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Multiscale modeling of thermoelastic workpiece deformation in dry cutting

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Abstract

In dry cutting an intensified heating of workpiece, tool and machine tool results in thermoelastic deformation which in turn causes dimensional and geometrical deviations of the machined parts. This paper presents a multiscale simulation method to calculate and compensate this effect. A chip formation model is used to compute the thermomechanical energy conversion and to determine the heat source of the cutting process on a mesoscopic model scale. This heat source is transferred on a macroscopic model that simulates the workpiece heating for a complete process sequence in order to analyze, reduce and compensate thermoelastic deformations. The multiscale simulation method is validated regarding the temperature and the resulting longitudinal workpiece deformation in dry turning of a gear shaft. However, the prediction of thermal deformation in radial dimensions needs additional validation with improved experiments and model features in future works.

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Keywords: Chip Formation Simulation; Heat Partition; Thermoelastic deformation; Dry cutting; Multiscale modeling

1. Introduction and state of the art

Dry machining is an important milestone in manufacturing technology with geometrically defined cutting edge. However, some drawbacks do exist. Without cooling lubricant, a higher heat flux to tool and workpiece promotes for example thermal expansion and work material modification.

With the objective to offer solutions for such problems the priority program 1480 “CutSim - Modelling, simulation and compensation of thermal effects for complex machining processes” was initiated and funded by the German Research Foundation in 2010 [1]. Within this program numerous models for different cutting processes are developed. Many of these models are dealing with the challenge of the determination of the thermal fluxes resulting from process heat generation, because these are often necessary input or optimization variables.

The heat source and heat partition were mostly estimated by experiments and are sometimes extended by analytical and numerical models according to the recent research [2]. For example Pabst investigated the heat distribution inside the workpiece in dry milling with a calorimetric methodology [3]. Abukhshim analyzed the heating partition in dry cutting process to identify the thermal field in the cutting zone [4]. For knowledge about mechanics of dry cutting process, the cutting force was also determined in addition to temperature measurement. Besides, Sölter used an inverse method to analyze the heat flux into workpiece in dry milling based on experiments and simulations [5]. Deppermann also used an inverse experimental-numerical method to compute the heat flux into the workpiece based on thermal imaging in dry turning [6]. The idea of using experiments to determine the heat source and heat partition is simple. However, a direct, precise measurement is still a big challenge. Physical phenomena such as reflections or varying emissivity as well as technical limitations impede detailed and efficient thermal analyzes of metal cutting processes.

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An opportunity to overcome these issues is the usage of multiphysics simulation models. This paper presents a numerical multiscale model to calculate the process heat generation and the thermoelastic workpiece deformation to compensate these deformations in dry cutting operations.

2. Multiscale model of dry turning

2.1. Model concept and methodology

Fig. 1 shows the concept of the multiscale model to analyze the cutting process and to compute the thermoelastic workpiece deformation by the simulation on different spatial and temporal scales. A mesoscopic model scale serves to simulate the chip formation by a thermomechanical finite element analysis. The goal is to determine the steady-state thermomechanical energy conversion of the cutting process and to calculate the heat flux that is entering the workpiece. Because of the high necessary spatial and temporal resolution of the mesoscopic model scale and thus long computation time, only a small cut-out of the workpiece and short cutting lengths of 10 - 30 mm are simulated.

The calculated heat flux is then transferred to a macroscopic model scale, also based on the finite element method. On this scale, the time increment Δt_{ink} and characteristic length of the finite elements l_{char} are increased resulting in a higher degree of model abstraction. It is necessary to calculate a full cycle of the turning process. The macroscopic model simulates the material removal, the heat input of the process, the heat exchange with the environment and computes the heating and thermoelastic deformation of the whole workpiece.

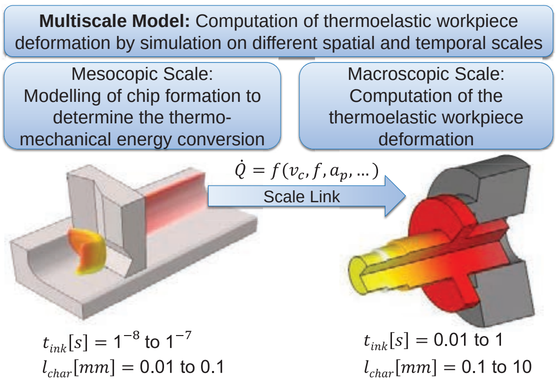

Fig. 1. Multiscale model concept to simulate dry turning

2.2. Case study

In this paper, the application of the model is demonstrated by means of a case study which represents external turning of a gear shaft. Two different sets of cutting parameters were used to define two process alternatives. Case 1 is an external longitudinal turning process with a cutting speed of v_c = 75 m/min, a depth of cut of a_p = 3 mm and a feed of f = 0.15 mm. Case 2 is an external radial turning process using v_c = 150 m/min, a_p = 3 mm and f = 0.15 mm. In both cases a CNMG120408 coated carbide cutting tool was used to machine the work material AISI 1045 in normalized state. Details about the part geometry, process kinematics and parameters can be found in [7].

The first step in the application of the model is to compute the heat flux into the workpiece by using the mesoscopic model. Fig. 2 briefly shows the concept of this 3D finite element model and a sample temperature distribution for the external turning process. To model the chip formation the coupled Eulerian-Lagrangian finite element method was employed using the commercial software package ABAQUS Explicit. With this model, the chip formation is simulated similar to fluid flow models. The "fluid" is in this case the work material which is continuously entering the Eulerian domain at the top and is then flowing against the tool which is fixed in space. Subsequently, the metal is separated into chip and workpiece and after that the workpiece and formed chip leave the Eulerian domain. After simulating the chip formation for a few milliseconds with this method a thermal steady-state condition is established in chip and workpiece.

To calculate the heat flux into the workpiece the change of internal heat energy inside a control volume was evaluated below the cutting edge. This was done for the main cutting edge $\dot{Q}_{w,m}$ and the corner radius $\dot{Q}_{w,r}$ separately for the two cases, see Fig. 2. To model the visco-elastoplastic material behavior, a Johnson-Cook material model (A = 546 MPa, B = 487 MPa, n = 0.25, m = 0.631, C = 0.027, T_m = 1500°C, T_0 = 20°C, ε_0 = 0.001 s^{-1}) was used that was obtained by inverse parameter identification [8]. Furthermore, a temperature dependent friction model was implemented as described in [7]. Convection and radiation were not considered in the mesoscopic model. Details about the methodology to calculate the heat flux into the workpiece, the CEL method, boundary conditions and model parameters are explained in [7] and [9].

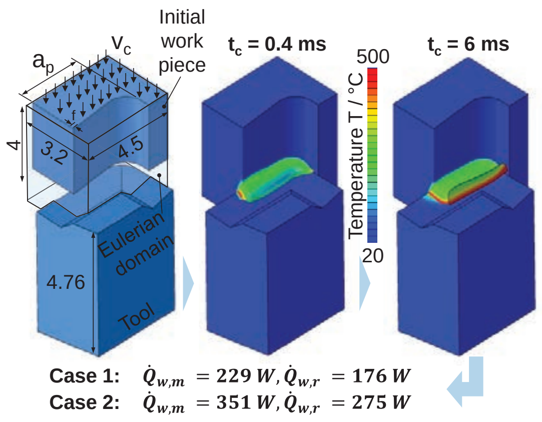

Fig. 2. Mesoscopic model scale

After calculation of the rates of heat flow, a heat source can be modelled within the macroscopic scale that was realized in the commercial software SFTC DEFORM. The transient, Lagrangian implicit 2D macroscopic model