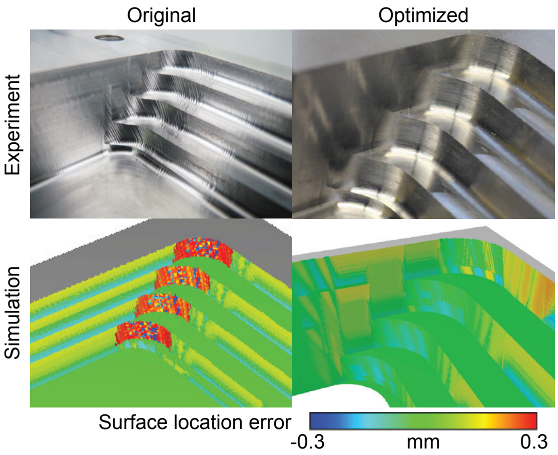
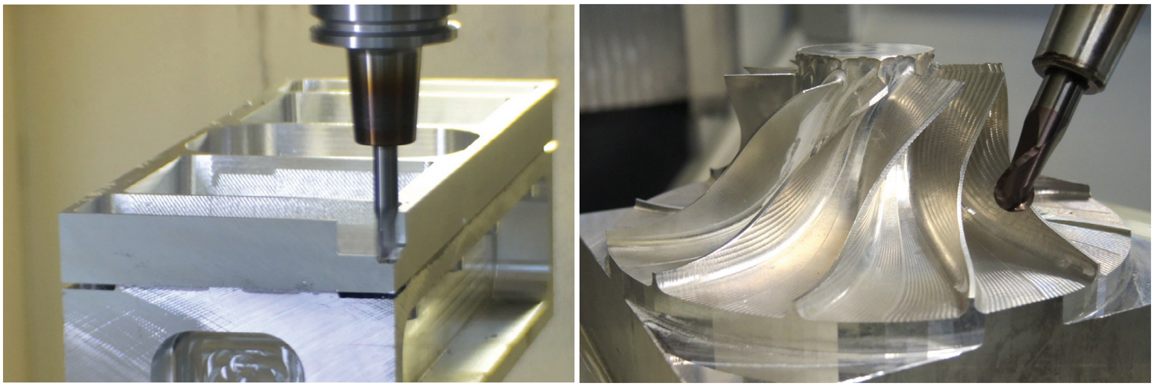


Figure 4: Simulation-based optimization of the milling of a pocket, where chatter marks are present in the corners (cf. [3,18]).



(a) Thin-walled structural part

(b) Impeller

Figure 5: Machining thin-walled aerospace parts.

In addition to the pose of the tool and the resulting kinematic configurations, the dynamic behavior of the machine is influenced by other effects, e. g., temperatures, as well. By measuring the FRFs of the tools in the spindle at different temperatures of the machine and modeling these FRFs with independent oscillator models, this influence can be taken into account during milling simulations [19].

4. Simulation of workpiece vibrations

When manufacturing different kinds of weight-optimized parts for the aerospace industry, workpieces with thin-walled structures have to be machined [1]. Figure 5 shows an exemplary structural part and an impeller. Due to the high susceptibility to vibrations of these parts, workpiece deflections can become relevant in addition to the vibrations of the tools or the machine tool. In contrast to the behavior of the tools, the dynamic compliance of the workpieces varies locally according to the mode shapes [1,20]. Therefore, it is not sufficient to measure and model the dynamic compliance at a single location of the workpiece surface [21]. An interpolation of the dynamic behavior between multiple discrete measurement points is possible using triangle meshes [22]. The measurements at these points can be conducted by exciting the workpiece at a fixed location with an impulse hammer while measuring the deflections at multiple different locations with a laser triangulation sensor. Using this information, the frequency response functions at each measurement point as well as any transfer function between the measurement points can be calculated, so the local dynamic behavior can be simulated at each of these points [23]. However, most of the time, the tool center point (TCP) is not located directly at one the measurement points. By connecting the measurement points with a triangle mesh, the three vertices of one of the triangles can be used to interpolate the local dynamic behavior for any tool pose. This triangle is chosen by finding the nearest neighbor to the centroid of the undeformed chip shape on the triangle mesh. The barycentric coordinates of this nearest neighbor can be used as weighting factors for interpolating the deflections at the three vertices of the triangle.

