EXPERIMENTAL SETUP FOR ANALYZING FUNDAMENTALS OF CUTTING PROCESSES USING A MODULAR SYSTEM

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Machining operations like milling exhibit complex process kinematics, which restricts the identification and analysis of fundamental cause-effect interrelations. In order to differentiate the impact of relevant process parameters, a reduction of influencing factors is necessary. For this purpose, a cutting operation with a linear cutting motion, like orthogonal cutting, is beneficial. Such an experimental setup requires suitable tools, workpieces and measurement systems. The experimental assessment of a developed modular design is presented in this publication. In addition to orthogonal cuts, oblique cuts, which are representative for machining operations with respect to the helix angle, were investigated. To analyze process dynamics, interrupted cuts, including a specifically compliant tool system, were performed.

KEYWORDS

Orthogonal cutting, oblique cutting, process dynamics, cutting fundamentals, modular experimental setup

1 INTRODUCTION

Cutting operations like turning or milling have specific process characteristics depending on the tools and workpiece materials used as well as its parametrization. Different aspects of a machining process such as engagement conditions can be optimized in terms of quality, productivity and efficiency. This requires the consideration of fundamental interrelationships between process parameters and process results. Therefore, the conduction of orthogonal cutting experiments is suitable as an analogy setup. Due to the simplification of the engagement situation, an isolated analysis with a reduced impact of influencing factors is possible [Merchant 1945]. Thus, the effect of individual process parameters on the process characteristics can be analyzed. Objectives of such investigations were, e.g., the mechanism of shear-localized chip formation using high speed imaging [Sagapuram 2016] or the temperature distribution during the cutting process using infrared thermography [Invester 2005]. An analysis of the occurring process forces were used, e.g., to optimize the micro shape of the cutting edge [Biermann 2018]. Furthermore, orthogonal cutting experiments are an important base for simulative modelling approaches such as finite element analysis (FEA) [Melkote 2017] or geometric physically-based process simulations [Bergmann 2019]. Especially process-related effects on the integrity of the machined surface were subject to a multitude of research activities using FEA [Melkote 2017]. In this regard, machining-induced residual stress [Outeiro 2006] or the influence of the cutting process on the microstructure of the workpiece material [Liu 2014] were of particular interest. The fundamentals of the chip formation process can be utilized to adjust more complex processes such as milling operations with regard to the requirements of the manufacturer. For this purpose, an experimental analogy setup is required, which allows an analysis of different process-related effects. Important target values of process analyses are, e.g., process forces, the resulting surface topography or the occurrence of vibrations. Dynamic effects such as regenerative chatter vibrations can limit the productivity and efficiency of machining operations [Schmitz 2008].

The setup presented in this publication is designed for the conduction of comprehensive investigations using a modular tool system. Orthogonal cuts can be performed with a negligible occurrence of disturbing dynamic effects due to the high structural stiffness of the setup. The modularity of the system allows the conduction of oblique cuts with a defined angle of inclination. Additionally, the application of a flexure hinge can be used to perform cutting processes with a specific compliance. As a result, dynamic effects that, for instance, can occur during milling can be investigated. Cutting elements with a defined shape of the cutting edge are used. These segments can be reconfigured without dissembling the tool system, which ensures an efficient conduction of the experiments.

2 CONSTRUCTION OF THE EXPERIMENTAL SETUP

The constructive design of the developed experimental setup consists of a workpiece and tool holder system (Fig. 1). These were defined both by the boundary conditions and by the requirements for analyzing the fundamentals of cutting operations. Therefore, the setup has to provide a high degree of structural stiffness in order to reduce the influence of disturbing effects on the cutting operation and the experimental results.

The system was designed for the application on a three-axis machine tool, which was particularly built for the conduction of orthogonal cutting experiments. Its machine table is equipped with a linear direct drive along the x-axis and allows cutting velocities of up to $v_{c,\,max}$ = 180 m/min. Thus, a significant range of typical cutting velocities is covered [Klocke 2011]. In order to position the tool for defined engagement conditions, the cross table can be moved simultaneously along the y- and z-axis.

