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Compensation of thermo-mechanically induced workpiece and tool deformations during dry turning

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Abstract

Dry turning is accompanied by considerable process-induced deformations of the workpiece and the tool. Such deformations decrease the accuracy of machining. In this paper, finite element models are used in order to calculate the deformations of the workpiece and the tool regarding the cutting condition used. The correction of the depth of cut according to the calculated deformations allows for the compensation of the workpiece and tool deformations. The compensation is carried out by a computer-aided-design / computer-aided-manufacturing (CAD-CAM) approach. The results reveal a significant increase of the machining accuracy in dry turning when compensating the workpiece and tool deformations.

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Keywords: Turning; Deformation; Compensation of workpiece and tool deformation

1. Introduction

Workpiece and tool are subjected to a significant thermal load during dry turning due to the missing heat convection through a cutting fluid and the increased friction. This thermal load causes deformations of the workpiece [1] and the tool [2]. The greater the thermal load, the greater the deformations and thus the deviation from the nominal depth of cut. As a result of this deviation, shape inaccuracies occur on the manufactured workpiece [3].

The magnitude of the thermal load when dry turning a workpiece with a specific tool is primarily affected by the cutting condition used and the wear of the tool. Tool wear considerably increases the thermal workpiece and tool load [4]. The cutting speed, the feed and the depth of cut influence the amount of generated heat and the heat partitioning between the tool, the workpiece and the chips [5]. The use of adequate cutting conditions hence allows for a significant decrease of the thermal workpiece and tool load [6]. However, despite the use of an adequate cutting condition, workpiece and tool are still deformed during turning. This causes a remaining deviation between the nominal and the actual depth of cut [7]. The remaining deviation can be corrected by compensating the deformations of the workpiece and the tool through an accordingly adapted depth of cut. For this purpose, the magnitude of the deformations needs to be calculated prior to actual machining. Finite element (FE) models enable this calculation [8]. Recently, such models were developed for drilling [9], milling [10], and turning [11].

In this paper, a computer-aided-design/computer-aided-manufacturing (CAD-CAM) approach for the compensation of the deformations of the workpiece and the tool during dry turning is outlined. FE models of the workpiece and the tool are used in order to calculate their deformations regarding the cutting condition used and the feed travel. These results are used to correct the CAD-model of the workpiece according to the magnitude of the calculated deformations. The numerical control (NC)-code for the lathe, which is corrected by the deformations of the workpiece and the tool, is generated using computer-aided-manufacturing.

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2. Finite element models of the workpiece and the tool

The finite element models of the workpiece [12] and the tool [11] were already outlined in detail in prior publications of the authors. Within this paper, these models are used in order to calculate the deformations of the workpiece and the tool with regard to the cutting condition used and the feed travel (l_f). Required boundary conditions for the FE models are: the heat flow into the workpiece/tool due to turning, the heat convection with the ambient air, the heat conduction into the chuck (workpiece model), the heat conduction into the dynamometer (tool model), and the forces. The forces were experimentally determined. The thermal boundary conditions were inversely identified by means of a least square curve-fitting algorithm within the program MATLAB. For this purpose, the calculated temperature evolution is compared with the experimentally measured temperature evolution. The fitting algorithm tries to find the magnitude of each thermal boundary condition, which minimizes the residuum of the square of the difference between the calculated and the measured temperature evolution. For a detailed description of this method, we refer to [13].

The thermo-mechanical load is applied to the workpiece in the area of chip formation. A self-developed preprocessor evaluates the NC-code of the lathe to calculate the time-dependent position of the area of chip formation. The mesh is refined in order to be able to perform the removal of material using an h-adaptive mesh refinement (variation of element lengths and number of elements), whereby each hexahedral element is subdivided into eight new elements. The new nodes required are positioned exactly on the nominal tool path under consideration of the thermally and mechanically caused deformation of the workpiece. The removal of material is performed by element deactivation. The deactivation of all elements above the nominal tool path under consideration of thermal expansion and mechanical deformation thus allows for the calculation of the actual workpiece geometry after turning.

