

Chapter 2

Model-Based Representation of Thermo-energetic Effects in Cutting Tools and Part Clamping Devices

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Abstract In the representation of the machine tool's manufacturing accuracy, involving thermo-elastic deformations in the tool and its chuck in the considerations is unavoidable, since a portion of the process heat is transmitted into the tool. Capture and estimation of the resultant thermo-elastic deformations is of significant importance for their compensation and correction. This paper presents the investigation and evaluation of thermo-elastic displacements in the tool-chuck system resulting from the heat flows from machining. The temperature and displacement measurements were conducted on a test bed with measuring equipment. In the first series of experiments, the transient heat conduction in the stationary tool and the chucking system, decoupled from the motor spindle, was captured. The chucks were compared in terms of their working principle. The identification of the thermal boundary and contact conditions was assisted by Finite Element models. The paper describes the experimental setups, the methods of measurement and the numerical models. An additional section discusses the determination of realistic heat sources generated in the machining process. Since measurement of these heat flows is either impossible or expensive and time-consuming, they are determined by numerical simulation of the machining process itself. This way, it can be determined to what extent the heat flows generated in the experiments by means of heating cartridge or induction correspond to those generated by the actual machining heat sources.

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2.1 Introduction

2.1.1 *Motivation and Problem Definition*

The machining heat generated immediately in the tool-workpiece contact area is a major heat source in the overall system of the machine tool. Heat dissipates into the tool chuck and from there into the motor spindle, as well as through the part and the part clamping system into the machine table. The temperature fields cause non-negligible thermo-elastic deformations in the systems tool chuck—spindle, as well as the part clamping system—machine table that work against the requirement for manufacturing accuracy. The trend towards high performance cutting (HPC) and dry metal cutting or minimal quantity lubrication increases the thermal stresses and thus thermally-induced workpiece errors. The conflict among the criteria of accuracy, productivity and energy consumption is complicated by small manufacturing batches, changing manufacturing orders and tool changes, as well as shut downs of the base load power to conserve energy. The result would be a thermally unstable machine tool structure with low manufacturing accuracy.

2.1.2 *Aim*

The aim of the subproject A01 on “Deformation of tool and clamping device” consists of modelling the tool and its clamping system (chuck) under the assumption of real process parameters, such as process heat and the self- and externally-excited bypassing flows as the input variables, the boundary and environmental conditions of the workspace, and the heat transfer conditions at the relevant interfaces of the tool and its clamping system.

The exploration of the thermal manufacturing influences for complex metal removal processes is the subject of the DFG main programme 1480. The general aim is modelling and simulation of, as well as compensation on, the component or workpiece through experimental and simulation assisted investigations (Biermann and Iovkov 2013). Subproject A01 limits this overall focus to tool-oriented studies.

Experimental and model-assisted investigations are conducted to identify the relevant parameters, such as temperature, dislocations and heat flows. The challenge in the experiment is to realise the process heat, whereas, in simulation, assumptions regarding the convective heat transfer conditions have to be agreed. The two methods of investigation—experiment and simulation—supplement one another and provide a verification of the parameters mentioned above.

The identification of the temperature fields makes it possible to abstract compensation measures in order to obtain stable thermo-elastic characteristics in the future.