2.1 *Tool system*

The tool system is designed to be installed on the cross slide at the portal of the machine. To be able to analyze a variety of process characteristics, such as specific engagement conditions, the tool system can be assembled modularly (Fig. 2).

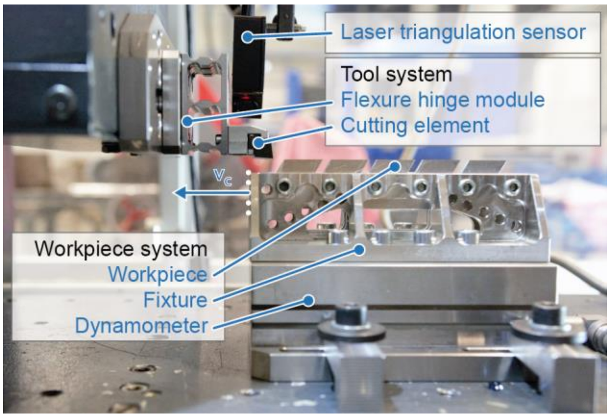

Figure 1. Exemplary configuration of the modular experimental setup.

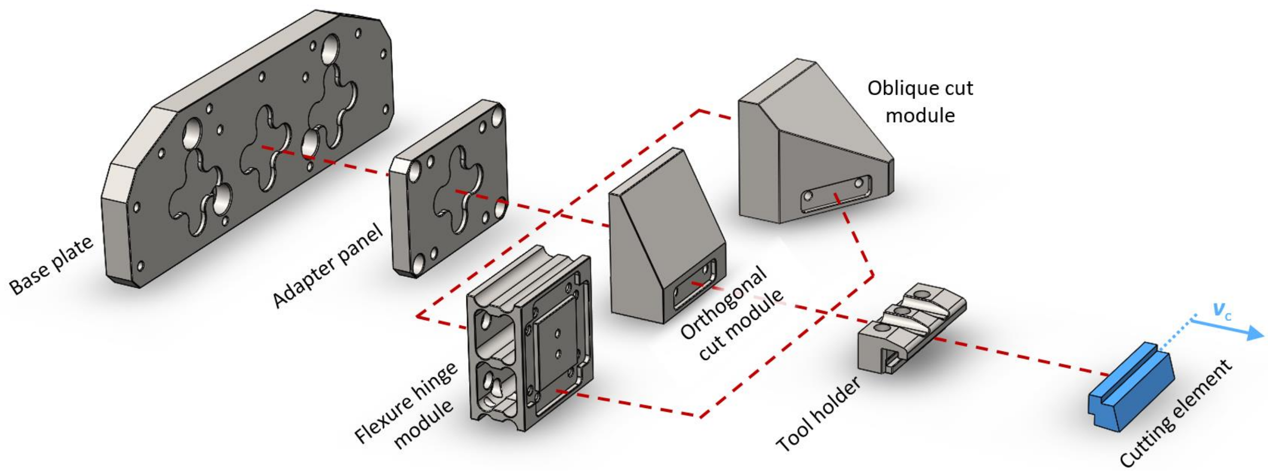

Figure 2. Modular components of the tool system.

Different modules, which are manufactured of the tool steel AISI D2, can be installed on an adapter panel, which is mounted to a base plate on the cross table using a system-specific cloverleaf-shaped interface with a defined tolerance of the contour of ±0.01 mm. The cutting elements can be manufactured to incorporate different shape specific properties of a cutting edge (Fig. 3). This includes, e.g., the angles of the cutting edge, cutting edge chamfers and serrations, face and edge preparations [Denkena 2014]. The cutting element is equipped with reference and clamping faces, which allow a reproducible and stiff clamping in a defined position and orientation. The relatively simple geometric design of the cutting elements enables the use of various cutting tool materials. These can be manufactured in different process chains such as hard milling and grinding of high-speed steel (HSS), or a combination of sintering, eroding and grinding processes of powder metallurgical HSS and cemented carbide materials. The width of a cutting element of up to $w_{ce,\,max}$ = 60 mm allows an efficient experimental execution, as multiple cutting segments are provided adjacently. The tool holder module can be mounted on the orthogonal cut module and the adapter panel to be used for orthogonal cutting operations (Subsection 3.1). Additional modules can provide, e.g., different inclination angles for conducting oblique cuts (Subsection 3.2) and specific compliances conditions (Subsection 3.3). In order to determine relevant process characteristics as analysis targets, different sensor systems and measurement techniques, such as displacement, temperature and optical sensors, can be applied. In addition, the modular design allows the integration of additional functions.

