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# Process parallel simulation of workpiece temperatures using sensory workpieces

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ABSTRACT

Process induced heat causes workpiece shape deviations during machining and may result in rejected parts. As unpredictable processing and boundary conditions cannot be simulated in the process planning phase, a process parallel simulation of the workpiece temperature is required to observe and compensate thermal effects. To parametrize the process parallel simulation model, a parameter identification method for milling operations is developed. With model order reduction (MOR) the computational time is reduced to enable the process parallel simulation. An observer based on a few temperature measurements during machining is designed to reconstruct the non-measurable temperature distribution. A validation proves the methods' potential.

## Introduction

Machining induces thermal energy into the workpiece, which can result in residual tensile stresses and deformations. The induced heat is generated from friction at the rake face and the material deformation in the shear zone. Thermally induced deformations cause difficulties especially in precision manufacturing and dry cutting processes. In dry cutting the lack of cooling leads to higher temperatures and, thus, larger deformations. To increase the workpiece quality and avoid rejects, a compensation of thermal induced shape errors is required. This is achieved in the process planning with process simulations. The thermal induced deformation is determined and the tool path is adapted accordingly. However, the accurate determination of heat development and distribution during processing is a non-trivial task. The thermal conditions depend on changing boundary conditions during machining. The changes are caused by the varying heat generation in the cutting process due to tool wear and the inconstant temperature of the ambient air and machine components. For this reason, the actual heat distribution cannot be simulated exactly in the process planning phase. Consequently, the development of a process parallel measurement of the actual workpiece temperature and a real time estimation of the thermal inducted deformation can increase the quality of the compensation of thermal induced shape errors.

## Related work

Several studies investigate the development and distribution of temperature into the workpiece in dry machining. There are two common model types:

Empirical models determine the heat input depending on the cutting parameters based on experimental results. Schweinoch et al. [1] combined an empirical model for the heat input with a numerical workpiece model to simulate the heat flow into a milled workpiece. Based on process forces calculated with the Kienzle equation, they estimated the resulting heat. To simulate the heat flow and the boundary conditions a finite difference model was used. The material removal is represented by deactivating elements of the finite difference model. For dry drilling Fleischer et al. [2] presented a regression based approach to determine the heat input as a function of the cutting parameters. The research was focused on the influence of the feed rate and the cutting speed. Other important parameters such as the drill geometry and the workpiece material were not considered. Pabst [3] extended this regression approach on dry milling, drilling and reaming. However, these methods require an adjustment of the model parameters for every combination of tool, workpiece material and process

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## Nomenclature

| | |
|---|---|
| $A$ | Heat capacity matrix of the thermal differential equation |
| $\alpha_{cd}$ | Heat transfer coefficient of the heat conduction |
| $\alpha_{cv}$ | Heat transfer coefficient of the convection |
| $\alpha_{cvfr}$ | Heat transfer coefficient of the free convection |
| $\alpha_{cvfo}$ | Heat transfer coefficient of the forced convection |
| $a_e$ | Width of cut |
| $a_p$ | Depth of cut |
| $B$ | Input matrix of the thermal differential equation |
| $C$ | Output matrix of the thermal differential equation |
| $CJ$ | Clamping jaw |
| $c_p$ | Thermal capacity |
| $CS_W$ | Clamping situation of the workpiece |
| $\triangle T$ | Temperature difference |
| $D$ | Diameter |
| $E$ | Thermal conductivity matrix of the thermal differential equation |
| $\varepsilon$ | Emissivity |
| $FE$ | Finite element |
| FEM | Finite element method |
| $f_z$ | Feed per tooth |
| $\lambda$ | Thermal conductivity |
| $\mathcal{L}$ | Characteristic length |
| MOR | Model order reduction |
| $n$ | Spindle speed |
| $n_I$ | Quantity of sections for the moving heat source |
| $n_{IO}$ | Amount of in and out puts of the reduced system |
| $q$ | Heat flux density |
| $\rho$ | Density |
| $\dot{Q}_{cd}$ | Heat flow of the conduction |
| $\dot{Q}_{cvfo}$ | Heat flow of the forced convection |
| $\dot{Q}_{cvfr}$ | Heat flow of the free convection |
| $\dot{Q}_{hr}$ | Heat flow of the heat radiation |
| $\dot{Q}_{wi}$ | Heat input flow |
| RTD | Resistance temperature detectors |
| $t$ | Time |
| $t_p$ | Processing time |
| $T$ | Temperature |
| $T_{Meas}$ | Measured temperature |
| $T_{Sim}$ | Simulated temperature |
| $u$ | Output vector of the thermal differential equation |
| $V$ | Transformation matrix between full and reduced system |
| $v_c$ | Cutting speed |
| $w$ | Flow velocity of the ambient air |
| $WP$ | Workpiece |
| $x$ | State vector of the thermal differential equation |
| $x_0$ | Initial point |
| $y$ | Output vector of the thermal differential equation |
| $z$ | Number of teeth |
| $\mathbf{z}$ | Reduced state vector of the thermal differential equation |

