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A novel FEM-CFD interface for multi-physical simulations to model the effects of cutting fluid on the tool temperature during orthogonal cutting

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Abstract

Numerical modelling is a widely used method for predicting machining process variables such as cutting forces, chip formation and temperature development. The coupled Eulerian-Lagrangian method (CEL) is one of the most important methods due to its robust handling of large deformations occurring during machining. So far, the CEL method has mainly been used for dry machining simulation. In order to simulate the influence of the cutting fluid on the tool temperature, a coupling between fluid simulation and CEL model needs to be implemented. To enable a simulation of the thermo-mechanical as well as fluid-structural interaction, the simulation results from the CEL model are transferred to the flow simulation. The proposed paper presents a Python script-based interface for coupling the CEL simulation with the fluid dynamics simulation and vice versa. First, the chip formation, the temperature fields in the cutting zone and the heat source were calculated in the CEL simulation and then the chip shape as well as the temperature distribution and the heat flow in the cutting zone were imported into the fluid simulation as initial conditions by the interface program. In the fluid simulation, the cooling effect of the cutting fluid was calculated. For the validation of the heat transfer model, fundamental investigations on orthogonal cutting of the nickel-base super alloy (Inconel 718) under cooling-lubrication were performed. The tool temperature was measured with a pyrometer and provided together with the measured cutting force a validation of the simulation.

Orthogonal cutting; Finite Element Simulation (FEM); FEM-CFD interface; INCONEL 718

1. Introduction

Cutting is a complex process associated with a variety of different mechanical and thermal physics. The mechanical energy applied to the chip formation is largely converted into heat in the shearing and friction zones. The resulting extraordinarily high mechanical and thermal stresses lead to thermally induced displacement of the tool tip and tool wear [1]. This limits the tool life and the applicable cutting speeds and thus the productivity of the machining process. In order to reduce tool wear and carry away the chips, cutting fluids are often used in machining operations. However, for different cooling strategies, the use of energy and resources and the impact on the environment are very different, which leads to enormous cost differences. Therefore, the knowledge of the suitable cooling strategy for different applications is an essential part of the efficient and economical design of the manufacturing process. However, due to the limited measuring conditions, the influence of the coolant on the temperature and heat distribution and the effect on chip formation cannot be observed directly during the machining process. This insufficient understanding of the process leads to the fact that the cutting fluid cannot be used to its full extent.

In addition to the empirical method, numerical simulation is increasingly used in the design of cooling systems. Compared to the experimental method, the simulation method reduces the cost of experiments and it is possible to analyze the mechanism of cooling effects in the cutting processes. So far, various numerical models and methods for the analysis of the cooling effect have been developed, such as [2], [3], [4]. Many of the methods simulate the cutting process and the cooling effect of the cutting fluid separately and do not consider the thermal and mechanical interactions between process and coolant. This leads to a large deviation in the simulation results, which cannot analyze the effect of the coolant quantitatively. Therefore, for a comprehensive modeling of the coolant effect on the tool temperature, mechanical and thermal effects and their interaction need to be considered, which consequently requires the coupling of finite element method (FEM) and computational fluid dynamics (CFD) models. The present work shows a method for coupling the CEL cutting simulation with the CFD fluid cooling simulation. First the chip formation, the heat source and the temperature distribution are calculated in the FEM simulation without considering the effect of the fluid. The results are then imported into the fluid simulation via the interface program as initial boundary and geometric boundary conditions. The influence of the coolant on the tool temperature is then calculated in the CFD simulation. By comparing the measured tool temperature with the calculated tool temperature, the accuracy of the simulation can be evaluated. In order to automate this procedure, a Python-based program has been developed which automatically performs the conversion and transfer of the simulation results.

2. FE-CFD Interface

The numerical method shown in this article is based on two simulation software. First, the heat development and chip formation during the machining process was modelled with the coupled Eulerian-Lagrangian (CEL) formulation. The model was solved with the commercial simulation program ABAQUS. Then the cooling effect of the cutting fluid is calculated by the CFD software OpenFOAM. The task of the interface program is to realize the exchange of physical parameters and geometric conditions between the two programs in order to simulate the thermo-mechanical interaction between the cutting process and the cutting fluid. The workflow of the interface program is shown in Figure 1.

First, ABAQUS calculates the stationary state of the orthogonal cutting without considering the effect of cutting fluid. The interface program accesses the result file (ODB file) via the ABAQUS python library and reads the chip geometry as well as the temperature and heat flow distribution. Then the data is converted into the VTK format (Visualization Toolkit). The rules for writing VTK files refer to the literature [5]. The generated VTK file can be post-processed through the python library provided by the open source software PARAVIEW, so that it can be directly imported into the CFD simulation. The fluid properties of the coolant and the cooling effect are then calculated in the CFD simulation. The result of the simulation is the temperature of the tool in steady state under the influence of the cutting fluid.

