Numerical Modeling for the Calculation of Temperatures in Multiple Coated Tools

Andrew Otieno
College of Engineering and Engineering Technology
Northern Illinois University
otieno@ceet.niu.edu

Toshiyuki Obikawa and Kazuaki Kamio
Institute of Industrial Science
The University of Tokyo
Japan

Abstract

Machining applications in the past were carried out by uncoated tools due to the fact that surface coating technology was still advancing. Today, with the development of advanced coatings and lower cost of producing coated tools, between 80 and 85 percent of inserts are coated. Coatings provide needed high-temperature wear resistance and better heat transfer, allowing for higher cutting speeds to be achieved with minimal use of coolants, thus increasing machining productivity. The influence of heat in machining, however, still remains a major concern. Even with coatings, tools may still fail due to thermally-activated softening or may experience increased wear through thermally-activated conditions. It is therefore important to be able to determine machining temperatures as accurately as possible. This paper reports a numerical approach to the determination of temperatures in the high-speed machining of aluminum 6061-T6 alloy. Two types of tools are considered. The first has a K10 carbide substrate with layers of TiCN, Al_2O_3, and HfO_2, with diamond-like compound (DLC) as the outer coating. The second has a substrate of Al_2O_3, with a layer of HfO_2 and TiN as the outside coating. The multiple coatings have been modeled as composite layers. AdvantagEdge™ finite element software has been utilized to calculate the temperature distributions in the tool and work material. Results compare well with experiments. The composite approach is seen to offer a more realistic calculation of the tool temperature distribution.

Introduction

In the past, most machining processes were carried out with uncoated tools due to lack of coating technology. It was not until the late 1960s that CVD coated tools appeared in the market. Today, with the development of advanced coatings and the lower cost of producing coated tools, between 80 and 85 percent of tools are coated [1]. In the later years, tools with multiple coatings were introduced. Coatings provide much needed high-temperature wear resistance and better heat transfer. This allows for much higher cutting speeds to be achieved with minimal use of coolants, thus increasing machining productivity.

ISBN 978-1-60643-379-9

The influence of heat in machining, however, still remains a major concern. Even with coatings, tools may still fail due to thermally-activated softening or may experience increased wear through thermally-activated conditions. It is therefore important to be able to determine machining temperatures as accurately as possible.

Machining research has produced many analytical and numerical solutions for temperature determination in the cutting zone. Available literature suggests that more research has been carried out for the case of uncoated tools. This could be attributed to two reasons. A coating added to a substrate complicates the thermal treatment by adding more boundary conditions between materials with different properties. Secondly, it has been difficult to obtain data for thermal properties for hard coatings. Available data have shown wide variations, and either have been based on approximations from previous tests or have been provided by manufacturers based on room-temperature tests [2, 3]. For these reasons, a more rigorous treatment is needed for coated tools.

A more recent approach for modeling of multiple coated tools has been to treat the coatings as a composite layer [2, 4]. This allows for the thermal effects of each layer to be adequately accounted for and can further provide insights into the thermodynamics occurring around the interfaces of the coatings. This section of the report focuses on the analytical determination of cutting temperatures with TFT tools, utilizing the finite element method. It proposes a composite approach for multiple coatings to determine the initial thermal properties of the tool.

Theory

To compute temperatures accurately, thermal properties such as thermal conductivity, heat capacity, and heat transfer coefficient need to be known. For the case of an insert, it will be assumed in this treatment that heat transfer occurs mainly by conduction from the cutting zone. The composite approach therefore seeks to find an effective thermal conductivity that represents the heat conduction of the coated carbide. To begin, we consider the basic heat flow equation for 1-D conduction through a medium of thickness *t*, as shown in Figure 1 below.

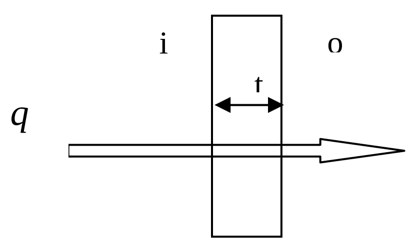

Figure 1: 1-D heat conduction

The 1-D conduction equation can be expressed as [5]

$$q = kA\frac{(\theta_o - \theta_i)}{t}, \quad (1)$$

where q is the rate of heat flow, k is the thermal conductivity, A is the cross-sectional area across which the heat conduction takes place, and t is the thickness of the conducting media. The subscripts i and o denote temperatures for interfaces i and o respectively. This equation can be re-written as follows:

$$q = A\frac{(\theta_o - \theta_i)}{\left(\frac{t}{k}\right)} \quad \ldots\ldots(2)$$

When two or more media exist, as shown in Figure 2, the heat conduction equation, following equation (2), can be re-written as follows [4, 5]:

$$q = A\frac{(\theta_o - \theta_i)}{\left(\frac{t_1}{k_1}\right) + \left(\frac{t_2}{k_2}\right) + \bullet\bullet + \left(\frac{t_n}{k_n}\right)}, \quad \ldots\ldots(3)$$

where k_1 through k_n are the thermal conductivities of the materials 1 to n that form the 1-D composite.