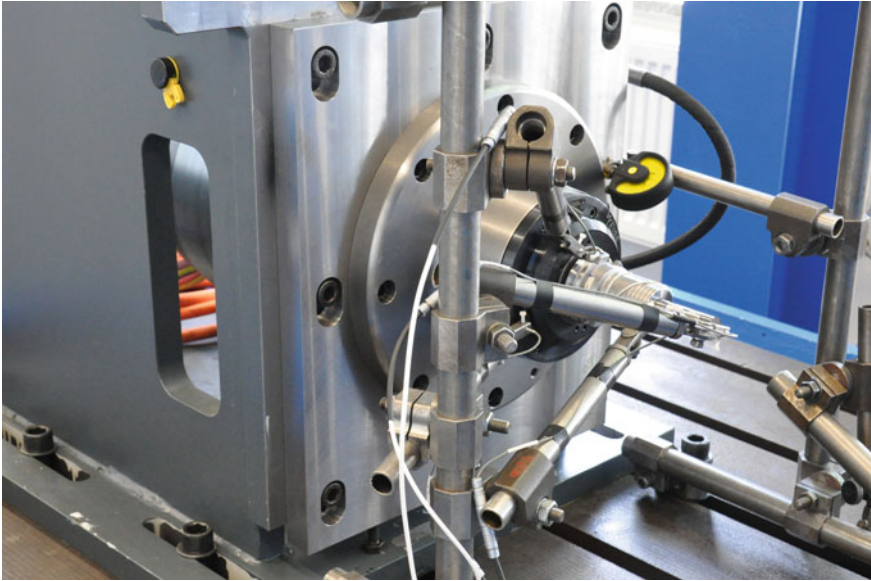


Fig. 2.1 Test bed equipped with measuring equipment

2.2 Approach

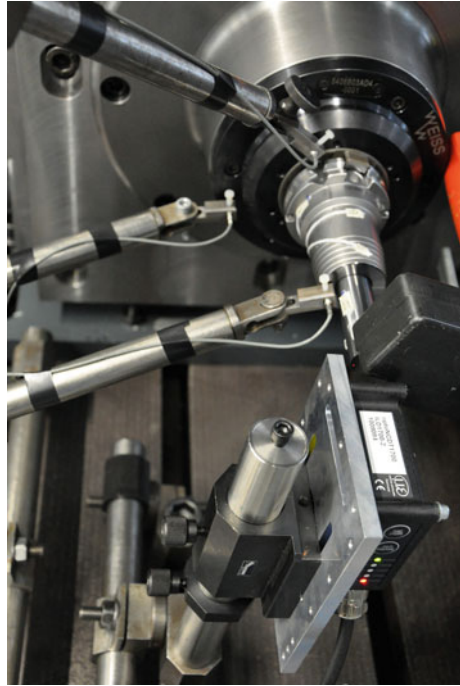
2.2.1 Test Bed Description

A test bed equipped with measuring instruments was designed and built (Fig. 2.1) to investigate the thermal behaviour of the cutting tools and the clamping systems—that is, the tool chuck and part clamping device—experimentally. The placement of the setup in an air-conditioned room allows for long-term-experiments with temperature monitoring. The test bed consists of machine bed, motor spindle to be mounted both in horizontal and vertical positions, control, cooling lubrication system and measuring equipment. In addition to the influence of the self-circulating and forced moving air on the thermal behaviour, the influence of the cutting fluid can be shown.

2.2.2 Subject of Experimental Investigations

A 20 mm diameter end mill made entirely of carbide was used as the tool. The milling cutter can be integrated into the test bed, has cooling channels inside, and allows for transferability of the results to other tools and machining processes, such as drilling. For tool clamping, three tool chuck principles were investigated in detail: hydraulic chuck, shrink fit chuck and chuck with a lateral clamping surface

Fig. 2.2 Measurement setup for the rotating tool



(Weldon type chuck) each with SK40 spindle interface. Up to 16 measuring points for temperature and 4 measuring points for deformation were attached to the tool and the chuck. Temperature measurement was predominantly executed by resistance thermometers designed using thin-film technology as Pt100 or Pt1000 sensors. The displacements were traced by inductive sensors, eddy current sensors and laser sensors. For tools in standstill position, the measurements were conducted at the SK40 interface, whereby the tool was clamped in the motor spindle and thermally insulated at the SK40 interface. Rotating tools were measured under the influence of motor spindle tempering. For rotating tools, the temperature measurement signals were transmitted to the measurement amplifiers by means of slip ring assemblies. Contactless eddy current transducers and laser sensors were employed exclusively. This decision made it necessary to have available planar measurement surfaces on the tool. To fulfil this condition, initially a dummy end mill was employed in the experiments. The transfer to the real tool's geometry was conducted using the simulation assisted investigations. The measurement setups for the various operation modes are described in detail in (Drossel et al. 2013). Figure 2.2 illustrates the measurement installation applied to the rotating tool.