2.2 Workpiece system

The fixture system for positioning, clamping and supporting the workpiece was designed and manufactured as a weight-reduced, reinforced structural component. A light-weight design is necessary to reduce the mass-effect on the dynamic properties of the cutting-force measurement system.

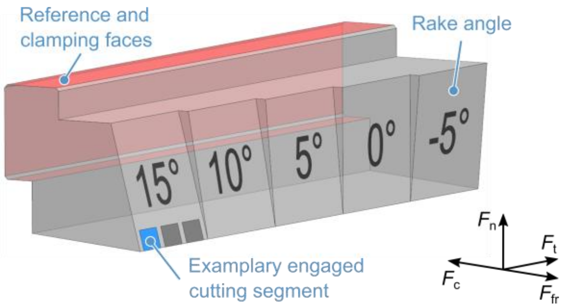

Figure 3. Exemplary cutting element.

For this, a multi-component dynamometer of the type Kistler 9257B was used. The setup is depicted in Fig. 4. The measured force components F_x, F_y and F_z correspond to the cutting-force vectors in transverse, cutting and normal direction F_t, F_c and F_n, respectively.

The workpiece is clamped using aluminum sheets and grub screws, allowing for specimens with a thickness of up to $w_{WP,\,max}$ = 9 mm, which is equivalent to the maximum width of cut $a_{e,\,max}$. The maximum length of a workpiece is $l_{WP,\,max}$ = 150 mm and the use of three repositionable dowel pins allows a defined positioning of workpieces with a variable height of about 10 mm to 50 mm and, thus, the conduction of numerous consecutive cuts. An additional aim of the design of the workpiece system was to ensure a high degree of accessibility in regard to the cutting zone. As a result, a high flexibility for the application of sensors or the positioning of imaging techniques is provided.

3 APPLICATION AND ANALYSIS OF THE WORKPIECE AND TOOL HOLDER SYSTEM

The cutting system was applied to investigate certain relevant process characteristics such as process forces, thermal and dynamic effects on a fundamental scale. The modularity of the tool system enables the adaption of the experimental setup in respect to the specific analysis targets.

3.1 Orthogonal cut

Orthogonal cutting was conducted focused on the analysis of process forces as an elementary process characteristic of machining operations and the suitability of the developed experimental setup. The used workpiece specimens consisted of the low alloyed steel AISI 4140 in a quenched and tempered state with a hardness of 600 HV 30. Numerous depths of cut a_p,

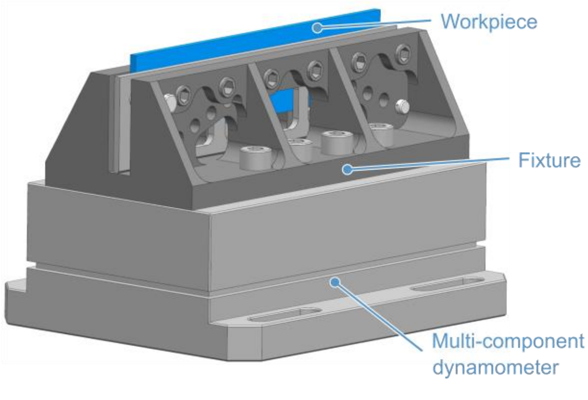

Figure 4. Cutting force dynamometer and fixture system.