The tool model consists of all parts of the tool: the polycrystalline diamond (PCD) insert, the cemented carbide substrate and the tool holder (AISI 4140). The element edge lengths were defined according to the present temperature gradient. In the PCD, the smallest element edge lengths of 0.4 mm and near the dynamometer the largest element edge length of 10 mm were used. The heat input into the tool takes place in the contact area with the chip, which is approximated as the cross-section of undeformed chip. The thermal and mechanical loads deform the workpiece and the tool only elastic. The material behavior of the workpiece and the tool can therefore be described using linear elasticity coupled with Fourier heat conduction under consideration of the thermal expansions.

3. Experimental design

The dry turning investigations were carried out on a computerized numerical control lathe. The workpieces were clamped using a chuck-center mounting in order to reduce the workpiece deflection due to the forces (Fig. 1a).

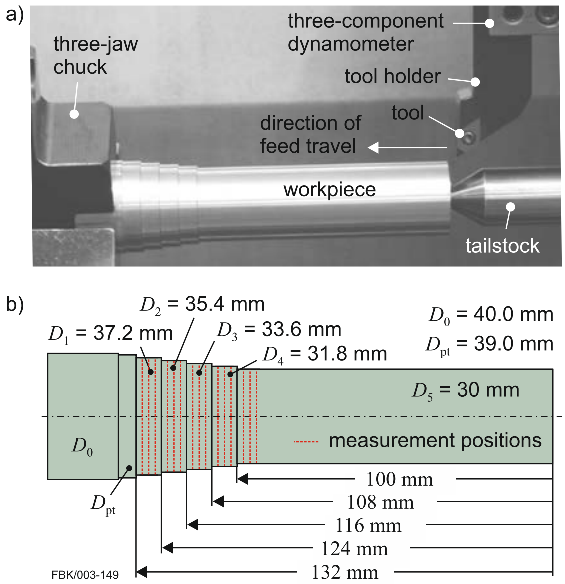

Fig. 1. (a) Experimental setup; (b) Workpiece geometry.

The tool geometry and the cutting conditions used are listed in Table 1. The cutting conditions were defined according to the prerequisite of a significant difference in the thermal load of the workpiece and the tool, and thus in their thermal expansion during turning. Each investigation was repeated three times.

Table 1. Tool geometry and cutting conditions.

Tool geometry (ISO-code DCMT 11T304)			
Clearance angle: $\alpha = 7°$	Tool cutting edge angle: $\kappa = 93°$		
Rake angle: $\gamma = 0°$	Tool cutting edge inclination: $\lambda = 0°$		
Cutting edge radius: $r_\beta = 12$ µm	Corner radius: $r_\varepsilon = 0.4$ mm		
Cutting conditions	1	2	3
Cutting speed [m/min]:	$v_{c1} = 100$	$v_{c2} = 200$	$v_{c3} = 300$
Depth of cut [mm]:	$a_{p1} = 0.9$	$a_{p2} = 0.9$	$a_{p3} = 0.9$
Feed [mm/rev]:	$f_1 = 0.1$	$f_2 = 0.2$	$f_3 = 0.3$

The workpiece material used was the aluminum alloy Al 2024, which is a common material for automotive and aerospace applications. Each workpiece was pre-turned to a diameter of D_{pt} = 39 mm. The workpiece has five different nominal diameters D_1 - D_5 (Fig. 1b) in order to be able to measure the actual workpiece diameter after each tool engagement. The diameter is measured using a coordinate measuring machine. Three measurements were carried out at each nominal diameter (Fig. 1b). The mean of these three measurements was calculated to evaluate the respective actual diameter.

The diameter deviation is the result of the subtraction of the nominal diameter D_i from the respectively determined actual diameter D_i^{act}. Generally, the diameter deviation d_i is affected by multiple factors of influence, such as the machine tool properties, phase transformations in the workpiece, or tool wear. However, most of these factors of influence are approximately constant at each tool engagement. On the contrary, the temperature of the workpiece and the tool and thus their thermal expansion varies at each tool engagement. Moreover, the deflection of the workpiece differs slightly due to the decreasing workpiece diameter. The difference in the diameter deviation d_i between individual tool engagements however represents primarily the change in the thermal expansion of the workpiece and the tool. For the experimental evaluation of these thermal expansions, we introduced in [13] the normalized diameter deviation d_i^{norm}. The normalized diameter deviation is calculated by subtracting the diameter deviation after tool engagement i (i = 1…5) from the diameter deviation after tool engagement 1.