For the investigations of the tool in standstill position, the tool was heated using a ceramic immersion heater. Effective heat transfer was provided by thermally conductive grease, so that heat immediately dissipated into the tool. In contrast, for rotating tools, the principle of contactless inductive heating was employed.

2.2.3 Simulation Assisted Investigations

In the measurement setup, the real amount of the heat flow introduced and the parameters for heat transfer to the environment or between tool and chuck, as well as between the chuck and the motor spindle were unknown. For their identification, FE models describing the tools employed (real tool and dummy tool), as well as of all chucks, were developed, and the parameters were adjusted by making use of the characteristic temperature and deformation parameters measured. Figures 2.3 and 2.4 illustrate the respective FE models, as well as the thermal boundary and contact conditions underlying the models.

The thermo-elastic and thermo-physical material parameters of the K40 tungsten carbide (tool material) and 1.2342 (X38CrMoV5-1) (chuck material) are taken from the material and manufacturer's information databases.

Thanks to these validated models, arbitrary thermal loads—varying in amount and timing—can be simulated without expensive and time-consuming experiments. This strategy targets simplified models for simulation in real time, capable of delivering the current correction values during the manufacturing processes.

The measurement and simulation results are introduced and discussed in the following section.

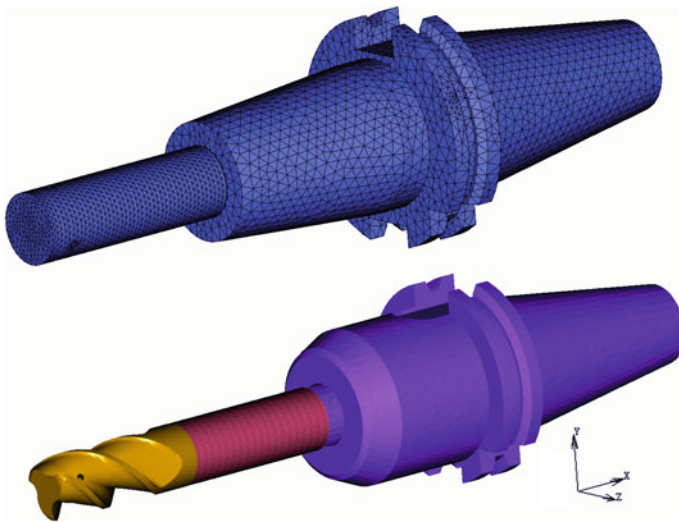


Fig. 2.3 Exemplary FE models—tool and chuck models (*top* dummy tool in shrink-fit chuck, *bottom* end mill and chuck with clamping surface, separated representation)

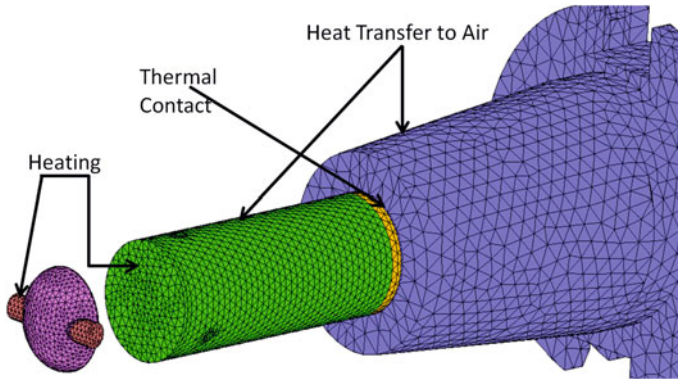


Fig. 2.4 FE model of dummy tool in shrink-fit chuck, with thermal boundary conditions and heat transfer between tool and chuck (from tool to chuck)

2.3 Results

2.3.1 *Temperature Fields and Thermo-elastic Elongation in the Chuck*

Initially, the clamping principles were compared in a preliminary test series. These tests had to verify the measurement methods and reliable repeatability of measurements in each test setup, as well as a relative comparison of the clamping principles, taking into account relevant influential factors in the real chip forming process. Figure 2.5 outlines the values provided for the stationary state of the three chuck types used.