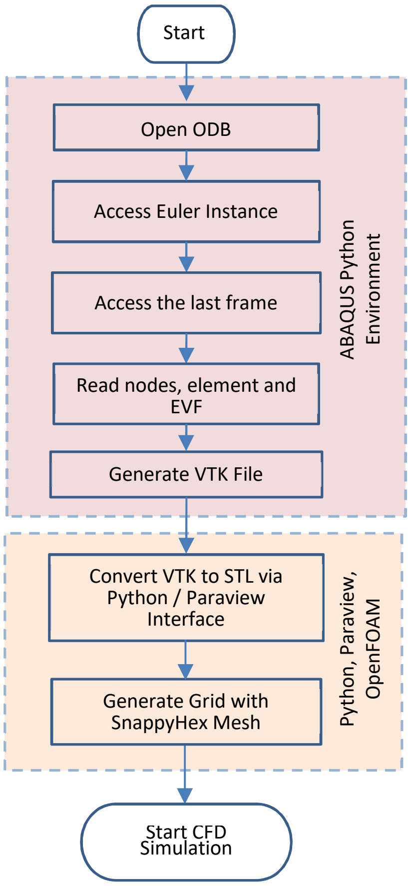

Figure 1. Major working procedures of the interface program

3. FEM modelling of orthogonal cutting

The chip formation simulation is performed using the CEL approach, in which the workpiece is modelled with Euler elements and the tool is modelled with Lagrange elements. Model structure, boundary conditions and mesh types are shown in Figure 2. The tool shown in grey is considered to be the ideal rigid body. The blue area in the Euler grid is the initial position of the material, and it moves at a constant velocity v_c through the Euler grids towards the tool. To describe the visco-plasticity of the Inconel 718, the Johnson Cook material model (Eq. 1) and the Johnson Cook damage model (Eq. 2) were used. Both models are described in [6] and [7]. The parameters for the equation were obtained from the work of Erice [8] and are listed in Table 1 and Table 2.

$$\sigma_{yid} = (A + B \cdot \varepsilon^n) \cdot \left[1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^m\right] \qquad (1)$$

$$\varepsilon_f = (D_1 + D_2 \cdot e^{D_3 \cdot \eta}) \cdot \left[1 + D_4 \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 + D_5 \cdot \left(\frac{T - T_0}{T_{melt} - T_0}\right)\right] \qquad (2)$$

Table 1. Johnson-Cook constitutive model parameters of INCONEL 718 [7]

A [MPa]	B [MPa]	n	C	m	$\dot{\varepsilon}_0$ [s^{-1}]	T_0 [°C]	T_m [°C]
1200	1284	0.54	0.006	1.2	0.001	25	1800

Table 2. Johnson-Cook damage model parameters of INCONEL 718 [7]

D_1	D_2	D_3	D_4	D_5
0.04	0.75	-1.45	0.04	0.89

The friction between workpiece and tool during cutting is described by the temperature-dependent friction model published by Puls [8]. The parameters of the friction model for the Inconel 718 were obtained from the literature [9] as shown in Table 3.

$$\mu_{app} = \mu_0 \cdot \left[1 - \left(\frac{T - T_f}{T_{melt} - T_f}\right)^{m_f}\right] \qquad (3)$$

Table 3. Friction model parameters of INCONEL 718 [9]

μ_0	T_f [°C]	m_f
0.46	200	2.4

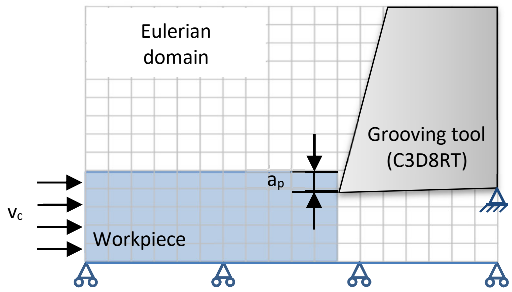

Figure 2. Concept of FE modelling of orthogonal cutting with coupled Eulerisch-Lagrangian (CEL) formulation

Figure 3 shows the chip shape from the simulation. The simulation results presented in this section are processed in the FE-CFD interface and used as boundary condition in the CFD simulation.

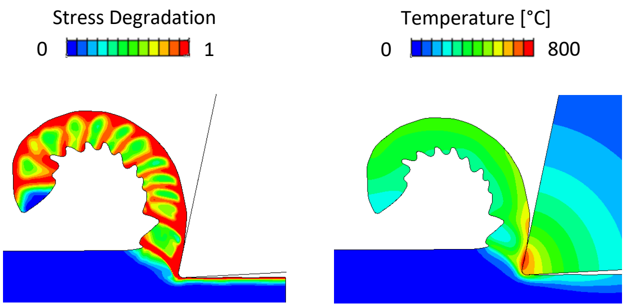

Figure 3. Chip formation and temperature distribution from the simulation (v_c = 50 m/min, a_p = 0.175 mm)

4. Computational Fluid Dynamics

The framework for the CFD simulation is provided by the OpenSource software OpenFoam using the exported 2-D chip geometry to generate the grid. This is done by converting the VTK output file from FEM into a STL (stereolithography) file format by using a python script with an embedded PARAVIEW library. Following this STL file used by the snappy hex mesh meshing tool of OpenFoam to generate the CFD geometry and boundaries conditions.

