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Consistent simulation strategy for heat sources and fluxes in milling

Matthias Putz[a], Christian Oppermann[a,]*, Ulrich Semmler[a], Michael Bräunig[b], Umut Karagüzel[c]

[a] Fraunhofer Institute for Machine Tools and Forming Technology IWU, 09126 Chemnitz, Germany
[b] Chemnitz University of Technology, 09010 Chemnitz, Germany
[c] Mechanical Engineering Department, Istanbul Technical University, 34437 Istanbul, Turkey

* Corresponding author. Tel.: +49-371-53971869; fax: +49-371-539761869. *E-mail address:* christian.oppermann@iwu.fraunhofer.de

Abstract

The paper presents a consistent numerical simulation method for calculation of heat sources and heat fluxes in milling processes. First of all, by means of finite element simulation of the interrupted chip formation process the cutting heat source is calculated. Next, the non-steady-state heat fluxes into the workpiece, the chips and the tool are computed numerically. The computed fluxes serve as boundary conditions for thermo-mechanical FE workpiece and tool models. The numerical models are fitted and verified by experiments of S235 steel. The simulations show a good match with the force and temperature measurements of the cutting processes.

Keywords: Milling; Finite element method; Simulation; Experimentation

1. Introduction

Machining is responsible for 30 % of the value of all produced goods; hence it is one of the most important manufacturing processes. While performing machining operations, it is important to remove or avoid generated heat in order to minimize tool wear, to lower the temperature induced displacements and to maintain the surface integrity. Cooling lubricants play a key role to control the cutting temperature; however, environment, health care and economics lead manufacturers to perform dry machining. On the other hand the problems regarding the machining operations are still needed to be overcome. In order to handle these problems the cutting parameters should be selected carefully which requires a better understanding of generation, partitioning and transferring of heat in machining.

In machining the mechanical energy is mostly converted into heat by plastic deformation in the primary shear zone and friction in the secondary deformation zone. Under dry machining conditions, the generated heat energy dissipates into chip, workpiece and tool. Researchers developed a lot of analytical or numerical methods and performed multifaceted experiments to understand the heat generation, partitioning and temperature distribution in machining. Knowing the resultant force F and the cutting speed v_c the mechanical work W can be represented by $W_{mech} = F \cdot v_c$ whereby a partition η~0.95 is transferred into heat.

On the other hand, statements about the heat partitioning differ a lot between several researchers. According to Shaw [1] 90 % of the generated heat is removed by the chip and only 5 % of it dissipates into the workpiece and cutting tool. In another study, Takeuchi et al. [2] assumed that the cutting tool receives 10-30 % of the total heat generation. Especially in analytical modeling of machining operations, principle proposed by Blok [3] is widely used which takes account two bodies in relative motion, in which one is stationary while the other is moving that refers to chip flow on rake face. The partition ratios can also vary with respect to different kinds of machining processes. Fleischer et al. [4] summarized the relevant investigation before the year 2007, see also table 1.

Investigating temperature distribution in workpiece, chip and tool is another challenge for machining industry and researchers. In contrast to turning operation, in milling operations the chip thickness varies with the time. Furthermore, heat generation is an interrupted process in milling operation

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whereby heating periods are followed by cooling ones. Therefore, time should be a parameter in a relevant analysis of milling operation. Stephenson and Ali [5] proposed an analytical model which uses Green's functions to solve the three dimensional transient heat conduction equations for interrupted cutting and validated it with contour cutting experiments. Similarly, Radulescu and Kapoor [6] developed an analytical model for a milling insert in contrast to [5] which takes into account the convective boundary conditions. Islam et al. [7] applied for milling operation a numerical model based on the Finite Difference Method which can predict the cutting temperatures in chip, workpiece and cutting tool, they also verified the model with different workpiece and tool materials under various cutting conditions. Sölter and Gulpak [8] derived an empirical model for heat flux into workpiece in dry milling of steel which includes the effects of cutting speed, feed rate, depth of cut and chip thickness. They found that chip thickness has a significant effect on heat flux and heat partition. As mentioned above besides cutting temperatures, it is also important to determine their effects on the process itself. Schweinoch et al. [9] presented a fast geometric process simulation which can predict cutting forces, heat generation and thermal loading in dry milling. It is also shown in [9] that it is possible to calculate the thermally induced deformations in the machined part. Cui et al. [10] used the Finite Element program DEFORM^{TM} 2D to calculate the heat fluxes into tool and contact length values for different chip thickness values during face milling. The calculated heat flux values were considered as input in an analytical model which predicts the transient tool temperatures.