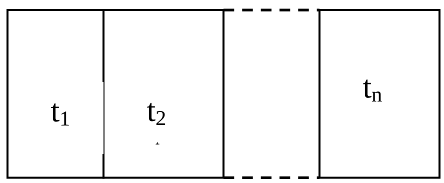

Figure 2: Composite conducting material

The denominator represents an equivalent conductivity term, k_{eq}, and the equation can now be re-written as

$$\frac{\sum_1^n t_i}{k_{eq}} = \frac{t_1}{k_1} + \frac{t_2}{k_2} + \cdots + \frac{t_n}{k_n} \quad \ldots\ldots(4)$$

It is seen from the above equation that when the thickness of a substrate is very large compared to the coatings, the effective conductivity approaches that of the substrate. The section below illustrates this effect for various cases.

Calculation of Effective Conductivity for Multiple Coated Tools

Two types of tools have been considered. The first has a K10 carbide substrate with layers of TiCN, Al_2O_3, and HfO_2, with diamond-like compound (DLC) as the outer coating. The second has a substrate of Al_2O_3, with a layer of HfO_2 and TiN as the outside coating. These tools have been fabricated and tested with Aluminum 6061 T6 [6, 7]. Thermal properties (shown in Table 1 and Table 3) have been obtained from a number of sources [8–11]. Calculations for the conductivities of the individual coatings and the effective conductivities are shown in Table 2 and Table 4. Figure 3 and Figure 4 are plots of the conductivities against temperature.

Table 1: DLC coated tool

Function	Material	Thickness	Thermal conductivity W/(m·K)
Substrate	Al_2O_3	4.7×10^{-3} m	$40.00 - 0.049510\theta + 0.00001703\theta^2$
Coating 1	HfO_2	2.15×10^{-6} m	1.66222
Coating 2	DLC	1.0×10^{-6} m	10.0

Table 2: Conductivity calculations for DLC coated tool

Temperature (K)	0	200	400	600	800	1000	1200	1400
Substrate conductivity (W/m·K)	40	30.78	22.92	16.42	11.3	7.52	5.11	4.06
Hafnium conductivity (W/m·K)	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Protective coating (DLC) conductivity (W/m·K)	10	10	10	10	10	10	10	10
Effective conductivity (W/m·K)	39.56	30.52	22.78	16.36	11.3	7.51	5.11	4.06

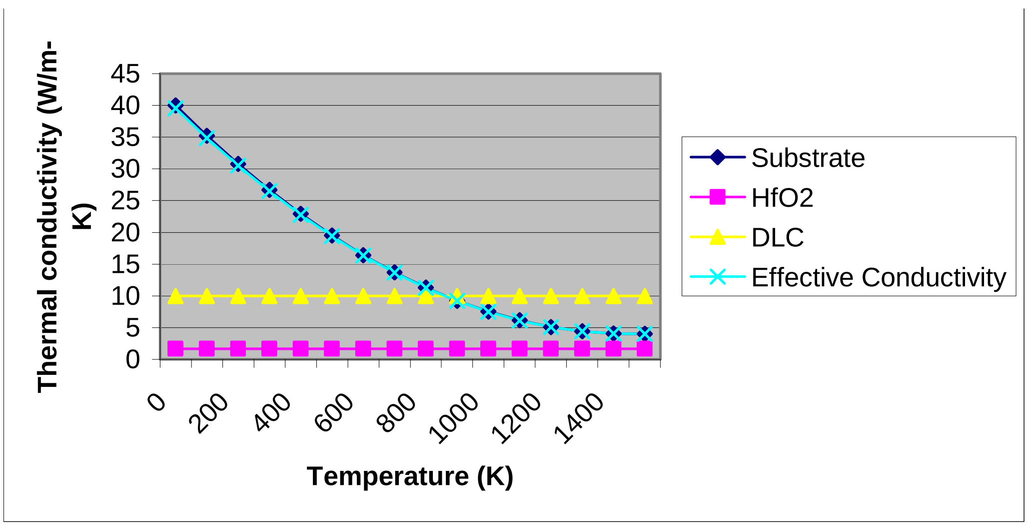

Figure 3: Effective conductivity for DLC coated tool

Table 3: TiN coated tool

Function	Material	Thickness	Thermal conductivity W/(m·K)
Substrate	Al_2O_3	4.7×10^{-3} m	$40.00 - 0.049510\theta + 0.00001703\theta^2$
Coating 1	HfO_2	6.0×10^{-6} m	1.662222
Coating 2	TiN	3.0×10^{-6} m	$25.21 + 0.001270\theta - 0.00000029\theta^2$

Table 4: Conductivity calculations for TiN coated tool

Temperature (K)	0	200	400	600	800	1000	1200	1400
Eff. Conductivity (W/m·K)	38.84	30.10	22.55	16.24	11.2	7.49	5.10	4.06