Analyzing the shrink-fit chuck, a homogeneous drop in temperature along the rotational axis can be observed. For the process parameters mentioned, tool tip displacement amounts to approximately $60\ \mu\text{m}$. The hydraulic chuck suggests that the hydraulic clamping principle isolates the tool from the chuck, because the temperatures inside the tool are clearly higher. Significantly lower displacements can be detected on the chuck with a lateral clamping surface. Geometry has an important influence on the thermo-elastic elongation. The chuck is smaller in size and cannot be directly compared with the other clamping principles. The tool is arrested by means of a setscrew, and an air gap emerges as a result. The air gap has an insulating influence on the tool, and, consequently, less heat is transferred to the chuck. The temperatures in the chuck are less versus shrink-fit- and versus hydraulic chucks.

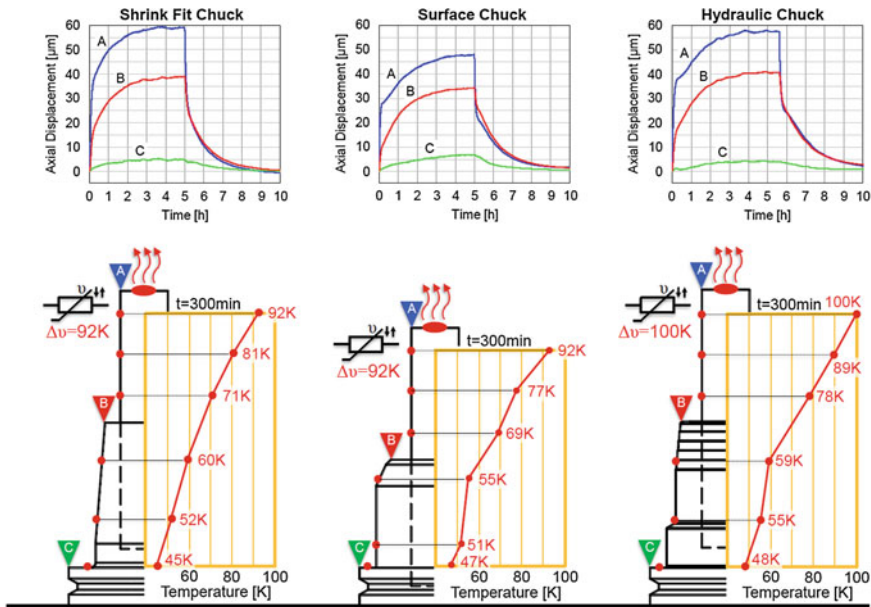


Fig. 2.5 Comparison of the displacement values measured and the stationary temperature profiles for shrink-fit chucks, chucks with damping surface and hydraulic chucks

2.3.2 Simulation Results and Adjustment with Experimental Investigations

The thermal boundary and contact conditions for the test series with the standstill tool were exemplarily adjusted for the shrink-fit chuck. The closest correspondence with the measurements was achieved for a heat transfer coefficient $\alpha_{Luft} = 8 \text{ W/m}^2\text{K}$ to the environment and a heat flow of 8.1 W into the tool's tip. Figures 2.6 and 2.7 show the measured and simulated temperature values for these parameters, as well as the axial displacements at the tool tip and on the chuck's face. The temperature measuring points TMP1–TMP5 correspond to the measuring points in Fig. 2.5—from tool tip to chuck.

In the stationary temperature range, the absolute deviations between the values measured and calculated amounted to a maximum of 4 K in the case of temperatures and 7 µm in the case of displacements.

The contact heat transfer coefficients in the tool-chuck contact cannot be traced directly. In the FE models, based on investigations of the subproject B02, a value of $\alpha_{therm} = 12,000 \text{ W/m}^2\text{K}$ (see Chap. 11 and Ustinov et al. 2010) was used. However, these coefficients turned out not to play a significant role in the heat flow out of the tool, as can be seen for different α values by the temperature curve along the interface (Fig. 2.8).