which is equal to the undeformed chip thickness h in orthogonal cutting, ranging from $a_{p,min} = 0.05$ mm up to $a_{p,max} = 0.21$ mm were investigated. Exemplary force progressions for process configurations with a low and high depth of cut are depicted in Fig. 5. The initial excitation of the experimental setup led to dynamic effects, which influenced the process forces at the beginning of the engagement. After this time span of approximately $\Delta t = 0.01$ s the measured force signals converge to a quasi-static value with negligible deviations. In each conducted experiment, the highest force amplitudes occurred in cutting direction F_c. The inclination angle of $\lambda_s = 0°$, which is characteristically for orthogonal cutting, led to a negligible transversal force component F_t. The relation between the cutting and normal force is determined by the defined depth of cut. The ratio $\Phi_F = F_c / F_n$ is higher if the depth of cut a_p increases. The control behavior of the linear direct drive effects the force progressions especially at low depth of cut in the cutting and normal direction F_c and F_n and leads to minor periodic variations. The analysis of the dynamic behavior of the experimental setup at the beginning of the engagement indicates the sufficiency of the tool system in terms of the desired stiffness, as the critical compliance does not relate to the tool system. Fig. 6 depicts the frequency response function (FRF) of the tool system in cutting direction compared to the related Fourier transform (FT) of the dynamically affected cutting forces at the beginning of the engagement.

3.2 Oblique cut

Most machining tools like milling cutters are equipped with a helix angle λ, which can be projected to oblique cutting. Using a wedge module (Fig. 2) oblique cutting tests could be conducted. An exemplary cutting force progression, applying a tool inclination angle of $\lambda_s = 30°$, is depicted in Fig. 7.

In contrast to the previously described experiments in Subsection 3.1, the oblique cut leads to significant force amplitudes in transversal direction F_t. Under oblique cutting conditions, the width of cut a_e increases linearly over time until a nominal width of cut $a_e = 3$ mm is reached, which leads to a less transient excitation of the dynamic system.

3.3 *Interrupted cut and specific compliance*

An important, productivity-limiting factor in machining operations is the occurrence of dynamic effects like regenerative chatter vibrations. Such vibrations result from the excitation of a naturally compliant production system, which is caused by the periodic tooth engagement. To be able to investigate such dynamic effects on a fundamental scale, an analogous experimental setting (Fig. 1) was used. A representative compliance [Wöste 2019, Hung 2016] was synthesized by applying a specific, simulation-based design of a flexure hinge module. The interrupted cut was realized by implementing notches in a workpiece consisting of the aluminum alloy EN AW-7075. The geometric properties of the notches correspond to the engagement conditions analogous to a milling process using a cutter with a diameter of $D = 10$ mm. An exemplary process force progression for a compliant and periodically interrupted cut is depicted in Fig. 8.

The process forces are subdivided in five sections of increased force amplitudes according to the implemented notches. The force component in cutting direction F_c is dominant. The interrupted cut causes a periodic excitation at the beginning of each section of engagement. A significant, periodic variation of the force progression is obvious. In order to determine the component, which is assigned to the excited compliance, further measurements and analysis were conducted.

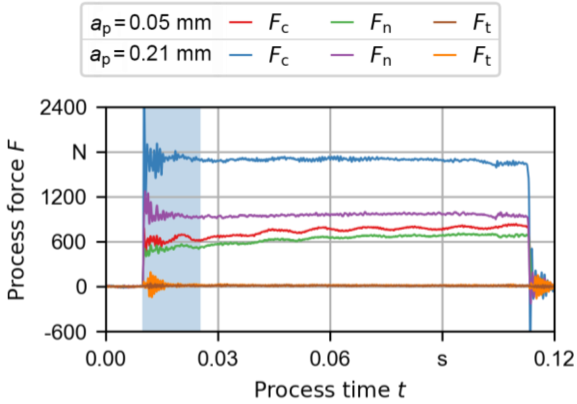

Figure 5. Measured forces of an orthogonal cut for undeformed chip thicknesses of $a_p = 0.05$ mm and $a_p = 0.21$ mm and a cutting velocity of $v_c = 60$ m/min. The time interval of the initial engagement is marked (light blue).