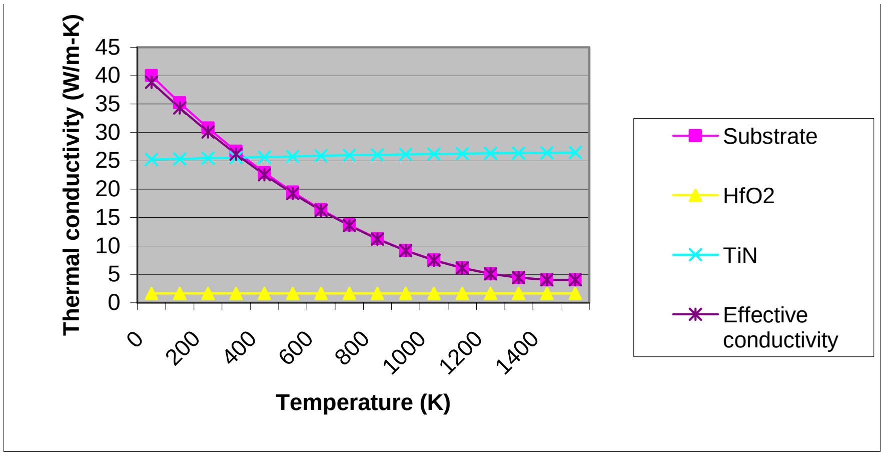

Figure 4: Effective conductivity for TiN coated tool

Finite Element Simulations for Temperature Calculation for TiN Coated Tool

The standard finite element analysis for temperature calculation involves solving the steady-state heat conduction equation, which for a 2-D case is given by

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\rho C_p\left(u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}\right)+\dot{Q}=0 \text{ , ...(5)}$$

where T is the temperature, C_p is the heat capacity, and Q is the heat generation. The boundary conditions are given as follows:

i) $T=T_\infty$ (the ambient temperature) at the edge and center of work away from the cutting zone.

ii) the temperature gradient normal to the chip-tool interface is given by $-k\frac{\partial T}{\partial n} = h(T - T_i)$, where h is the heat transfer coefficient at the interface, having a temperature T_i.
iii) the temperature gradient normal to the machined surface is given by $-k\frac{\partial T}{\partial n} = h_\infty(T - T_\infty)$, with h_∞ being the heat transfer coefficient representing heat loss to the atmosphere immediately after the cutting zone.
iv) the temperature gradient in the axial direction after the cutting interface is zero; i.e., $-k\frac{\partial T}{\partial n} = 0$.

FEM simulations were carried out using the same cutting conditions as in reference [7] with a negative 5° rake angle. The tool was modeled with coatings as a composite material shown below in Figure 5. AdvantEdge FEM software has been utilized for the analysis. The composite model below is chosen because the FEM software has features that allow for the meshing of coatings with the substrate, thus enabling a model with predictable boundary conditions. Details of the mesh are shown in Figure 6.