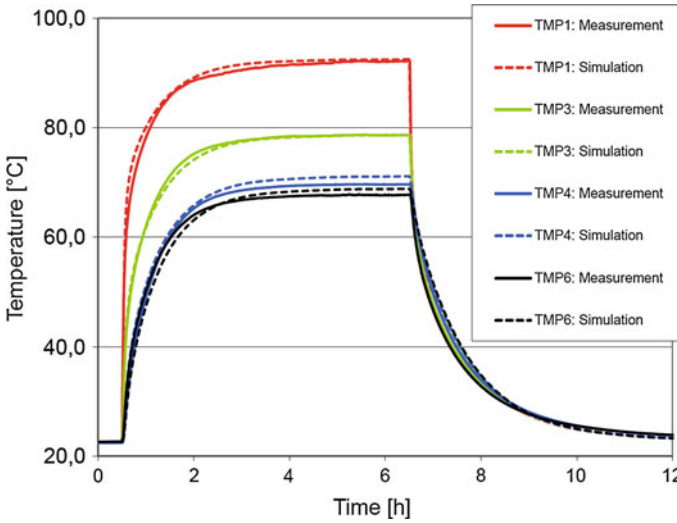


Fig. 2.6 Measured versus simulated temperatures for the shrink-fit chuck with clamped dummy tool

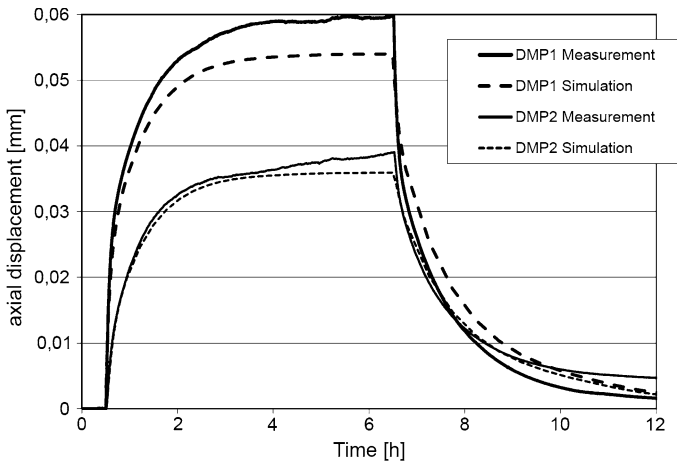


Fig. 2.7 Measured versus simulated displacements (*DMP1* face side of tool, *DMP2* face side of chuck)

The temperature jumps are shown for two cross sections, which correspond to the positions of the temperature measuring points TMP4 and TMP5 (upper curves 20 mm, lower curves 40 mm distance to face of the chuck).

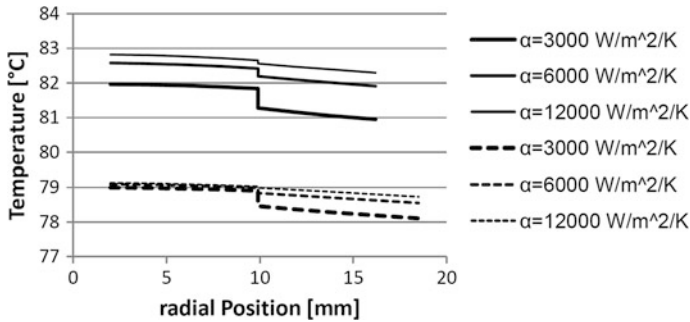


Fig. 2.8 Temperature jumps calculated in the tool-chuck contact for different heat transfer coefficients α

2.3.3 Determination of Process Heat Parameters

The amounts of heat generated in the machining process, their introduction in the form of heat flows dissipating into the tool, the workpiece and the chips (which, in turn, also introduce heat into the machine tool at the point at which they are deposited or removed) and the TCP displacements to be corrected or compensated are of crucial importance for thermo-energetic machine tool design. It has still to be verified how accurately the heat sources in the measurements, either by ceramic immersion heater or by induction heating, represent realistic sources, and, consequently, to what extent the TCP displacements measured or simulated are representative for the system of the chuck-tool-part-clamping device. Complex measurement equipment is needed to directly measure the heat content generated in the machining process, and measurements are only possible for simplified process conditions with tools and parts of adequate design (Davies et al. 2007).