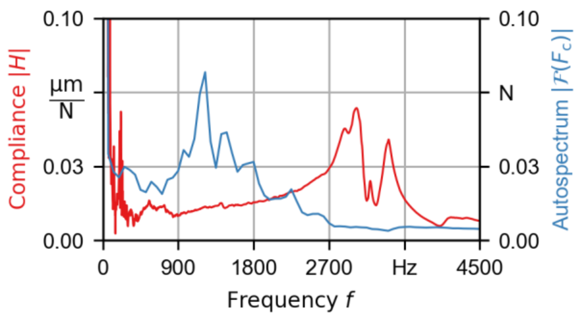

Figure 6. FRF of the tool system in cutting direction (red) compared to the related FT of the dynamically affected cutting forces (blue).

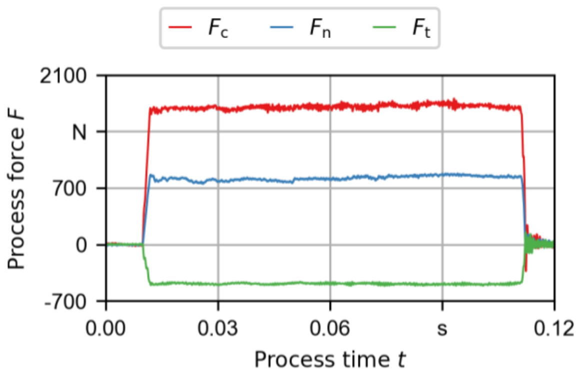

Figure 7. Measured forces of an oblique cut for an undeformed chip thickness of $a_p = 0.21$ mm and a cutting velocity of $v_c = 60$ m/min.

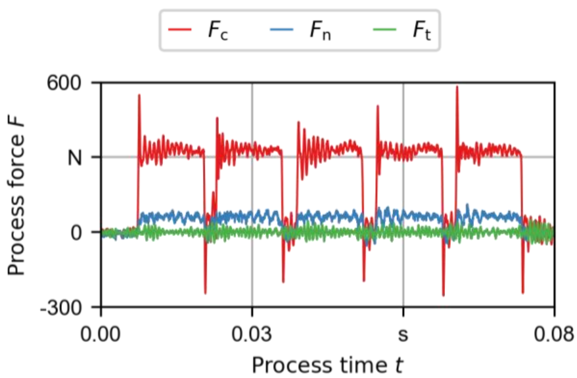

Figure 8. Dynamically affected process forces of an interrupted cut with $v_c = 120$ m/min, $a_p = 0.12$ mm.

The determined FRF is compared to the FT of the tool displacement, which was measured using a laser triangulation sensor. As shown in Fig. 9, the dominant eigenfrequency of the tool system including the flexure hinge module f_0 = 1409 Hz (orange mark) is excited during the cutting operation. Beside the eigenfrequency f_0, the externally excited vibration with the engagement frequency f_e and its harmonics exhibit increased amplitudes at f_e = 70 Hz and its integer multiples (brown marks). Force measurements are subjected to a specific transfer behavior, which could be critical, if process forces are dynamically influenced. The related transfer function G_{FF} of the cutting force dynamometer with the attached fixture system and workpiece is depicted in Fig. 10. Additionally, the autospectrum of the excitation force, which is induced and measured by an impact hammer system of the type 8206-002 by Brüel & Kjær, is included. Whereas the transfer function depicts an amplification of force measurement signals in the range of the first eigenfrequency at about $f_{0,1}$ = 1000 Hz, the transfer behavior at the relevant frequencies of f_e and f_0 is near to 1. The transfer function G_{FF} can be used for inverse filtering to correct the measured force amplitudes [Hense 2012]. The force F_{ex} provides a sufficient excitation within the relevant frequency ranges resulting in low deviations of the transfer function G_{FF} (grey interval). A variation, especially an increase of the mass of the fixture system, is critical with respect to the transfer behavior and, thus, the validity of the force measurement.