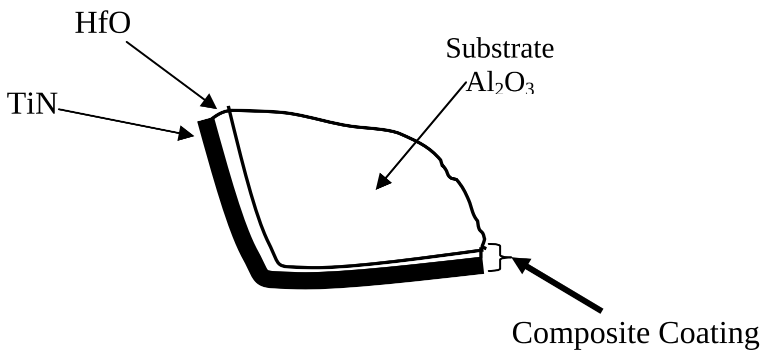

Figure 5: Composite model of the multiple coatings

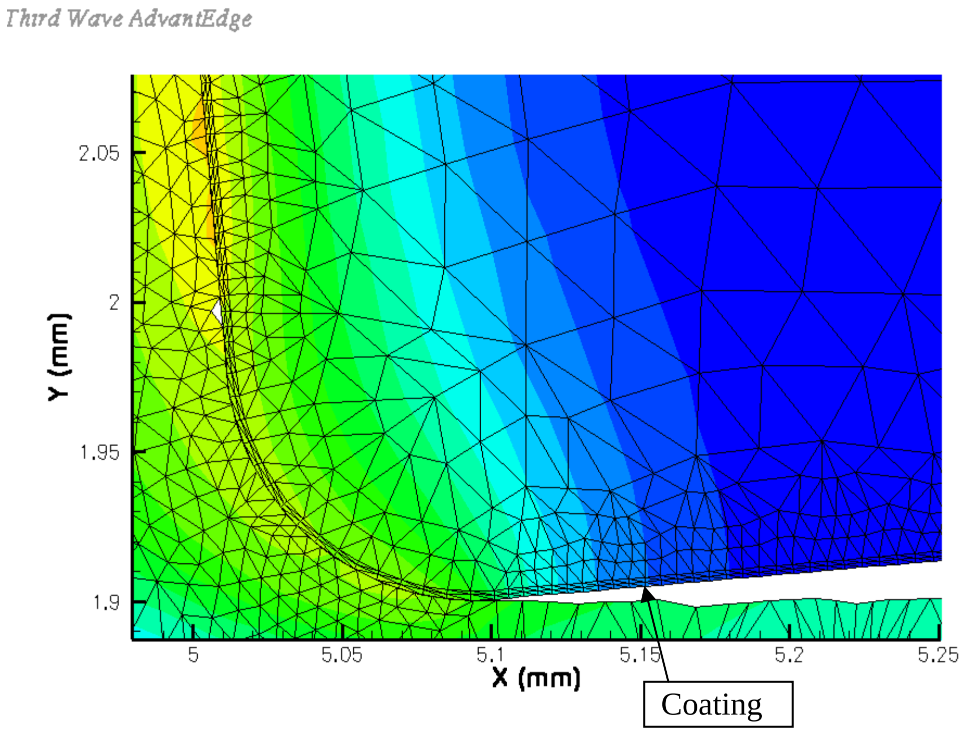

Figure 6: Tool substrate and composite coating mesh

The table below shows the results of the simulation. The comparison between experiment and simulation is shown in Figure 7 through Figure 13.

Table 5: FEM simulation results for TiN coated tool

Results of FEM simulation with TiN coating						
Workpiece – Al 6061 T6; Tool – CNMG 120408; feed – 0.1 mm/rev; width of cut – 1.0 mm						
V (m/sec)	F_c (N)	F_t (N)	Chip contact length (mm)	Chip thickness (mm)	Shear angle (deg)	Peak tool temperature (K)
5	119.1	98.5	0.385	0.340	19.1	658
8	107.4	82.8	0.266	0.244	21.0	704
10	103.6	81.4	0..290	0.242	19.0	728
12	102.8	80.2	0.278	0.196	18.1	745
14	101.4	75.0	0.260	0.207	20.9	768
16	100.1	78.0	0.202	0.203	19.2	780

Below are some comparisons of experiments [7] and FEM Advantage simulations.

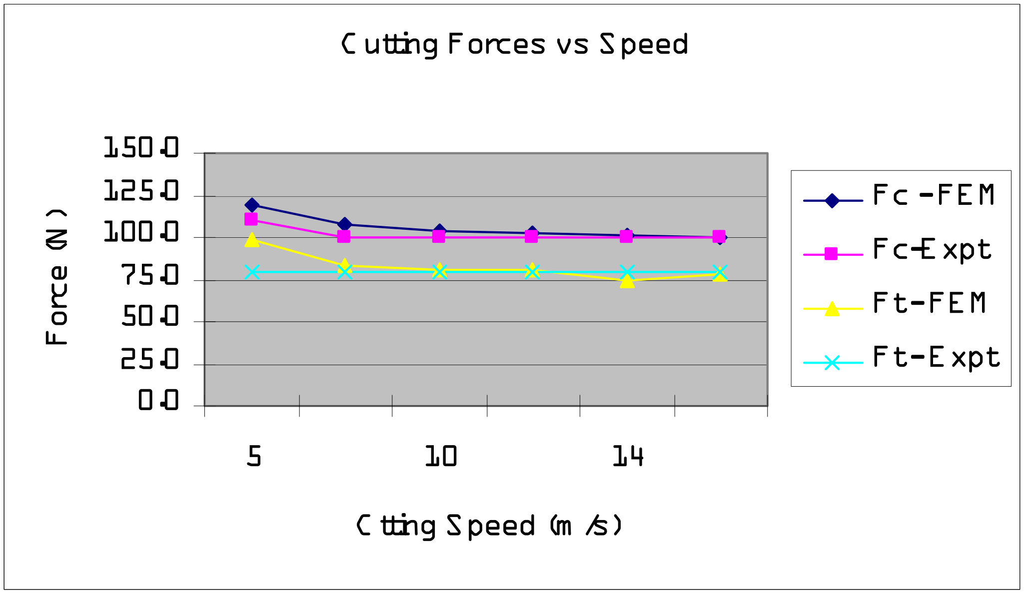

Figure 7: Comparison of simulation and experiment – cutting forces vs. cutting speed

