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FEM-Modelling of the thermal workpiece deformation in dry turning

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Abstract

The substitution of wet machining processes by dry processes is an important development in manufacturing technology. A central challenge is the significant higher heating and thus the resulting thermal expansion of the workpiece which leads to geometrical deviations of the machined part. According to the state of the art these processes are optimized by trial and error approaches and therefore result in high costs. This paper presents a two-scale finite element model which calculates the thermal deformation of the workpiece in dry turning of normalized steel C45E / AISI 1045. The approach consists of two submodels. The first submodel is a fully coupled finite element chip formation model for the calculation of the generated heat and temperature distribution in the chip, workpiece and tool. On this basis the rate of heat flow into the workpiece is determined. In a second model this rate of heat flow is applied to a macroscale model that calculates the instationary temperature distribution and deformation of the whole workpiece. The chip formation model has been validated by an orthogonal cutting process realized on a broaching machine tool while the workpiece model is validated by thermal imaging of an orthogonal turning process.

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Keywords: Dry machining, Thermal workpiece deformation, FEM modelling

1. Introduction

The substitution of wet machining processes by dry processes is an important development in manufacturing technology. Due to the absence of cutting fluids, a central challenge of dry machining is the significant higher heating and thus the resulting thermal expansion of the workpiece which leads to geometrical deviations of the machined part. The correction of these deviations is based on trial and error approaches and is therefore inefficient in small-series production. Today, a calculation of the workpiece heating due to the machining process is still not state of the art.

Numerical methods like the Finite Element Method (FEM) are in principle able to solve the instationary heat transfer problem which occurs in a dry machining process. Nevertheless the heat source and its heat partition to the work-piece have to be determined for such an approach, which is the central scientific task. In recent approaches the heat source was calculated based on experimental results. Pabst for example used a calorimetric approach by analyzing the temperature distribution inside the workpiece in dry milling [1]. A similar calorimetric methodology for turning can be found in [2]. Sölter used an inverse procedure to determine the heat flux which is heating up the workpiece in dry milling [3]. Though, experimental determination of the heat source is always very cost intensive and limited to the used process conditions.

Therefore an analytical or numerical determination would be desirable. In general, the mechanical process energy that is converted to heat flows into the workpiece, tool, chip and the environment. Due to the complex phenomena which are related to the chip formation process analytical methods, which can be found for example in [4-7], mostly exclude local effects of the chip formation process and are limited to the two dimensional orthogonal cutting process in the majority of cases.

Due to these reasons the numerical FE-modeling of the chip formation is a promising approach to determine

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the temperature in the chip, workpiece, environment and tool and the corresponding heat partition. The FE chip formation simulation is able to calculate the local heat generation caused by plastic deformation and friction during the chip formation. In addition it is able to account for complex tool geometries which are used in machining practice.

2. Two Scale FEM Model

This paper presents a two scale FEM-model which consists of two submodels in order to predict the thermal deformation in dry turning. The first submodel is a fully coupled finite element chip formation model for the calculation of the generated heat and temperature distribution in the chip, workpiece and tool. Based on this calculation the rate of heat flow into the workpiece is determined. In a second model the rate of heat flow is applied to a macroscale model that calculates the instationary temperature distribution and deformation of the whole workpiece. Figure 1 shows a schematic overview of the approach.

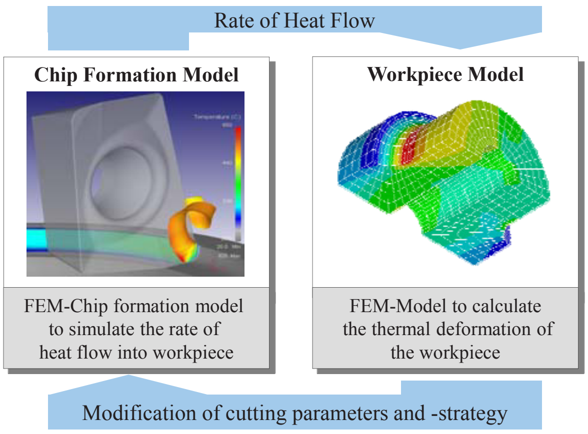

Fig. 1: Two Scale model to calculate the workpiece deformation in dry turning.

2.1. Chip Formation Model

In this paper a two dimensional chip formation model of an orthogonal turning process has been used to calculate the generated heat and temperature distribution within the process. Figure 2 shows the schematic calculation procedure to determine the heat rate which causes the heating of the workpiece. The numerical efficient approach is based on the calculation of heat amounts in different volumes inside the workpiece. Figure 2 illustrates two volumes for this purpose. The first volume which represents a small section of the workpiece rim zone is moving with the cutting velocity v_c. In a small time period this volume moves a distance L and heat will be generated and transferred into this volume by the process. In a quasistationary process, the temperature profile underneath the cutting edge is constant and therefore the amount of the transferred heat in this time period can be calculated by simply computed the heat stored in Volume 2.

