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## Finite element modelling of temperature distribution in the cutting zone in turning processes with differently coated tools

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**Abstract:** The aim of this study is to create a FEM simulation model in order to obtain numerical solutions of the cutting forces, specific cutting energy and adequate temperatures occurring at different points through the chip/tool contact region and the coating/substrate boundary for a range of coated tool materials and defined cutting conditions. Commercial explicit finite element code Thirdwave Advant Edge [1] has been used in simulations of orthogonal cutting processes performed by means of uncoated carbide and coated tools. The latter were equipped with progressively increasing number of thin layers including TiC, TiN and Al<sub>2</sub>O<sub>3</sub> films deposited onto ISO P20 carbide substrates. Results showing how the tool-chip interfacial friction influences the temperature distribution fields as the effect of using coated tools are the main and novel findings of this paper. The various thermal simulation results obtained were compared with the measurements of the average interfacial temperature and discussed in terms of various literature data.

**Keywords:** Finite element simulation; Tool coating; Cutting temperature distribution

### 1. INTRODUCTION

For the past fifty years metal cutting researchers have developed many modelling techniques including analytical techniques, slip-line solutions, empirical approaches and finite element techniques. In recent years, the finite element method has particularly become the main tool for simulating metal cutting processes [2, 3]. Finite element models are widely used for calculating the stress, strain, strain-rate and temperature distributions in the primary, secondary and tertiary sub-cutting zones. In consequence, temperatures in the tool, chip and workpiece, as well as cutting forces, plastic deformation (shear angles and chip thickness), chip formation and possibly its breaking can be determined faster than using costly and time consuming experiments.

It is specially important that FEM analysis can help to investigate some thermodynamical effects occurring in the cutting zone which, as so far, cannot be measured directly [3]. An example for such effects is the influence of cutting tool coatings on the heat transfer and friction, and resulting cutting temperature distribution in the chip and the tool.

It should be noted that the majority of previous orthogonal metal cutting simulations is devoted to uncoated carbide tools and now the opposite trend to consider single and multiply

coatings has been observed [3-5]. In fact, the first completed work focusing on the evaluation of a predictive orthogonal cutting model for coated carbide tools with multiple coating layers using the FEM was presented by Yen et al [3]. The main finding from this simulation was that for AISI 1045 steel the predicted steady-state interface temperatures are in good agreement with the experimental values given in Ref. [6] within 5-11% difference.

## 2. FINITE ELEMENT MODELLING

### 2.1. Description of the simulation model

In this paper, a Lagrangian finite element code *AdvantEdge* was also applied to construct a coupled thermo-mechanical finite element model of plane-strain orthogonal metal cutting with continuous chip formation produced by plane-faced uncoated and differently coated carbide tools. The entire cutting process is simulated, i.e. from the initial to the steady state phase. The workpiece material of choice, AISI 1045 carbon steel, is modeled as thermo-elastic-plastic, while the flow stress is considered to be a function of strain, strain-rate and temperature to represent better the real behaviour in cutting. Friction between the tool and chip is of Coulomb type with the  $\mu$  value of 0.5.

The initial arrangement of both the workpiece and the tool in the simulation model is shown in Fig. 1a. In simulations with Thirdwave AdvantEdge the initial mesh becomes distorted after a certain length of cut as shown in Fig. 1b and is remeshed in this vicinity to form a regular mesh again. There is no separation criterion defined and then chip formation is assumed to be due to plastic flow. Therefore, the chip is formed by continuously remeshing the workpiece.