4. Compensation of calculated thermo-mechanically induced workpiece and tool deformations

The CAD-model of the workpiece is modified according to the calculated deformations (using the FE models) of the workpiece and the tool in order to compensate these deformations when dry turning. The CAD-model is designed using multiple grid points (Fig. 2). The distance between consecutive grid points is 1 mm. The contour of the workpiece between the grid points is interpolated linearly.

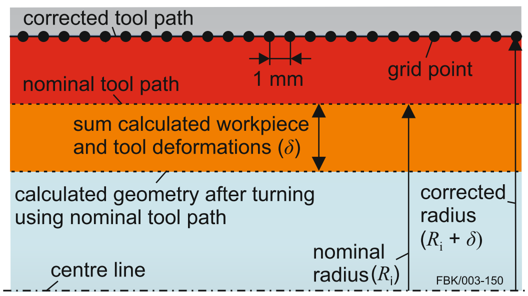

Fig. 2. CAD-model of a workpiece section.

The deformation of the workpiece and the tool varies along the feed travel due to the varying stiffness of the system machine tool-workpiece along l_f, the temperature gradient in the workpiece and the increasing tool temperature with rising l_f. The workpiece and tool deformation therefore needs to be evaluated in the FE models with regard to the feed travel. The evaluation positions match the positions of the grid points in the CAD-model of the workpiece. The evaluation of the workpiece deformation in the FE model is carried out on the element nodes. The element edge length (1 mm) in axial direction is therefore defined regarding the distance between the grid points. The radial element length (0.9 mm) matches the depth of cut. The deformation of the tool is calculated in terms of the time of tool engagement. This time-dependent deformation is related to the respective evaluation position using the NC-code of the lathe. The radial position of each grid point is displaced according to the sum of the calculated workpiece and tool deformations in order to compensate these deformations. The corrected radial position of each grid point of the workpiece CAD-model is allocated to the CAD-CAM software (NX) as tabular data. The CAD-software positions each grid point according to the allocated information.

The direction of the grid point displacement (i.e. an increase or decrease of the nominal workpiece radius) depends on the influence of the deformations on the depth of cut. Thermal expansions of the workpiece and the tool during turning cause, contrary to mechanically induced deflections, a greater actual depth of cut a_{pa} than nominal depth of cut a_p. Superior thermal effects thus require a rise of the nominal radius in order to compensate the workpiece and tool deformations (Fig. 2). In the present case, thermal effects are superior. The change in depth of cut due to the correction can influence the arising thermal and mechanical loads. However, the measurements revealed a negligible influence of the change in depth of cut on the loads.

The NC-code required for the lathe to manufacture the intended workpiece geometry (Fig. 1b) is generated using CAM. The use of CAM allows for the correction of the NC-code at each nominal diameter, and thus the actual depth of cut by the sum of the calculated deformations.

5. Results

The normalized diameter deviation when compensating and not compensating the deformations of the workpiece and the tool are depicted in the Figures 3-5 with regard to the cutting condition used and the nominal workpiece diameter.

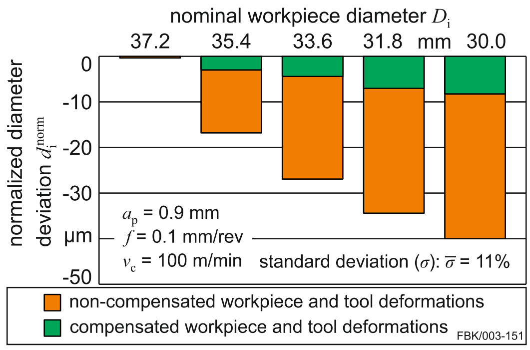

Fig. 3. Comparison of the normalized diameter deviation d_i^{norm} when compensating and non-compensating the workpiece and tool deformations.