The used OpenFoam solver accounts for multiphase fluids meaning that gaseous ambient air as well as liquid cooling lubricant are modelled. Further, conjugate heat transfer between lubricant (fluid) and chip, workpiece (solid) is considered.

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u_i \frac{\partial T}{\partial x_i} = \lambda \frac{\partial^2 T}{\partial^2 x_i} + \dot{q} \tag{4}$$

$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial u_i u_j}{\partial x_j} = \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial^2 x_j} \tag{5}$$

Exemplary results of the CFD simulation are presented in Figure 4 showing the volume fraction of cooling lubricant and the corresponding redirection of fluid due to the chip geometry.

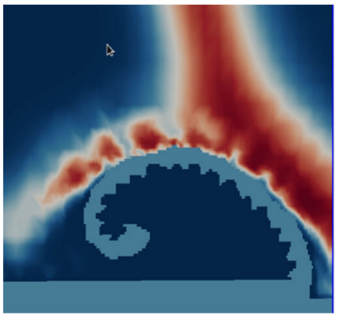

Figure 4. Exemplary CFD Simulation Results of the Cooling Lubricant approaching the Chip

5. Experimental Setup

To validate and evaluate the simulation models, orthogonal cutting tests are carried out on a broaching machine. The experimental setup is shown schematically in Figure 1. The test material INCONEL 718 was machined into 2.5 mm thick sheets and fastened to the slide of the broaching machine. A grooving insert made of uncoated cemented carbide was fixed to the Kistler Multi-Component Dynamometer Z21289 and mounted on the worktable of the broaching machine. The applied grooving insert has a rake angle of 12°, a clearance angle of 3° and a cutting radius of 5 µm. The temperature inside the tool is measured by a pyrometer. Thereby the infrared radiation is captured by a glass fibre integrated in the grooving tool and transmitted to the pyrometer. During the test, the workpiece moves with the broaching slide against the tool at constant speed v_c and cutting depth a_p. The chip formation process as well as temperature distribution and process forces were recorded and used as validation parameters for the simulation.

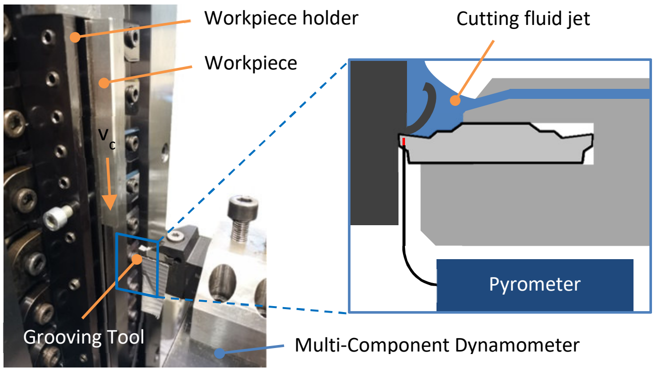

Figure 5. Experimental setup of orthogonal cutting

6. Acknowledgements

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Reference:

[1] Klocke, F., 2011, “Manufacturing Processes 1”, Springer-Verlag Berlin Heidelberg

[2] Shet, C.; Deng, X.; E. Bayoumi, A., 2003, “Finite element simulation of high-pressure water-jet assisted metal cutting” In: International Journal of Mechanical Sciences. Jg. 45, Nr. 6-7, S. 1201–1228

[3] Dix, M.; Wertheim, R.; Schmidt, G.; Hochmuth, C., 2014, “Modeling of drilling assisted by cryogenic cooling for higher efficiency” In: CIRP Annals - Manufacturing Technology. Jg. 63, Nr. 1, S. 73–76

[4] Aurich, J. C.; Zimmermann, M.; Schindler, S.; Steinmann, P., 2013, “Analysis of the machining accuracy when dry turning via experiments and finite element simulations” In: Production Engineering

[5] Liu Q.B., Li J., 2016, “ParaView visualization of Abaqus output on the mechanical deformation of complex microstructures”, Computers & Geosciences, Volume 99, 135–144

[6] Johnson, G.R., Cook, W.H., 1983, “A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures”, In: 7th International Symposium on Ballistics, The Hague, pp. 541–547.

[7] Johnson, G.R.; Cook, W.H., 1985, “Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures”, Engng. Fracture Mechanics, 21, 31–48.

[8] Erice B, G´alvez F., 2014, “A coupled elastoplastic-damage constitutive model with lode angle dependent failure criterion”, Int J Solids Struct 51(1):93–110.