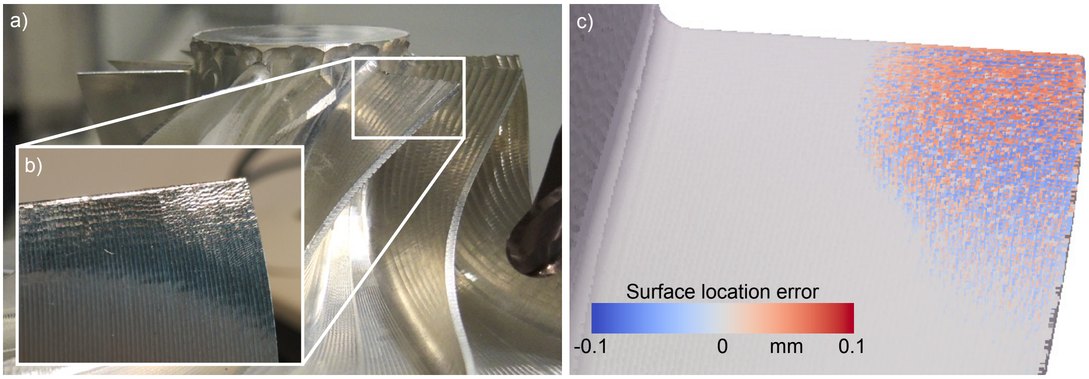


Figure 6: Comparison of chatter marks (b) on the tip of an impeller blade (a) to simulated surface location errors (c).

An application of the described model of workpiece vibrations for optimizing the milling of the impeller shown in Figure 5b is presented in Figure 6. During the finishing operation, the thickness of the blades is rather low already, resulting in chatter marks at the tip (Figure 6b). For this operation, a ball-end cutter with a diameter of $d = 4\,\mathrm{mm}$ and two cutting edges was used with a spindle speed of $n = 22\,000\,\mathrm{min}^{-1}$ and a feed velocity of $v_f = 2200\,\mathrm{mm\,min}^{-1}$. The behavior of the workpiece material (aluminium EN AW 7050) was modeled by using the cutting force coefficients $k_c = 611\,\mathrm{N/mm}^2$, $k_n = 123\,\mathrm{N/mm}^2$, $k_t = 0\,\mathrm{N/mm}^2$, $m_c = 0.21$, $m_n = 0.442$, and $m_t = 0$. The dynamic behavior of the blade was measured at nine different positions with impulse hammer tests after conducting the roughing operation. The parameter values of the oscillator-based model of the process dynamics were estimated as approximately 4.0 kHz, 7.7 kHz, 9.4 kHz, and 11.4 kHz. While the eigenfrequency are equal at all measurement points, the masses and damping coefficients vary according to the mode shapes The surface location errors were calculated using the simulation system and the result is shown in Figure 6c. In the simulation result, chatter marks with a surface location error of approximately 0.06 mm are clearly visible at the tip of the blade as well. Regarding the location and size of the chatter marks, a high correspondence with the experimental results can be observed, so the simulation system was applicable for this case, using the described method for interpolating the dynamic workpiece behavior.

5. Clamping of thin-walled workpieces

The described method for modeling vibrations of workpieces as presented in Section 4 can also be used to simulate the influence of clamping devices on the machining process. As with thin-walled workpieces, the dynamic compliance of the clamping devices varies at different positions according to the mode shapes. Additionally, the mass of the clamped workpiece is reduced due to machining, so the behavior of the fixture can be expected to change as well. To take this into account, the same interpolation approach which was already presented for modeling workpiece vibrations, can be used in the simulation. It was shown in Section 3 that information about the behavior of individual components of the machine tool is not required for modeling their influence on the milling process if the dynamic compliance of the milling tool was measured in the machine. This simplification can be applied to workpieces in complex clamping devices as well because only the deflections of the workpiece at the engagement position are influencing the process forces and, thus, the chatter vibrations.

Figure 7 shows an advanced clamping device for reducing workpiece distortions after the machining of medium-scale structural parts for the aerospace industry, which was designed by the Institute of Manufacturing Technology and Quality Management (IFQ) in Magdeburg [24]. If these kind of workpieces are clamped directly to the machine table, internal stresses in the material resulting from the production process are released during the machining process. By holding the workpiece in place while milling, deformations are restricted and a relaxation is prevented. However, as soon as the finished part is removed, significant distortions, e. g., bending along the longest side, can occur. The presented clamping system comprises floating, hydraulically actuated clamps which can be released to allow the workpiece to move freely in one direction. In order to reduce the final distortions of the workpiece, the machining is paused after removing a small amount of material. Then the floating degree of freedom of the hydraulic clamps is released, allowing the workpiece to relax. In the relaxed state, the clamps are fixed again and the milling process is continued. Using this approach, only the distortions occurring after the last reclamping step should be present when releasing the part from the fixture.