The compensation of the thermal expansions of the workpiece and the tool allows for a significant increase of the machining accuracy (Fig. 3-5). In particular, at low cutting speeds or feeds a considerable improvement of the machining accuracy was observed because workpiece and tool undergo at such cutting conditions a significant thermal load [7]. The percentage reduction of the normalized diameter deviation however does not depend on the magnitude of the thermal load. The normalized diameter deviation decreases at the present workpiece geometry approximately 85% at the first tool engagement (D_1 = 37.2 mm) and approximately 80% at the last tool engagement (D_5 = 30.0 mm). The reduction of d_i^{norm} by 85% due to the compensation results at the present workpiece geometry in a remaining normalized diameter deviation close to zero microns. Considering the smallest turned nominal diameter D_5, the remaining normalized diameter deviations are in the range from 4 µm (Fig. 5) to 8 µm (Fig. 3).

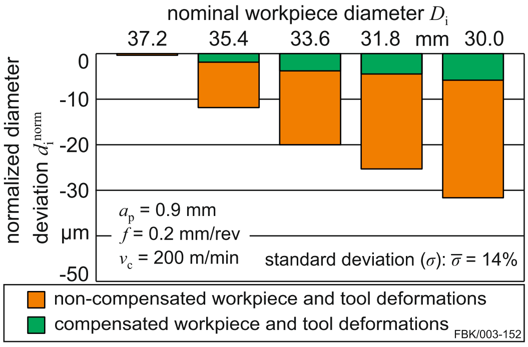

Fig. 4. Comparison of the normalized diameter deviation d_i^{norm} when compensating and non-compensating the workpiece and tool deformations.

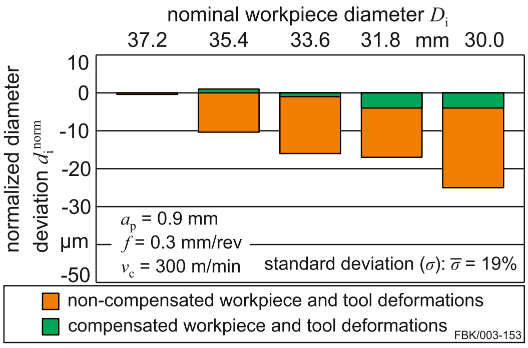

Fig. 5. Comparison of the normalized diameter deviation d_i^{norm} when compensating and non-compensating the workpiece and tool deformations.

The compensation of the deformations of the workpiece and the tool through an accordingly adapted depth of cut is subjected to numerical and experimental uncertainties. Experimental uncertainties are for example the formation of built-up edges (particularly at low cutting speeds), positioning inaccuracies of the machine tool or measurement uncertainties. Such uncertainties cannot be considered in the FE models; they are represented by the standard deviation. A least square curve-fitting algorithm compared the measured and calculated temperature evolutions and determined the boundary conditions required for the FE models. The slight uncertainties in the determination of the heat flow into the workpiece and the tool, and more strongly the heat flow to the environment are nevertheless the primarily numerical uncertainties. Inaccuracies in the boundary conditions for the tool have a more significant effect on the predicted temperature because of the considerably higher tool than workpiece temperature. The numerical uncertainties at a specific tool engagement are the sum of each prior tool engagement. Thus, the uncertainty of the predicted temperature and hence the remaining d_i^{norm} slightly increases with each tool engagement. d_i^{norm} also rises when not compensating the deformations. This is due to the increasing workpiece and tool temperature with each tool engagement and the accordingly rising deformations.

6. Conclusion and outlook

In this paper, a CAD-CAM approach to compensate the workpiece and tool deformations during dry turning was outlined. The deformations were calculated using a FE model for each component. The calculated deformations were allocated to the CAD-CAM software in order to generate a corrected NC-code for the lathe. The machining accuracy is significantly improved when compensating the workpiece and the tool deformations. However, the multiple further effects influencing the machining accuracy impede the achievement of an ideal workpiece geometry. Future work will be the use of the presented approach at other workpiece geometries and the further enhancement of the approach.

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