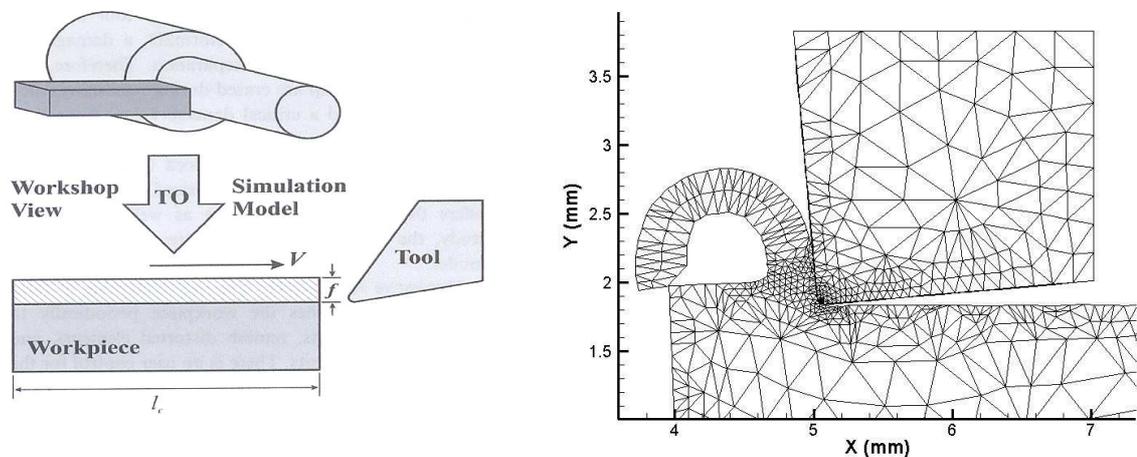


Figure 1. Simulation model of the turning process used (a) and shape of the deformed chip after a tool path of 4.0 mm with cutting edge radius of 33  $\mu\text{m}$  and 1460 nodes(b).

### 2.2. Cutting conditions

The tool geometry and the cutting conditions used for the orthogonal metal cutting simulation are presented in Table 1.

## 3. RESULTS AND DISCUSSION

In general, numerical simulations of the heat partitioning in the cutting zone including the tool and the chip were carried out for constant cutting parameters, i.e. cutting speed of 103.2 m/min, feed rate of 0.16 mm/rev and depth of cut of 2 mm.

Table 1  
Cutting conditions and tool geometry

Tool rake angle ( $^{\circ}$ )	-5	Width of cut (mm)	2.0
Tool clearance angle ( $^{\circ}$ )	5	Cutting speed (m/min)	103.2
Measured cutting edge radius ( $\mu\text{m}$ )	17-33	Coulomb friction coefficient	0.5
Undeformed chip thickness (mm)	0.16	Type of cutting tool: P20 uncoated: coated with TiC; TiC/TiN and TiC/Al <sub>2</sub> O <sub>3</sub> /TiN	

### 3.1. Intensity of heat sources

It can be concluded based on cutting simulations that the average intensity of heat source (the volumetric specific cutting energy) ranges in all cases approximately from  $e_c = 7000\text{--}9000 \text{ W/mm}^3$ . It was also observed that the heat rate increases in the vicinity of the cutting edge and changes for the cutting tool materials used. The minimum value of  $e_c$  equal to  $17742 \text{ W/mm}^3$  was computed for a P20 uncoated carbide, whereas the maximum one of  $38494 \text{ W/mm}^3$  was obtained for a single TiC layer.

### 3.2. Isotherm patterns in the cutting zone

The temperature distribution in the workpiece, tool and chip after a tool path of 4.0 mm, is shown in Fig. 2. In order to compare the differences in the isotherm images for uncoated and coated tools this figure illustrates the magnified temperature distribution in the vicinity of the cutting edge.

