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Improving performance of turn-milling by controlling forces and thermally induced tool-center point (TCP) displacement

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Abstract

Improving performance during fine turn-milling operations including accuracy and productivity requires controlling of *the cutting forces* and the thermally induced displacement of the cutting edge. The objective of this investigation is to determine the thermally induced displacement of TCP during turn-milling and to reduce this displacement by using pressurized cooled air. The forces and tool elongation simulated by FEM are compared to measured values. It was shown that the amount of tool elongation could be 40% of the depth of cut in fine turn-milling, and it is possible to predict the tool elongation by FEM. Furthermore, cooled air can reduce the tool elongation by 65%.

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1. Introduction

High performance cutting aims at providing precise dimensional accuracy and high quality of the machined part while maintaining high material removal rates, lower tool wear and high efficiency. Besides static and dynamic properties of cutting operations, heat generation is an important parameter that affects the accuracy and the quality of the machined part [1]. Heat generation in machining operations is caused by two mechanisms: severe plastic deformation and friction. As a result most of the power consumed is converted into heat, which in turn causes significant increase in cutting temperature [2]. It is known that continuous cutting with constant parameters produces higher cutting temperatures than intermittent cutting [3]. Therefore, turn-milling using a multi-edge tool can be a solution for reducing temperatures in turning operations. Turn-milling is an intermittent cutting process which is basically a turning operation with a milling tool providing higher removal rates. This unique kinematics provides heating and cooling cycles and the cutting temperatures tend to be lower compared to conventional turning operations.

Reduction and compensation of thermally induced displacements are significantly important regarding product quality and machining accuracy. Thermally induced displacements can be caused by the environment or internal heat sources [4]. However, they can also be caused by the process itself. In this case it is essential to model cutting temperatures in order to simulate the thermally induced displacements. There are various attempts found in literature, including numerical and analytical solutions to simulate the cutting temperatures. Proposed analytical models generally cover orthogonal cutting process [5]. However, the interrupted turn-milling process is more complex and requires the problem to be solved as a function of time. Few models concerning interrupted cutting processes were published in the past years. Stephenson used Green’s functions to solve the three-dimensional conduction problem and found that cutting temperatures are lower in intermittent cutting than those in continuous cutting [3]. Radulescu and Kapoor developed an

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analytical model which includes time-dependent heat fluxes and the effect of convection in interrupted cutting [6].

This study presents a thermo-mechanical model and experimental validation for predicting thermally induced displacements in fine turn-milling operations. Additionally, the study proposes a cooling strategy to reduce the thermal displacements during cutting operations. The paper is organized as follows: The details of proposed process model are given in Section 2. The experimental study to validate the process model and to reduce thermal displacements is presented in Section 3. In Section 4, results are given and a discussion is made on obtained results. In Section 5 the conclusions are summarized. Moreover it is indicated that while performing fine turn- milling operations it is essential to take into account the thermally induced TCP because the amount of displacement could be up to 40% of given depth of cut that affects the machining accuracy. Furthermore it is shown that these displacement values can be predicted by simulations and could be reduced by using appropriate cooling techniques.

2. Modeling of turn-milling operation

2.1. Proposed process model for turn-milling operation

In this study thermally induced TCP displacement during turn-milling operations is simulated by developing a thermo-mechanical model. The model includes 3D FEM analysis combined with analytical and mechanistical tools. Cutting forces are evaluated using the mechanistical approach which takes into account uncut chip geometry and calibrated cutting coefficients. By means of cutting forces, generated heat input on the tool-chip interface is calculated for one revolution of the milling tool. Then the heat flux related to the generated heat is applied to the cutting edge and the transient heat conduction problem is solved by using commercial FE code (MSC. MARC) for the whole tool geometry, including heating and cooling cycles which are described in detail in Section 2.4. Finally the displacement values of TCP are determined and compared to those obtained by experiments.

2.2. Uncut chip geometry and cutting forces

The basic kinematics of the turn-milling process is shown in Fig.1. The main forces acting on the tool are the cutting force F_c and the axial force F_a. The forces can be used to determine the heat flux and the cutting temperatures during machining operations. In turn-milling, unlike in conventional turning operations, the uncut chip geometry varies with time, which results in periodic forces during the process. Fig. 2 shows the uncut chip geometry and the variation of the axial force as a function of tool position.

The first step in process modeling of the turn-milling operation is to determine the uncut chip geometry in a detailed area of a specific case of turn-milling, as shown in Fig. 2. W is the width of the workpiece to be removed. The eccentricity (e), which is the distance between tool and workpiece, is determined according to length of cutting edge and has a significant effect on the contact length between workpiece and the cutting insert. In orthogonal turn-milling, which is applied in this study, chips are formed by both the bottom and the side cutting edge of the tool [7]. However, in this study the chip is formed only at the bottom of the tool due to the low depth of cut (fine turn-milling) and selected eccentricity value.

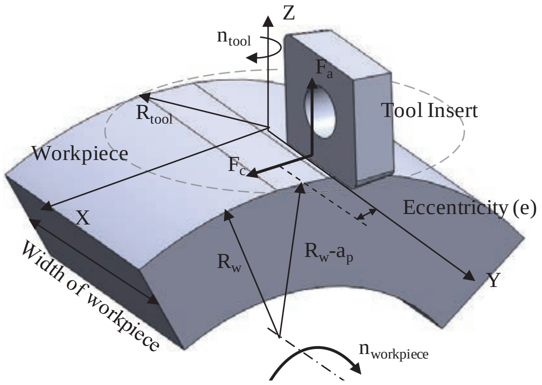

Fig. 1. Geometry and kinematics of turn-milling operation.

The boundaries of the uncut chip geometry are defined by points x_1, x_2 and x_3. The angle θ between the lines x_1x_2 and x_1x_3 is expressed as:

$$\theta = \frac{2\pi}{m \cdot r_n} \tag{1}$$

with m as the number of cutting teeth and r_n as the ratio of tool revolution (n_{tool}) to workpiece revolution ($n_{workpiece}$).

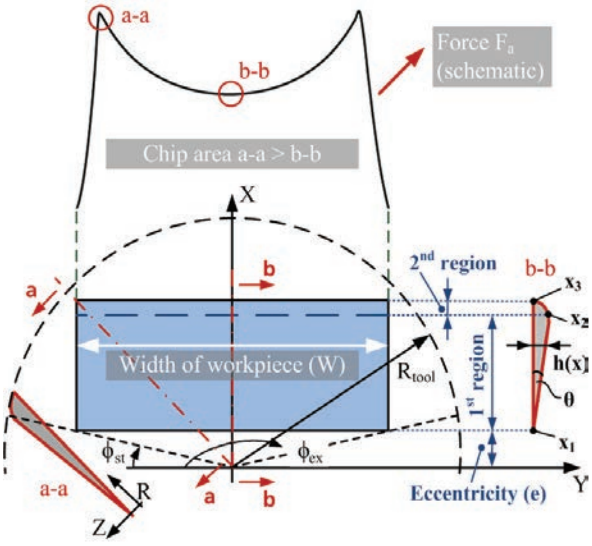

Fig. 2. Uncut chip geometry for cutting force calculation.

The chip thickness $h(x)$, shown in Fig. 2, varies along X direction. There are two different regions for $h(x)$. In the first region (Fig. 2), $h(x)$ can be expressed as:

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