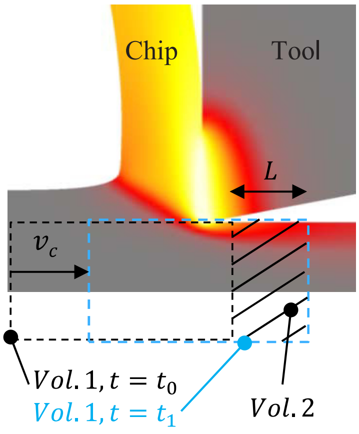

Fig. 2: Schematic representation of the volumes used for the heat rate calculation.

Subsequently, equation 1 calculates the rate of heat flow $\dot{Q}_{WP}$ which is heating up the workpiece. This formula has been implemented in a user subroutine in the commercial FE code SFTC DEFORM™ which was used for the computations. The software provides a lagrangian implicit FE formulation and an automatic remeshing procedure to simulate the chip formation.

$$\dot{Q}_{WP} = \frac{v_c \cdot \rho}{L} \int_{Vol.2} c_p(T) \cdot (T - T_0) dV \quad (1)$$

The methodology can be utilized within two dimensional machining processes like orthogonal turning processes. For complex kinematics, e.g. grooving and external turning processes, the calculation volumes have to be modified. In three dimensional chip formation models, the workpiece domain can be divided into the chip and the workpiece by kinematic criterions. For example, a chip element node can be identified by analyzing its velocity vector. Once the chip and workpiece elements are identified, the periodic change in the heat amounts in the chip and workpiece, the rate of heat flow, can be calculated analogously.

In this paper, the model parameters listed in Table 1 have been used to simulate the orthogonal turning process of AISI 1045. A Johnson-Cook material model has been used to model the viscoplastic behavior of the steel alloy AISI 1045 [8]. A hybrid coulomb-shear friction model has been used to model the mechanical contact between chip and tool. The friction model for the material combination AISI 1045 / Sandvik H13A is described in [9]. Convection and thermal radiation have been neglected. The temperature dependent thermal conductivity and heat capacity as well as the coefficients of linear expansion for AISI 1045 have been obtained from [10], see Appendix A. The temperature dependent thermal conductivity and heat capacity of the tool material Sandvik H13A with similar composition (WC-6Co) was obtained from [11, 12].

Different cutting velocities and feed rates have been used to investigate the influence on the workpiece heating. In addition, the chip formation has been simulated for these parameters with an initial flank wear land width of 50 µm.

Table 1: Used parameters for the chip formation model.

AISI 1045			
A:	546 MPa	C:	0.027
B:	487 MPa	m:	0.631
n:	0.25	h:	1000 N/(s·mm·°C)
Process parameters			
Cutting Speed:	100; 125; 150; 175; 200 m/min		
Feed:	0.05; 0.1; 0.15; 0.2 mm		
Tool geometry	$\alpha = 10°$, $\gamma = 0°$, $r_\beta = 25$ µm		

2.2. Results and Validation of the Chip Formation Model

The major objective of the chip formation model was to calculate the rate of heat flow which causes the workpiece heating. Because this variable cannot be directly measured the validation of the whole model requires two steps.

First, the chip formation model will be validated with respect to the cutting and feed force and in addition with respect to the chip compression ratio. The cutting force has to be validated because it is directly related to the required mechanical energy of the process which is subsequently converted into heat. In addition the chip compression ratio indirectly validates the shear angle.

In a second step, the workpiece model is validated by orthogonal turning tests and thermal imaging (section 2.4). For the validation of the chip formation model an orthogonal cutting process realized on a broaching machine has been utilized (Figure 3). The machine tool has an electromechanical drive to provide a maximum cutting velocity of v_c = 100 m/min. The linear geometry of the workpieces allows an exact comparison to the 2D FE-simulations, since the exact same kinematic conditions are realized in the experiments. The cutting forces are measured by a piezoelectric dynamometer. The results in Figure 4 show a very good agreement between the cutting and thrust forces.