Table 1. Percentage heat partitioning in different cutting processes [4]

	Turning	Milling	Drilling
Into tool	2.1-18	5.3-10	5-15
Into workpiece	1.1-20	1.3-25	10-35
Into chip	74.6-96.3	65-74.6	55-75

Our paper presents a theoretical and experimental study with the aim to define cutting temperatures, heat fluxes and thermally induced tool center point (TCP) displacements in milling of S235 steel (AISI 1010). At first, for milling operations a 2D chip formation model with varying chip thickness is generated in DEFORM^{TM}. Afterwards, heat fluxes into workpiece, chip and tool and their partition ratios are calculated using the described by Putz et al. [12,13] methods. Then, separately developed FE models for workpiece and tool are presented. In the first workpiece model the calculated heat flux is applied as moving heat source along the cutting tool engagement path. The crucial point of this model is that it allows to calculate the heat which is removed from the workpiece during the following engagements and, this way, to compute the remaining in the workpiece heat. Using the remaining heat, in a second workpiece model the temperature development in the workpiece is calculated in comparison with experimental results. Finally, the calculated heat flux into tool is used in a FE model of the tool, again in comparison with experiments. It is shown that the results of the described simulation technique agree very well with experiments.

2. Experimental Study

Dry milling experiments were carried out on a 5 axis machine tool in order to validate the proposed coupled FE models. The cutting conditions were the following: workpiece material S235 steel, peripheral cutting tool with three uncoated WC inserts and diameter $d = 20\ mm$, cutting speed $v_c = 100\ m/min$ and 200 m/min, axial depth of cut $a_p = 5\ mm$, radial depth of cut $a_e = 3\ mm$, feed per tooth $f_z = 0.1\ mm$, rake angle $\gamma = -5°$, inclination angle $\kappa = 0°$, clearance angle $\alpha=7°$, cutting edge radius $r = 0.02\ mm$.

Fig. 1 shows the experimental setup with force and temperature measurement equipment.

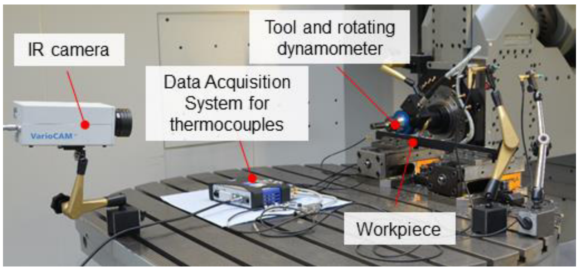

Fig. 1. Experimental setup

Cutting forces were measured by a Kistler rotating dynamometer which can measure forces in three independent directions, namely, F_x, F_y and F_z, and the moment around Z direction during cutting. A high sampling rate of 9600 Hz was used in order to obtain reliable data during each insert engagement for comparison with simulations (see Fig. 5). The temperature was measured both with a thermo-camera and with 3 thermocouples positioned 1 mm below the cutting surface, see Fig. 2.

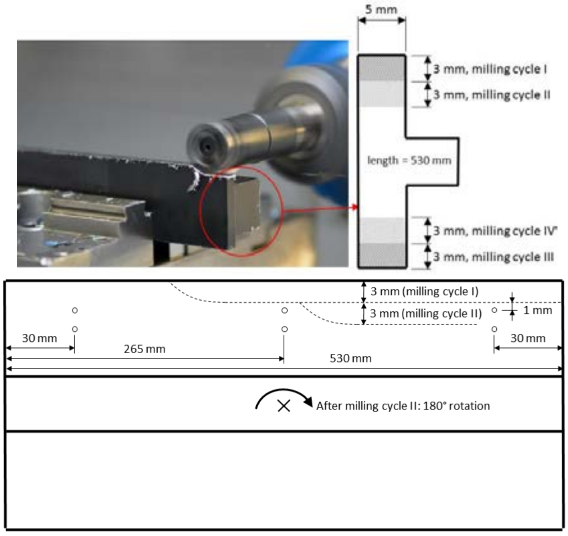

Fig. 2. Workpiece geometry and thermocouple positions

The experiment for each cutting speed v_c=*100 m/min* and v_c=*200 m/min* was repeated twice. Fig. 3 shows IR images for