While there are some positive side effects when using the presented fixture, e. g., reduced setup times and the ability to machine both sides of the part without a second clamping, the application of the hydraulic clamps can be expected to result in a higher susceptibility to workpiece vibrations in comparison to a classical setup. Using process simulations, the influence of these fixture systems can already be taken into account during the design of the device. Classically, Finite Element simulations are used to analyze the Eigenfrequencies of different designs, but no direct statements regarding the machining process are possible. By modeling the dynamic behavior based on the Finite Element model, process forces and deflections using different designs can be predicted in the design phase. For the presented setup, process simulations were conducted as shown in Figure 8. A milling tool with two cutting edges, a diameter of $d = 12\,\mathrm{mm}$, a corner radius of $c_r = 1.5\,\mathrm{mm}$, and a helical angle of 30° was used. The cutting force

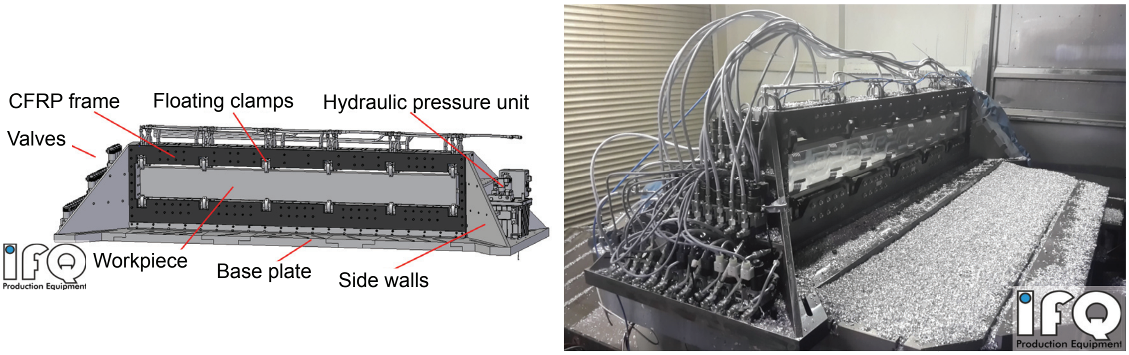


Figure 7: Hydraulic clamping system for reducing part distortions (IFQ, Magdeburg).

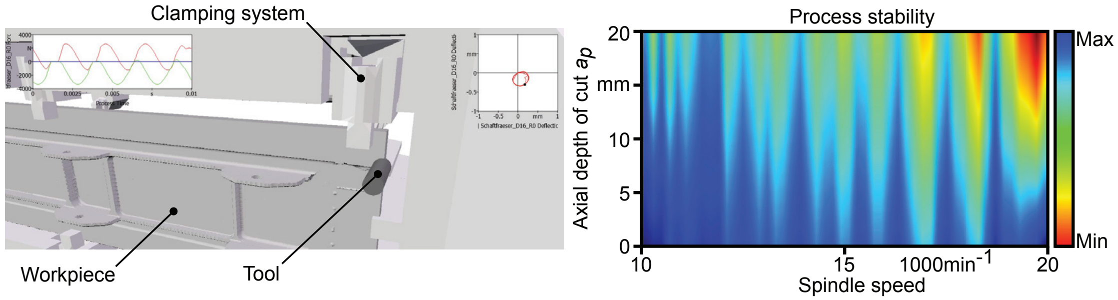


Figure 8: Simulation of the process stability using the hydraulic clamping system shown in Figure 7.

coefficients were $k_c = 1450\,\mathrm{N/mm^2}$, $k_n = 600\,\mathrm{N/mm^2}$, $k_t = 0\,\mathrm{N/mm^2}$, $m_c = 0.2$, $m_n = 0.35$, and $m_t = 0$. In order to find suitable process parameter values, stability charts can be calculated. The depicted results show that stable process conditions can be achieved with an axial depth of cut of 20 mm. The calculation of the process stability corresponds to the diameter of the poincare section of the history of deflections of the tool.

6. Thermo-mechanical deformations

Beside process dynamics leading to chatter vibrations, thermo-mechanical effects can cause deviations of the machined workpiece from the required shape. During the milling process, the workpiece is heated by the thermal energy resulting from the cutting process. Due to the increasing workpiece temperature, deformations can occur. These deformations are influenced by several parameters of the process setup. The amount of thermal energy, which flows into the workpiece for each tooth engagement, varies with the parameter values of the milling process, e. g., the cutting and feed velocity. The milling strategy and the clamping situation influence the heat distribution in the workpiece as well. Therefore, these parameters can be optimized in order to reduce the final surface location errors and shape deviations.

For this optimization, a hybrid simulation system comprising the geometric physically-based approach and a thermo-mechanical model [25,26] is used. Two thermo-mechanical models have been integrated, which can be selected depending on the desired optimization criterion. If only the temperature distribution has to be known, a finite-difference model can be used, where the workpiece is discretized as a hexahedron mesh, which changes due to material removal by the machining process [25]. In each simulation step, a heat-source is defined at the tool engagement. The amount of heat input by this heat-source is calculated based on the process forces.