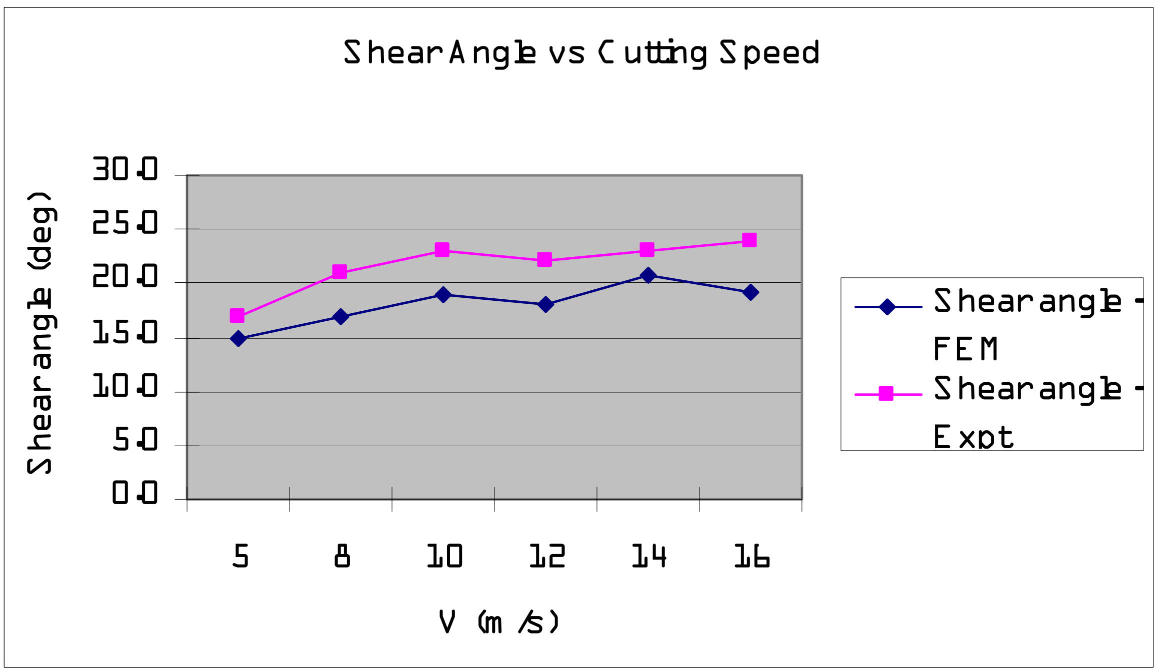

Figure 8: Shear angle vs. cutting speed

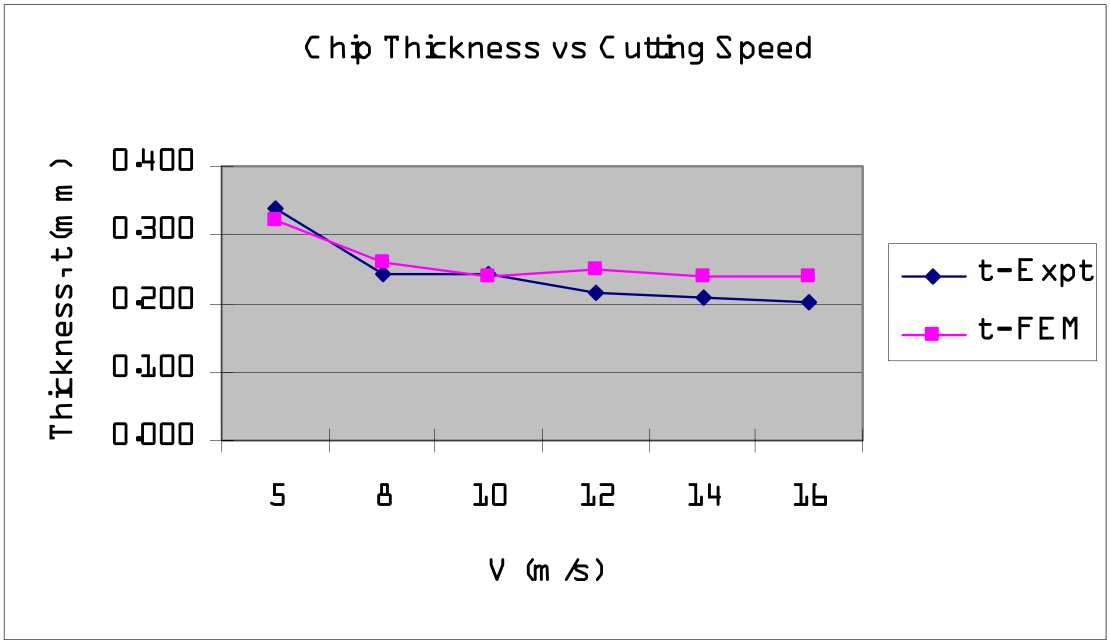

Figure 9: Chip thickness vs. cutting speed

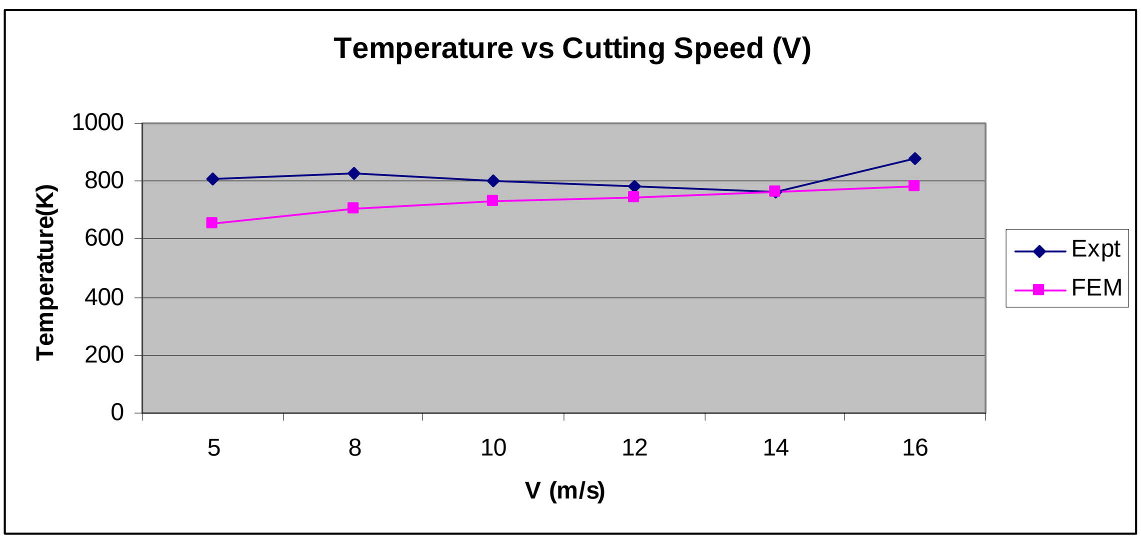