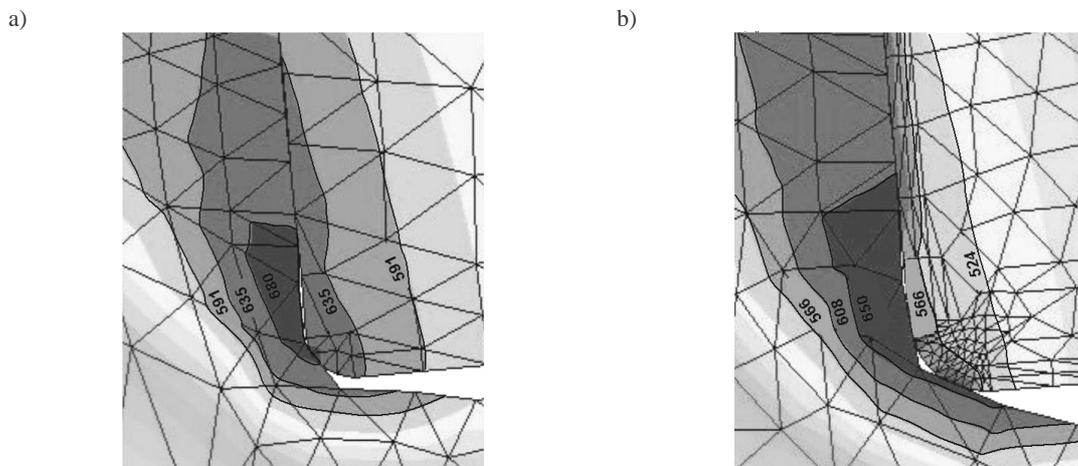


Figure 2. Contour plots of the temperature rise in the vicinity of the cutting edge for P20 uncoated carbide (a) and TiC/Al<sub>2</sub>O<sub>3</sub>/TiN coated carbide (b).

It can be observed that more heat is transferred to the chip and workpiece and areas with the maximum temperatures are localized near the chip and workpiece. In consequence, the maximum interface temperature exists in the vicinity of the cutting edge. i.e. in the first part of the tool-chip contact. This effect is especially visible for the three-layer TiC/Al<sub>2</sub>O<sub>3</sub>/TiN coating as shown in Fig. 2b. Also the substrate is cooler in comparison to uncoated tools and other tools coated with TiC and TiC/TiN layers. This is due to the fact that the thermal conductivity of Al<sub>2</sub>O<sub>3</sub> ceramic layer in the TiC/Al<sub>2</sub>O<sub>3</sub>/TiN coating decreases distinctly and at higher contact temperatures the carbide substrate is partly thermally insulated by the coating.

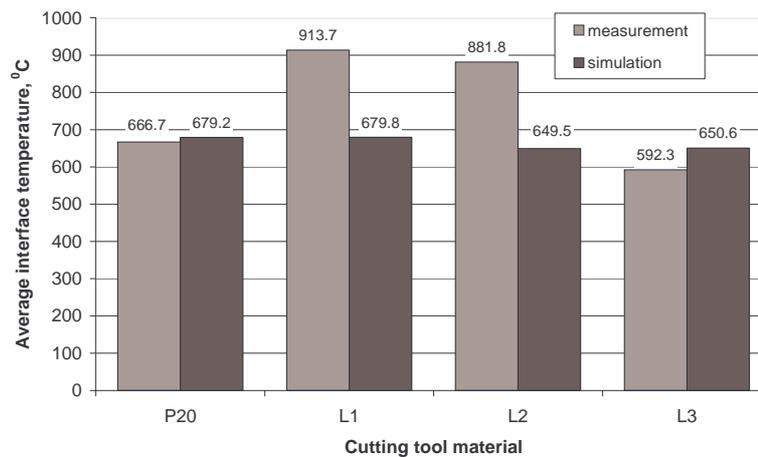


Figure 3. Comparison between measured and computed values of the average interface temperature. Work material: C 45 steel, cutting parameters: cutting speed  $v_c=103.2$  m/min, feed rate  $f=0.16$  mm/rev. Symbols: L1-TiC, L2-TiC/TiN, L3-TiC/Al<sub>2</sub>O<sub>3</sub>/TiN

The validation between measured and computed values of the average tool-chip interface temperature is presented in Fig. 3. Maximum discrepancies observed for TiC and TiC/TiN coated tools are equal to 25 and 26 % respectively. For TiC/Al<sub>2</sub>O<sub>3</sub>/TiN coating this divergence was found to be about 10%, and for uncoated tools it was less than 2%.

#### 4. CONCLUSION

The finite element simulations performed demonstrate the existence and localization of the secondary shear zone.

A good agreement was achieved, especially for uncoated and three-layer coated tools, between predicted and experimental values of cutting temperatures.

It was documented that coatings cause that areas with the maximum temperatures are localized near the chip and workpiece. In consequence, the maximum interface temperature exists in the vicinity of the cutting edge. i.e. in the first part of the tool-chip contact. Also the substrate is distinctly cooler in comparison to uncoated tools.

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