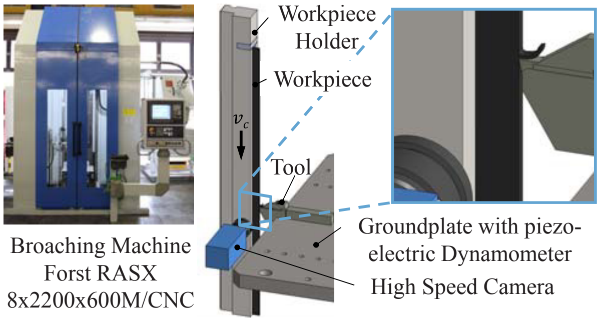

Fig. 3: Experimental setup for an orthogonal cutting process.

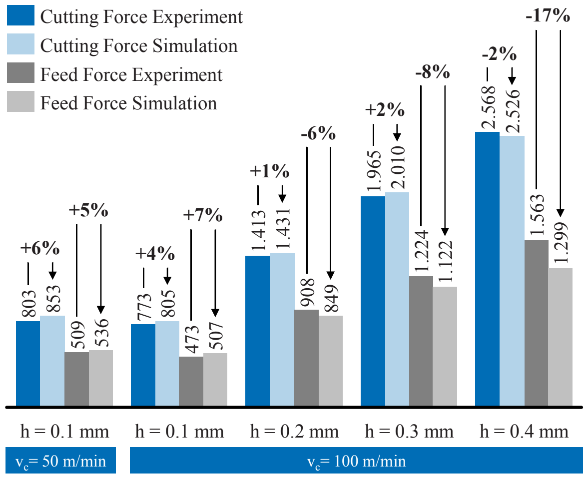

Fig. 4: Comparison of the simulated forces to experimental measured forces for different cutting parameters (width of cut b = 3 mm).

In addition, the agreements between experimental measured and simulated chip compression ratios are also good. The compression ratios have been determined experimentally by dividing the workpiece length by the chip length, which was measured by digital microscopy.

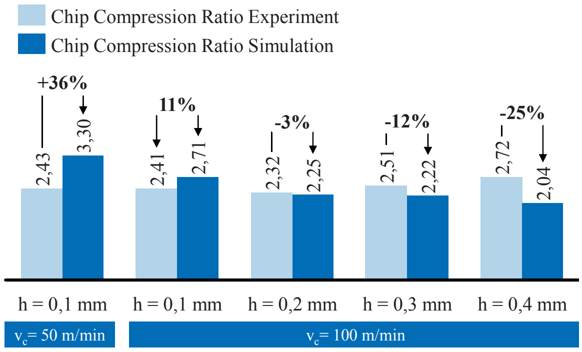

Fig. 5: Comparison of the simulated and experimental measured chip compression ratio.

From the validation results it can be concluded, that the chip formation model provides reasonable results for the required mechanical process energy which is converted into heat and that the simulation provides an appropriate shear angle. This indicates that the model will also provide good results for the calculation of the rate of heat flow into the workpiece.

Figure 6 shows the results for the calculated rate of heat flow for different cutting speeds and feed rates according to equation 1. As expected, the rate of heat flow increases with increasing feed and cutting speed. On the other hand if the material removal rate is also considered, the workpiece heating will decrease if the material removal rate is increased. The rate of heat flow is only increasing about 20% if the feed is doubled but on the other hand the process time is halved. Therefore the heating of the workpiece will be significantly decreased. Furthermore, Figure 6 shows the percentage rise in the rate of heat flow if a flank wear land width of 50 µm is considered in the chip formation simulation. The rate of heat flow increases by approximately 20-30% for the chosen parameters. The results clarify that tool wear has to be considered for an adequate calculation of the workpiece heating.

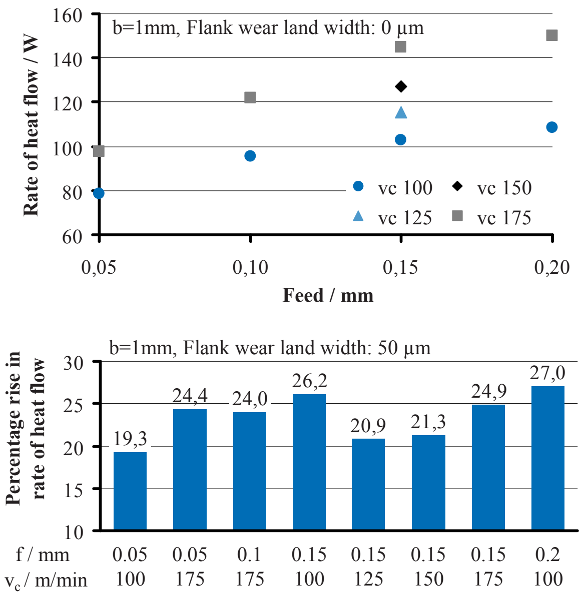

Fig. 6: Simulated rate of heat flow for different cutting parameters and the effect of simulated flank wear land width.