Figure 10: Peak tool temperature vs. cutting speed

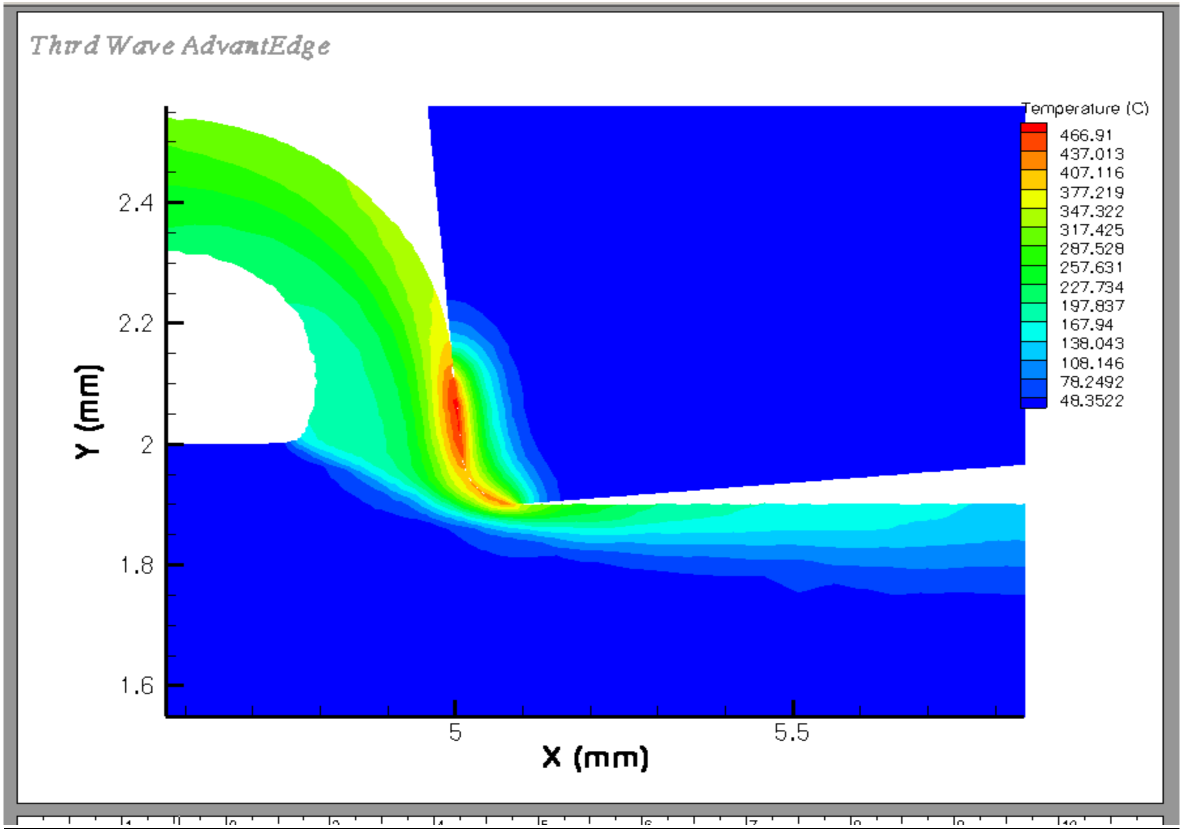

Figure 11: Temperature distribution at V = 16 m/s

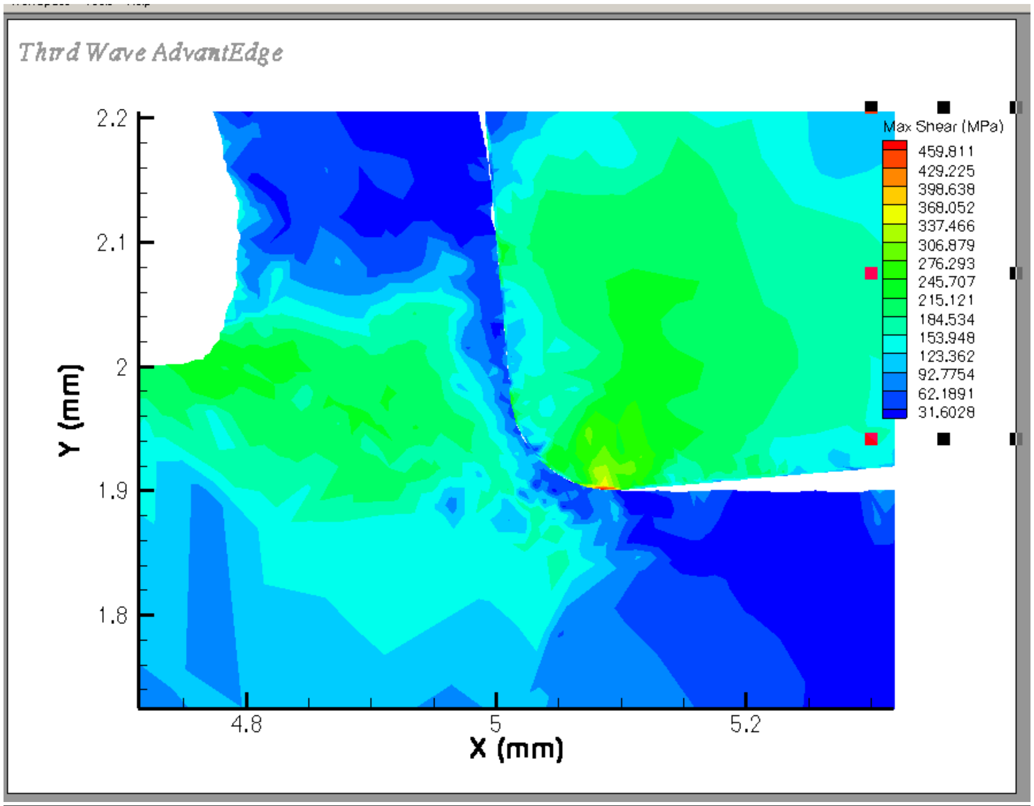