Dissipation of thermal energy into the clamps and the surrounding air is simulated by defining boundary zones using an adaptive environment temperature. An examplary application of the finite-difference model of the heat distribution in a structural part during a milling simulation is shown in Figure 9.

The described workpiece models, i. e., the CSG model, multi-dexel boards, and the finite difference model, share the limitation that deformations and their influence on the undeformed chip shapes and, thus, the process forces cannot be modeled easily. Therefore, another model based on an hp-adaptive finite-element model with a high-order fictitious domain approach [27], developed at the University of Salzburg, is used [28]. In this case, the workpiece is discretized with a hierarchical mesh of hexahedrons, tetrahedrons, prisms, and pyramids, which is adapativly changed for modeling the material removal process [28].

An exemplary application of the Finite Element model of the thermo-mechanical deformations is shown in Figure 10. In this case, a simple pocket with a reference surface (cf. Figure 10a) was machined and, thus, heated by the process, resulting in

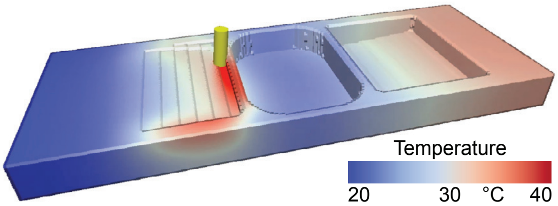
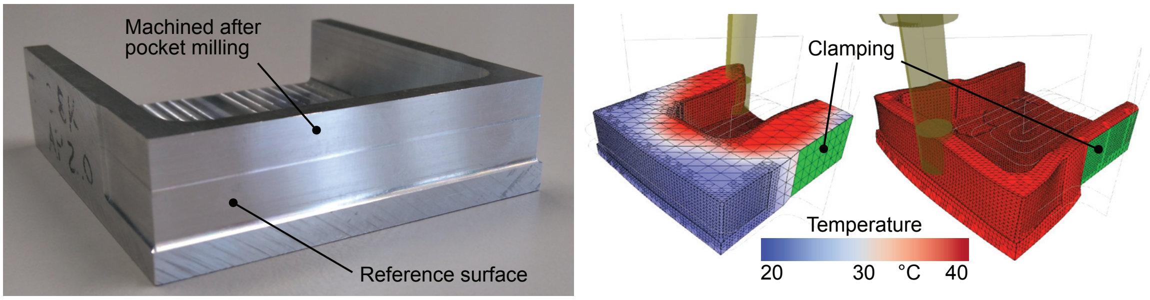
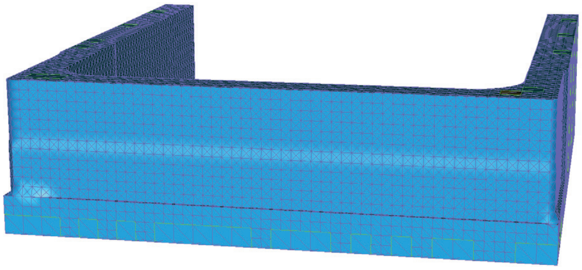


Figure 9: Finite difference model of the heat distribution in a structural part during a milling simulation.



(a) Experiment

(b) Simulation



(c) Finite Element mesh

Figure 10: Machined workpiece with shape deviations resulting from thermal deformations (a), the corresponding finite-element-based simulation (b), and the resulting FE mesh (c). The visualization of the displacements is exaggerated.

thermo-mechanical deformations. The size of the initial stock was$70\,\text{mm} \times 70\,\text{mm} \times 20\,\text{mm}$ and the workiece material was aluminium EN AW 7075. In the heated state, the reference surface was machined again with a reduced axial depth of cut in order create a step which can be measured to validate the simulated deformations. If no deformations were present, there should be no step between these surfaces. However, the radial depth of cut is increased due to the deformations and a step of 0.15 mm can be measured. The simulation of this milling process is shown in Figure 10b. In the visualization, the deformations of the workpiece are exaggerated to emphasize the effect. The final Finite Element mesh after running the milling simulation is shown in Figure 10c. The step that was measured in the experiments is present as well.

7. Conclusions and outlook

In this paper, a geometric physically-based simulation system, which is being developed at the Institute of Machining Technology, was presented. It could be shown that this system can be applied to analyze and optimize milling processes of the aerospace industry, where the resulting quality of the workpiece is influenced by different process effects. The analyzed problems range from process stabilities resulting from machine tool components, vibrations of thin-walled workpieces to thermo-mechanical deformations.

The range of possibly relevant process effects is not limited to the presented problems. In future research, effects like process damping and tool wear will be integrated into the simulation system.

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