2.3. Workpiece Model

The simulated rate of heat flow is now applied to the workpiece model to calculate the thermal deformation. In contrast to the chip formation model which considers just a small part of the workpiece, the workpiece model contains the whole workpiece on a more simplified level. Within the workpiece model, each simulation step represents one rotation of the workpiece. At the beginning of a specific simulation step *n* the computing procedure obtains the coordinates of a reference point of the cutting edge from an input file. Combined with parameters of the cutting edge geometry, the location of the cutting edge will be calculated. Subsequently the rate of heat flow will be applied along the cutting edge during the simulation step. The other boundaries are isolated to the environment. Considering the cutting edge position from the step *n+1* the cross sectional area of cut will be calculated. In the case of orthogonal cutting this area represents the ring volume which is removed during the rotation of the workpiece in step *n*. Therefore the area elements will be marked with a damage value. After the calculation of the FEM step *n*, the marked area will be removed by an element deletion routine and the procedure starts again in the next simulation step.

The subject of this paper is the orthogonal dry turning process. Therefore the workpiece will be modeled using an axisymmetric two dimensional FEM model. The methodology described above has been implemented in a user subroutine for the commercial, implicit FE code DEFORM™. The model is a coupled thermal and mechanical model based on a lagrangian formulation to solve the heat transfer problem as well as the mechanical problem. Therefore it calculates the temperature, deformation and stress distribution inside the workpiece. The chosen physical properties are the same as in the chip formation model. Figure 7 exemplarily shows the temperature and displacement profile in a 3D View for the parameters v = 100 m/min, f = 0.1 mm and width of cut b = 3 mm.

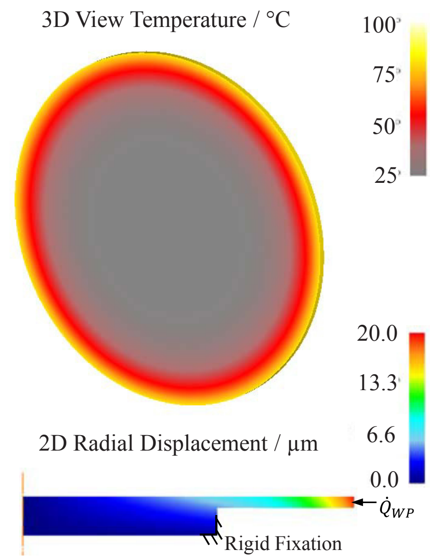

Fig. 7: Temperature and radial displacement profile of the workpiece after cutting.

The applied rate of heat flow was 287.1 W (see Figure 6). The disc diameter was reduced from 180 mm to 170 mm in the process. The cutting time is approximately 16.5 seconds. At the end of the process the radial displacement of the disc at the cutting edge, which would be the theoretical geometrical deviation, is approximately 20 µm after this relatively short cutting time. The temperature distribution shows that the major amount of heat is still in the outer region of the workpiece. In the next section the workpiece model will be validated by comparing the calculated temperatures with experimental thermal imaging for different cutting parameters.

2.4. Results and Validation of the Workpiece Model

The additional validation of the whole two scale model includes the comparison of the resulting simulated temperatures in the workpieces to the same experimental processes. Figure 8 shows the experimental setup. A thermal imaging camera has been installed in a lathe. In order to realize an observation of the process near the cutting edge, a lathe which provides a spindle feed movement has been used. In this case the tool is fixed and the camera always captures an image section in front of the cutting edge. The tools were the same as modeled in the chip formation model. For each experiment a new workpiece has been used. The starting diameter of the workpiece was 180 mm and it was machined to 170 mm within each experiment.

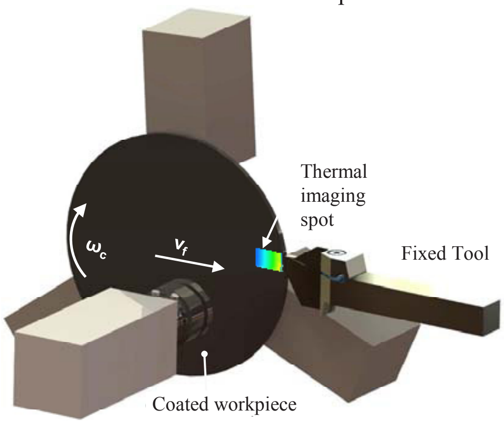

Fig. 8: Experimental setup of the orthogonal turning process.