parameters. This is not feasible in industrial practice due to the required effort.

The second approach are numerical models of the cutting zone. They include the chip forming and friction during cutting. The model input parameters are the material properties, processing parameters and the tool geometry. Schindler et al. [4] used a local numerical finite element (FE) model of the chip formation process to predict the heat flux resulting in dry turning. Additionally, a global FE model was used to simulate the temperature distribution and the thermal induced disorientation. Denkena et al. [5] and Niederwestberg [6] presented a simulation system applicable to NC-milling processes. The global material removal was simulated with a dexel-based model and coupled with an FE model to calculate the induced heat and the induced deformation. Biermann and Iovkov [7] presented a concept that included a numerical simulation of the heat input, an FE-based estimation of the deformation and a tool path adaption. In comparison to an empirical model, the use of a FE simulation reduces the effort for model parameter identification and calibration in case of changing boundary conditions. Relevant information for the settings of a simulation are the material properties, tool geometry, process parameters and heat exchange with the environment. These settings can be adjusted and verified easily in the FE software. In case of an empirical model the model parameters have to be determined by new adjustment attempts, which leads to a higher effort.

In order to parameterize numerical models automatically it is common to compare the simulation results with the actual measurements and adjust the model parameters in an iterative manner. The simulated heat flux and the thermal parameters for the heat exchange are varied until the simulated temperatures match the measured ones. Wernsing and Büskens [8] used this approach to parameterize the input heat flux density. The heat exchange with the environment was not considered. Schindler et al. [9] presented an extended application of this approach to determine the thermal parameters in dry turning. In addition to the heat flow into the workpiece, the convection with the ambient air and the heat conduction into the clamping device were identified.

These examples show that numerical models can be used to calculate the heat distribution within the workpiece and estimate the induced distortion. However, due to the long computation time, numerical simulations of thermal deformations are only suitable in the phase of process planning. Moreover, it should be noted that the actual temperature distribution in the workpiece during machining is influenced by tool wear and heat exchange with the environment depending on the ambient temperature.

The process parallel workpiece temperature modeling in a production environment has been subject to little research. To determine the generated heat during turning Liang et al. [10] presented an inverse heat conduction procedure. An analytical model of the heat flow from the tool into the tool holder was developed for that purpose. Based on temperature changes measured on the tool holder, the actual heat flow was calculated. The analytical approach is only suitable for simple geometries such as the tool holder in turning machines. For more complex geometries it is not possible to determine a solution. In general, temperature sensors are often used temporarily in workpieces for process developments and experimental investigations [11,12]. Furthermore, a use of infrared cameras in machine tools is not practicable. The investment costs are high, the emission behavior changes with the surface type and the workpiece can be covered by other moving machine components.

Recent studies on sensor integration focus primarily on machine components near to the process zone. In spindle slides integrated strain gauges [13], piezoelectric force sensors [14] and rotating dynamometers [15] are used for process force measurement. In clamping systems strain gauges [16,17], accelerometers [18], force sensor [19] are used for process monitoring. Großmann et al. [20] presented a model based approach to estimate and compensate the thermal deformation of a machine tool in real time. For this purpose, a finite element model of the machine tool was generated. The method of model order reduction (MOR) was used to enable a process parallel simulation. With this method, the

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