Figure 12: Shear stress distribution at $V = 16$ m/s

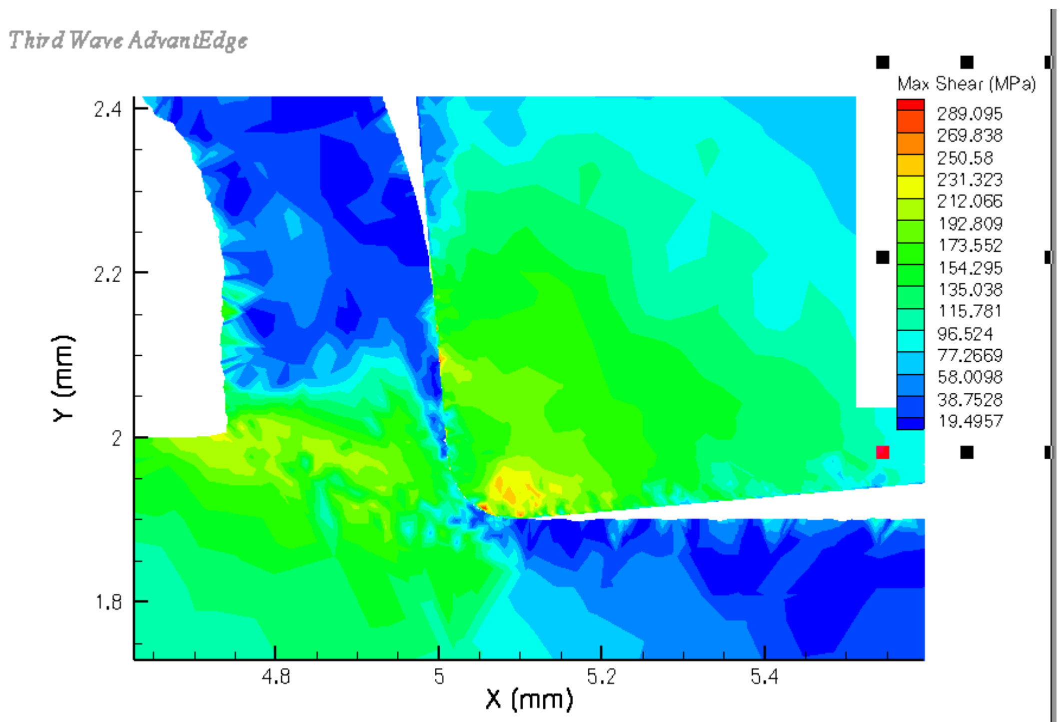

Figure 13: Shear stress distribution at $V = 8$ m/s

Concluding Remarks

The results from the finite element analysis show the following:

