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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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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).

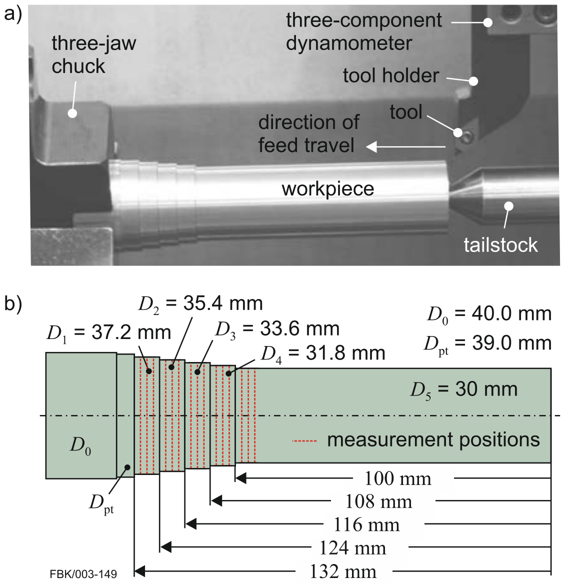

Fig. 1. (a) Experimental setup; (b) Workpiece geometry.

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