For temperature distribution in the chip formation and friction contact zone, empirical and analytical models are provided by Komanduri et al. (2001). However, all of these models are based on simplified model assumptions and are thus inaccurate and only transferable to a limited extent to most machining processes. Consequently, the input variable from process heat was selected so that the parameter is located in the range of conventional process representation and can be captured by means of thin-film sensors. This means that the absolute temperatures at the measuring points, particularly those located immediately behind the chip formation zone, should be less than 120 °C.

The heat source affecting a real machining process results from the plastic deformation energy transformed during chip formation and the frictional heat generated by the contact of tool and workpiece or chip. For heat source determination, numerical simulation of the chip formation procedure was used. The methodology is described in detail by Drossel et al. (2014). Simulation results are shown for machining of steel AISI-1045 in free orthogonal cut with the model parameters following:

cutting speed $v_c = 10, 35, 70, 140, 280, 560$ m/min,
 depth of cut $h = f_z = 30 \mu\text{m}$, cutting edge radius $r = 5 \mu\text{m}$,
 rake angle $\alpha = 2^\circ$,
 tool orthogonal clearance $\alpha = 7^\circ$.

Fig. 2.9 Heat flows calculated for different cutting speed values

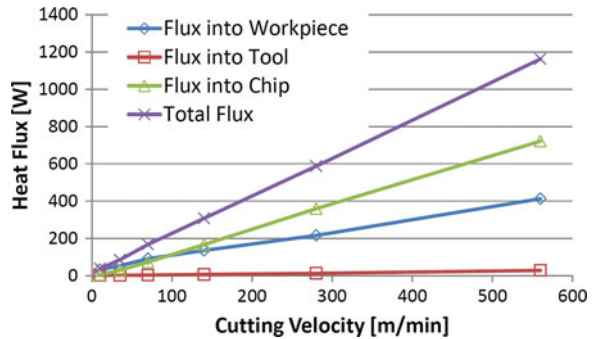
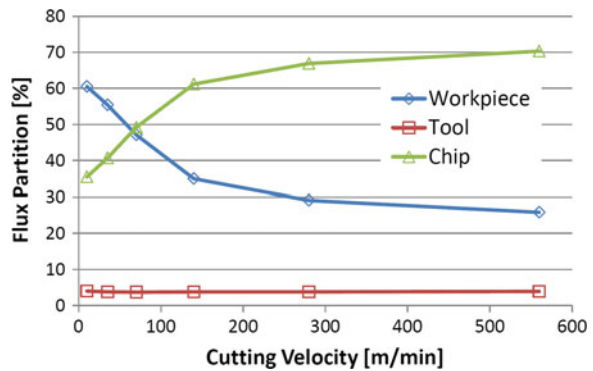


Fig. 2.10 Heat flow distribution in per cent, calculated for different cutting speed values



These parameters are referred to in Figs. 2.9 and 2.10.

Concerning the thermal balance of the machining process, heat generated in the machining process is increasing approximately proportionally with cutting speed (Fig. 2.9), whereby the fraction of the process heat that dissipates into the chips grows substantially (approximately 70 % for $v_c = 560$ m/min, Fig. 2.10), whereas the portion dissipating into the workpiece drops down to 26 %. For the consequences in the tool-chuck system investigated here, the tool fraction of process heat is important, which only slightly changes with increasing cutting speed and which is approximately 4 %.