a) A fairly good agreement between force, temperature and shear angle at higher cutting speeds.
b) An overall agreement between FEM and the experiment for the chip thickness values.
c) At lower cutting speeds, there seems to be a high discrepancy between the calculation and experiment (possibly because effects of friction or work hardening and thermal softening are not adequately accounted for).
d) The average computed shear stress (from Childs et al. [3]) at V = 16 m/s is 226 MPa. This is in agreement with the FEM calculations (see Figure 12). At a lower speed, V = 8 m/s, the shear stress is 230 MPa, which also agrees well with the FEM calculation (Figure 13).

The apparent consistency of the FEM, experiment, and manual calculations suggests that the composite approach for determining thermal characteristics of the multiple coatings provides a better approximation for temperature calculation. These results also reiterate the viability of multiple tools as temperature measuring devices, especially in machining applications.

References

[1] Cutting Tool Engineering "50 years of technological development" Vol. 57, No. 8, 2005; online: http://www.ctemag.com/pdf/2005/0508-50anniversary.pdf.

[2] Yen, Y.C.; Jain, A.; Chigurupati, P.; Wu, W.T.; and Altan, T. "Computer simulation of orthogonal cutting using a tool with multiple coatings," *Machining Science and Technology*, Vol. 8, No. 2, 2004, pp. 305–326.

[3] Childs, T.H.C., Maekawa, K., Obikawa, T. and Yamane, Y. "Metal machining — theory and applications," Arnold, Co-published by John Wiley & Sons Inc., 2000, pp. 101–112.

[4] Grzesik, W. "Composite layer-based analytical models for tool-chip interface temperatures in machining medium carbon steels with multi-layer coated cutting tools," *Journal of Materials Processing Technology*, Vol. 176, 2006, pp. 102–110.

[5] Patankar, S.V. "Numerical heat transfer and fluid flow," McGraw-Hill co., 1980, pp. 43–51.

[6] Kamio, K.; Obikawa, T.; Basti, A.; Shinozuka, J.; and Kamata, Y. "Development of a DLC-coated tool with thin film thermocouples," Proceedings of the 4th International Conference on Leading Edge Manufacturing in 21st Century, Fukuoka, Japan, Nov. 7–9, 2007.

[7] Basti, A.; Obikawa, T.; and Shinozuka, J. "Tools with built-in thin film thermocouple sensors for monitoring cutting temperature," *International Journal of Machine Tools & Manufacture*, Vol. 47, No. 5, 2007, pp. 793–798.

[8] Basti, A. "Development of cutting tools with built-in thin film thermocouples for measuring cutting temperature," Unpublished Ph.D. thesis, Department of

Mechanical and Control Engineering, Tokyo Institute of Technology, Tokyo, Japan, 2006, pp. 190–195.

[9] Cutting tool engineering, http://www.ctemag.com/dynamic.articles.php?id=179).

[10] National Institute of Standards and Technology, NIST Structural Ceramics Database, http://www.ceramics.nist.gov/srd/summary/scdaos.htm.

[11] Majumdar, P.; Jayaramachandran, R; and Ganesan, S. "Finite element analysis of temperature rise in metal cutting processes," *Applied Thermal Engineering*, Vol. 25, 2005, pp. 2152–2168.

Acknowledgements

This work was carried out while the author was on sabbatical leave at the Institute of Industrial Science, the University of Tokyo. The author would like to thank Prof. Toshiyuki Obikawa for the support throughout this project. Support from the entire research team at Obikawa laboratory is also hereby acknowledged. They include Dr. Yatsuhiro Kamata, research associate at Obikawa laboratory, and graduate students Kazuaki Kamio, Yuki Asano, and Tomomi Hakutani, who were very helpful in many ways.

Biography

Andrew Otieno is an associate professor in the Department of Technology at NIU. He has done extensive research in experimental and theoretical analysis of machining problems, including environmentally friendly manufacturing processes. His research and teaching interests include machine vision, materials and manufacturing processes, finite element analysis, and manufacturing automation.

Toshiyuki Obikawa is a professor in the Mechanical Engineering and Biofunctional Systems, Institute of Industrial Science (IIS), Tokyo University. He is also the Director of the Laboratory for Fine Machining and Fabrication Systems at ISS in the Komaba Research campus of Tokyo University. Prof. Obikawa's research interests include echo-machining, incremental microforming, and the development of thin-film thermocouple tools.

Kazuaki Kamio is a graduate student at Tokyo Institute of Technology and is currently attached to the Fine Machining and Fabrication Systems Laboratory at ISS. His research is in the area of thin-film thermocouple tools.