3.4 *Friction testing*

Due to the low occurrence of dynamic effects in the orthogonal and oblique cutting experiments, the presented experimental setup is appropriate for the evaluation of friction effects under cutting conditions. By using the same experimental setup, the influence of a defined contact between the flank face of the tool and the workpiece can be determined without the removal of material. Therefore, a relative motion between the tool and the workpiece in the reverse direction of cut is conducted in accordance to Puls et al. [Puls 2014]. Fig. 11 depicts the force progression of an exemplary friction experiment. The significant force components are the friction force F_{fr} in reverse cutting direction and the force in normal direction F_n. While the normal force F_n decreases, the process temperature T increases. The process temperature was measured using a fiber optical pyrometer (type Fire III by En2Aix). The fiber was installed as close as possible to the cutting edge facing the machined surface. F_n and T are affected by changing contact conditions during the experiment. By relating the force components with respect to the clearance angle α, a friction coefficient can be determined [Puls 2014]. This can be used for modelling and further analysis of cutting operations, e.g., by applying FEA [Melkote 2017].

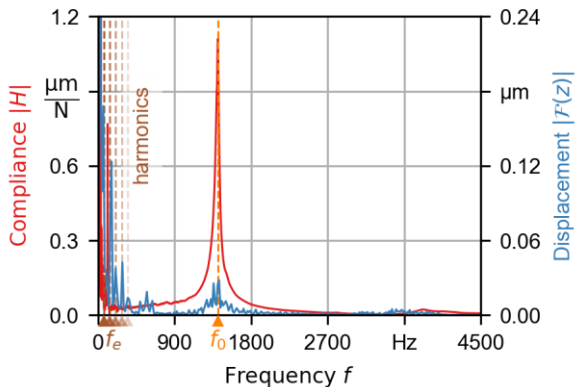

Figure 9. Dynamic properties of the specifically compliant tool system (red) and its dynamic behavior during a cutting operation (blue).

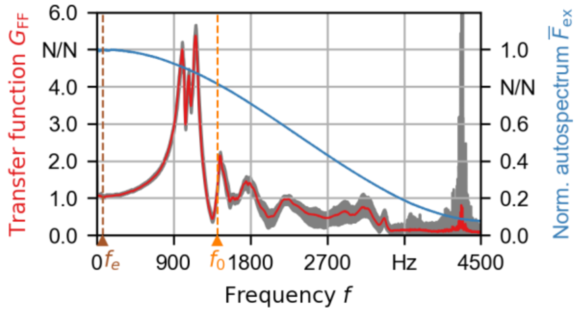

Figure 10. Averaged transfer function of the force measurement system (red) and the autospectrum of the excitation force (blue).

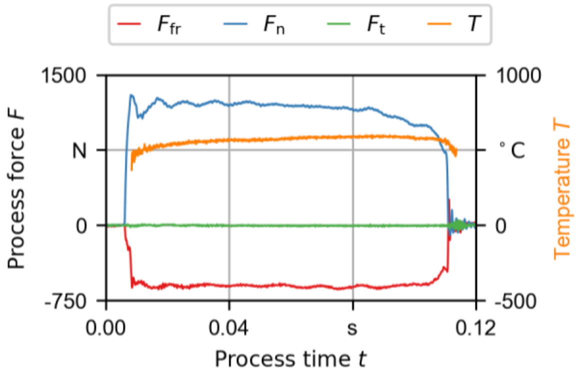

Figure 11. Measured force components F_i and temperature T during a friction test. The depth of engagement was a_{fr} = 0.2 mm and the relative velocity was v_r = 60 m/min.

4 CONCLUSIONS

The presented experimental results demonstrate the suitability of the developed setup for analyzing specific fundamental aspects of cutting operations. The experimental assessment is based on various investigations. This includes structural analyses like modal measurements and process-related experiments such as orthogonal, oblique, dynamically affected cuts as well as friction tests. The use of the modular design allows a more isolated analysis compared to, e.g., milling operations, by reducing the number of influencing and disturbing factors. This provides information about the fundamental cause-effect relationships of cutting and, thus, production processes like milling.

In further investigations, the presented setup will be used for, e.g., tool and process development and optimization efforts. The high degree of reproducibility enables an examination of specific process-related material behavior and its relevant cause-effect relationships in context of cutting operations. Supplementary modules can be designed and manufactured in order to investigate additional influencing factors and their impact on machining processes.

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