For other machining processes, such as turning (non-free cutting), milling and drilling, the heat flow values P_{sim} calculated in simulation have to be scaled with factors or correction values according to Table 2.1:

Table 2.1 Correction values for calculation of heat dissipating from machining

| Parameter | Meaning |
|--|--|
| $C_1 = \frac{A_{chip_real}}{A_{chip_sim}}$ | Other chip cross section |
| $C_2 = z$ | z cutting edges engaged |
| $C_3 \approx 1.5$ | 3D process (for instance external cylindrical turning) instead of simulated 2D process |
| $C_4 \approx 0.75$ | Process with varying chip area (milling) |
| $C_5 = \frac{t_{cut}}{t_{total}}$ | Process with interrupted cut |

$$P_{real} = P_{sim} \cdot C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot C_5 \quad (2.1)$$

For an HPC milling process using the end mill, as in the experiments ($d = 20$ mm, 3 cutting edges) with the cutting parameters $n = 2,228$ min^{-1} (that means $v_c = 140$ m/min), $a_e = 5$ mm, $a_p = 2$ mm, $f_z = 0.05$ mm (that means $A_{chip_real} = 0.1$ mm^2), the following correction values are obtained ($A_{chip_sim} = 0.03$ mm^2) $C_1 = 3.33$, $C_2 = 3$, $C_3 = 1.5$, $C_4 = 0.75$, $C_5 = 0.167$. Simulation of the 2D planing process results in a heat flow $P_{sim} = 13.1$ W, which results in a real heat flow of $P_{real} = 24.6$ W under the consideration of the correction values.

The thermal output of this heat source is approximately 300 % of the heat source of 8.1 W, which was used in the long-term experiments. In the real processes, these thermal impacts mostly appear over shorter periods of time; however, for instance when machining integral parts made of titanium, they can last longer. Taking this into account, the displacements of the experiments have realistic dimensions.

2.4 Classification of Outcomes in the SFB/TR 96

The temperature and deformation characteristics' models of the tool and the chuck—and in the future also of the workpiece and the clamping device, as well as the resultant heat flows into the motor spindle and the machine table—include coefficients of heat transfer between the parts clamped, resulting from explorations carried out in the subproject B02. Although, as has been demonstrated, these heat transitions are insignificant for the tool-chuck interface due to the high clamping forces, they will probably be relevant in the systems of part-clamping device—machine table and of chuck-motor spindle.

The force and temperature measurement results obtained on the test bed developed in subproject A02 (see Chap. 4) were used to adjust the simulation models for heat source calculation. Conversely, the simulation results are used to verify the analytical chip formation process model to be developed in subproject A02. The content and distribution of the machining heat is also important to know in this subproject. These results can and will be transferred to other, particularly

3-dimensional, cutting processes and processes with interrupted cut in the future (Klocke et al. 2011).

The numerical simulation method developed for the calculation of heat flows dissipating from metal cutting can be analogously transferred to machining processes with geometrically undefined cutting edge, like those investigated in the subproject A03. The proof of transferability has hitherto been given in the simulation of engagement of an individual grain, whereby the force and temperature measurements in subproject A03 are used for model adjustment. From the present state of expertise, it is impossible to determine the grinding process's heat source alone from the grain engagement temperatures measured alone, without the numerical simulation of the metal removal process.

2.5 Outlook

The measurements and simulations of the system tool chuck–spindle, without considering the influence of cutting fluids, have been completed. The simulation models considering the influence of air and cutting fluids on heat flow have been developed, but have yet to be explored regarding their effects on the thermo-energetic behaviour (Krettek 2014).

The evaluation of the identified parameters makes it possible to elaborate approaches for compensation, including, for instance, design optimisation through geometry and influence on heat flows through calculated measures.

Thermo-energetic investigations regarding the part clamping device will be performed in the future. As a precondition for these studies, a test bed was designed and installed, and the numerical models were developed.

The simulation methodology to balance the heat dissipated from metal cutting processes has to be extended to additional materials and manufacturing processes (turning as non-free cutting, milling, drilling). The correction factors C_1 – C_5 , which have been hitherto determined by means of exemplary models, have to be proven for these processes.

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