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Experimental Study and Modeling of Steady State Temperature Distributions in Coated Cemented Carbide Tools in Turning

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Abstract

Plastic deformation of the tool is one of the most important wear modes in metal cutting, especially in continuous cutting operations. Since the strength of the tool material depends strongly on the temperature, a correct temperature distribution in the cutting edge is of key importance for the prediction of plastic deformation of the cutting edge. The temperature distribution in coated cemented carbide cutting tools is investigated using experimental techniques (IR-CCD) and finite element analysis. CVD-coated cemented carbide inserts are tested in continuous turning of quenched and tempered steel (AISI 4340). Cutting forces and edge temperature distributions are measured in 2D orthogonal turning. Finite element simulations of orthogonal turning of AISI 4340 steel with CVD coated cemented carbide inserts are performed. The simulation results are used to predict steady state temperature distribution in tool by performing further coupled thermo-mechanical finite element simulations. Different methods of heat source on tool rake face are used. It is observed that steady state temperature distribution from simulation matches well with experimental result.

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Keywords: Cemented carbide; compressive strength; turning; plastic deformation; temperature; metal cutting; finite element.

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1. Introduction

Due to the high cost involved in obtaining machining data experimentally, there are strong motivations for development of methodologies for description of different machinability phenomena using a numerical approach. The temperature in the cutting zone plays a key role in practically all aspects of machinability and in particular for tool wear. The plastic deformation of tools is one of the most important wear modes in metal cutting.

In the case of modeling plastic deformation, knowledge of high temperature strength of the tool material together with stresses acting on the tool and the temperature distributions inside the tool tip are crucial. The strength of the cemented carbide depends strongly on temperature [1, 2], a dependency that increases with increasing temperature. Due to the strong influence of temperature on the strength of cemented carbide, small errors in predicted temperature will have a large effect on the predicted edge deformation of the cutting edge. In an earlier work [3], an attempt was made to model the plastic deformation. The boundary conditions (normal stresses and temperature distributions) were based on experimental results.

Simulation of the actual metal cutting and chip formation process is very time consuming, even with modern software packages and computers. The saturation of the tool-chip interface temperature is typically reached after a few milliseconds [4]. However, further development of steady state temperature distribution in the tool interior is a more sluggish process which requires several seconds of machining, corresponding to several meters of cutting length, which is practically impossible to simulate. Instead, steady state heat transfer analysis, e.g. using finite element method, can be employed in order to estimate the steady state distributions in tool interior.

In this work an attempt is made to predict tool temperature distribution numerically using 2D Finite Element (FE) methods. AdvantEdge [5], a dedicated FE solver for metal cutting is used to simulate orthogonal turning. The results from these simulations are used further to perform steady state

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heat transfer analysis using MSC Marc [6]. Different heat input data are used in the analysis.

Tool temperature distributions at steady state are measured using the IR-CCD technique. In case of worn tool, flank land, which is gradually developed during plastic deformation of the tool, has a strong effect on the temperature in the tool tip. Based on the results for un-deformed tool, an attempt was also made to predict steady state temperature distribution in the case of tool with a flank land.

2. Experiment

2.1. Tool materials

A fine-grained WC-10wt%Co alloy is examined in this study (WC grain size 1µm, hardness HV31620). The cemented carbide is of commercial grade, manufactured by standard production processes, i.e., pressing, sintering, edge treatment and finally deposition of a wear-resistant CVD coating. The coating consists of an inner MTCVD Ti(C, N) coating, an intermediate alumina coating and an outer, thin TiN coating, exhibiting a total thickness of 7 µm. Thermal properties for the cemented carbide are presented in Table 1.

Table 1. Thermal conductivity for the cemented carbide (W/m ^{O}C).

Temperature	25^{O}C	800^{O}C	900^{O}C	1000^{O}C	1100^{O}C
Conductivity	87.0	64.4	63.11	62.3	62.0

2.2. Turning tests

The cutting conditions are characterized by dry machining conditions (no coolant), high feed and a relatively high depth of cut (Table 2). The insert styles used in the turning tests is TNMA220416 (rake angle -6^{o}, clearance angle 6^{o}) with a flat rake face. Because the edge radius is known to affect the tool performance, inserts with a measured edge radius within a narrow range, approximately 40 µm, are used in the experiments.

Table 2. Turning test data.

Cutting speed (*m/min*)	Feed (*mm/rev*)	Depth of cut (*mm*)	Coolant
155-200	0.5	3.5	No

The machining tests include firstly regular longitudinal turning, with engagement of the tool corner, where the development of the flank land is monitored. Inserts with different machining times and different flank land in the range 0.3-0.5mm are produced and used in subsequent measurement of cutting forces and tool temperature.

Secondly, short time turning of a thin walled tube with wall thickness of 3.5mm is performed where cutting forces and edge temperature are measured. In these tests, the nose region of the insert is not engaged. Only the main edge is used for cutting. This set-up is chosen so that 2D conditions prevail along the main edge which corresponds to the 2D FE simulation of the cutting process.

The workpiece material involve quenched and tempered AISI4340 steel (Table 3) with improved machinability. The choice of workpiece material contributes to low tool wear and lack of interference from wear phenomena during tests.

Table 3. Properties of AISI 4340 steel.

Hardness HBN	YTS (*MPa*)	UTS (*MPa*)
290	810-880	950-1010

2.3. Measurement of cutting forces

The cutting forces are measured in orthogonal cutting directions using a Kistler type 5019A three-component force sensor. The force measurements are performed over the speed range of 155-200 m/min for negative TNMA tool geometry for new and worn inserts. Cutting forces are measured in a different set-up than the tool temperature measurement set-up.

2.4. Measurement of tool temperature distributions

The tool temperature distribution is measured during the orthogonal cutting of workpiece tube specimens using the near infrared charge-coupled device (IR-CCD) technique and the set-up developed in a previous investigation [7]. The experimental details, calibration procedure, error estimation and measured emissivity for cemented carbide also are presented in [7].

This CCD-sensor-based near-infrared (850-1100 nm) imaging technique covers a temperature range of 500°C-1000°C, and the suitable calibration of this method enables the measurement of the tool temperature with reasonably good accuracy (±10-15°C) and spatial resolution (~4.5 µm). Figure 1 depicts typical set-up used for temperature measurement.

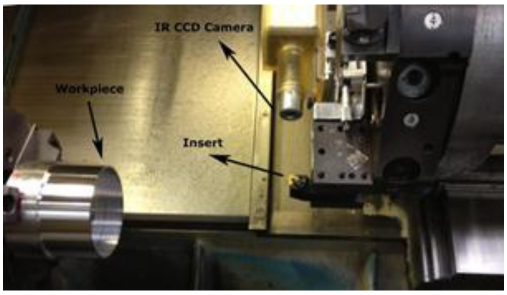

Fig. 1. Set-up for temperature measurement.

The inserts used in the tests are ground and polished on their lateral face prior to cutting and temperature measurements, to facilitate the observation of cutting zone. Only short-duration tests (~15 s) are carried out to limit the problems that could arise from the oxidation of the tool surface, which may become significant at longer cutting times.