Figure 9 shows an example thermal image during the process where the radial temperature gradient can be clearly observed. Due to the dimensions of the workpiece the curvature and thickness are neglected which means that the temperature gradient has only a radial dimension. Therefore thermal imaging videos have been analyzed by calculating the mean value of a line with 60 px in a fixed distance of 4.69 mm to the cutting edge at the middle of the thermal image. In the thermal image the cutting edge is not visible and hidden by a shield on the right side of the image to avoid reflections of the hot tool.

Using this measurement strategy, Figure 10 shows the measured and simulated temperature during the process at the workpiece diameter of 175 mm. The results show that the two scale FEM model is a promising approach to calculate the heating of the workpiece and its thermal deformation. The agreement between predicted and measured temperatures is excellent especially when an initial flank wear of 50 µm is considered.

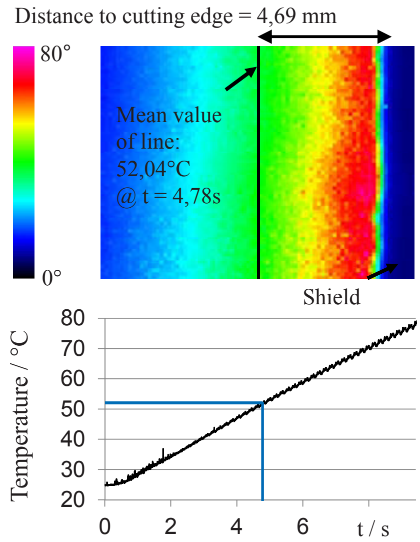

Fig. 9: Thermal Image for v_c = 150 m/min, f = 0.1 mm and t = 4.78 s and temperature history plot

In addition the results show that the microgeometry has an important effect especially at low feeds and uncut chip thicknesses. The model is able to account for the significant higher heating at lower feeds and the approach seems to be able to correctly calculate the conversion of mechanical to thermal energy due to plastic work and friction heat generation as well as its partition between the chip, tool and workpiece.

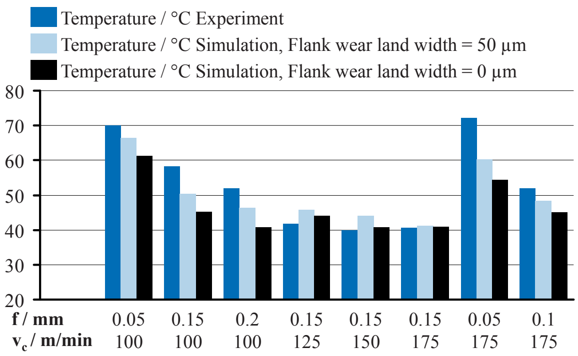

Fig. 10: Comparison of the simulated temperatures of the workpiece model and temperatures measured by thermal imaging.

3. Conclusion

A two-scale finite element model has been developed to calculate the thermal deformation of the workpiece in dry turning of AISI 1045. The approach is using a chip formation model for the calculation of the generated heat and heat partition to the chip, workpiece and tool. Subsequently, the calculated rate of heat flow into the workpiece is applied to a macroscale model that calculates the instationary temperature distribution and deformation of the whole workpiece.

In this paper the methodology has been applied for orthogonal turning of AISI1045. The validation of both models shows that the approach provides promising results. It is able to account for the thermal and mechanical effects which are related to different technological parameters of the process. The computations and experiments show, that the heating of the workpiece mainly depends on the uncut chip thickness and the microgeometry of the tool. The cutting speed has a considerable effect on the rate of heat flow into the workpiece but increased cutting speeds do not result in higher workpiece heating. The higher heat rate is overcompensated by the higher rotational speed of the workpiece which increases the partition of heat which is removed with the chip. In future works the model will be extended to 3D chip formation models to model external turning and grooving. Furthermore the heat transfer phenomena convection, radiation and heat conduction into the machine tool will be considered.

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Appendix A.

Table 2 shows the thermal properties of the steel 1045 which have been used in the chip formation and workpiece model.

Table 2: Thermal properties of AISI1045 which have been used in the two scale model [10].

Temperature / °C	Thermal conductivity / [W/(m·K)]	Volumetric heat capacity / [J/(mm³·K)]	Average co-efficient of linear expansion / K^{-1}
20	48.03	3.71	10.93
100	47.21	3.80	11.36
200	45.82	3.89	12.08
300	42.74	4.03	12.64
400	39.10	4.20	13.16
500	35.35	4.39	13.70
600	31.73	4.59	14.21
700	28.33	4.80	14.75
800	23.52	5.28	12.87
900	25.25	5.22	13.86
1000	26.61	5.17	14.74