TRANSIENT CONVECTION-DIFFUSION MODELLING OF PEAK TEMPERATURE IN ORTHOGONAL CUTTING

T. J. Burns[1,4*], S. P. Mates[2,4], R. L. Rhorer[3,4], E. P. Whitenton[3,4] & D. Basak[5]

[1]Information Technology Laboratory; [2]Material Measurement Laboratory; [3]Engineering Laboratory
[4]National Institute of Standards and Technology[†], Gaithersburg, Maryland 20899, USA
[5]Orbital Sciences Corporation, Dulles, Virginia 20166, USA

Summary Numerical finite-difference simulations of a two-dimensional transient fast convection-slow diffusion model of the temperature field in orthogonal cutting, due to Tlusty, have been shown to provide better predictions of the peak temperature during orthogonal cutting of AISI 1045 steel, than a commercial finite-element method (FEM) code that uses a conventional Johnson-Cook model for the material constitutive response. An analysis of the simpler Tlusty model is used to argue that the reason it gives better predictions than the FEM code is that the material has a stiffer response to shearing forces, under the conditions of rapid heating, high temperature, and high rate of deformation that are present in high-speed machining, than the response that is measured using conventional pre-heating methods, prior to compression testing, to obtain the constitutive response. Some recent experimental data from the NIST Pulse-Heated Kolsky Bar Laboratory are presented to support this hypothesis.

INTRODUCTION

During high-speed machining of many materials, high temperatures are generated in the primary shearing region and in a region along the tool-chip interface. In a simplified planar orthogonal cutting model that is still widely used in the literature (see, e.g., Tlusty [1]), the workpiece material enters a thin cutting region called the primary shear zone at temperature T_0, where it is deformed by rapid plastic shearing, and is heated to a much higher temperature, T_s. The bulk of the heat generated in the primary shear zone is rapidly convected away from the workpiece, along with the chip of removed material is that is being formed. Some of this heat is also conducted into the tool and into the workpiece material. The material continues to deform and rapidly increase in temperature as it moves up the face of the tool, under conditions of large frictional forces, in a region called the secondary shear zone; see Figure 1. Experimental measurements indicate that the maximum temperature, T_m, occurs along the interface between the chip and the tool, near the region where the chip begins to curl away and lose contact with the tool. There is also a large transfer of heat away from this secondary deformation zone, mainly by convection along with the chip, but also by conduction away from the contact region. This high temperature environment can cause rapid tool wear. Thus, there is considerable interest in obtaining a good estimate of the peak temperature, T_m, under realistic cutting conditions.

PEAK TEMPERATURE PREDICTIONS

Peak temperature predictions using state of the art finite-element (FEM) software have been found to underestimate the temperature in orthogonal cutting of AISI 1045 steel by as much as 33% [2]. Two likely reasons for this poor predictive capability are the following. The first is that the Johnson-Cook constitutive model for the shear stress in the work material that is frequently used in the simulations, due to Jaspers and Dautzenberg [3], which is composed of the product of three terms, corresponding to strain hardening, strain-rate hardening, and thermal softening, respectively, underestimates the true shear stress during machining. The second is that the usual Coulomb friction model that is used in the FEM software to simulate the friction along the tool-chip interface is inadequate.

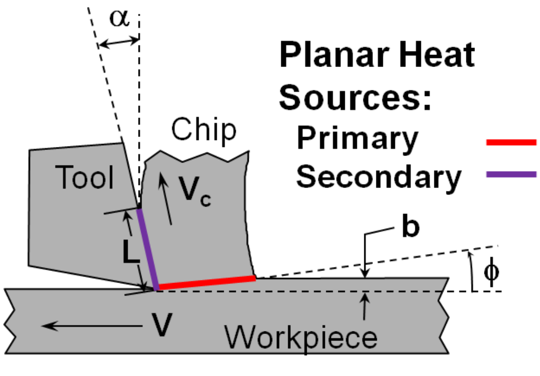

Figure 1 Schematic drawing of orthogonal cutting process. The first region of large heat generation during high-speed machining is in the primary shear zone, indicated in red, and the second region of large heat generation is in the secondary shear zone along the tool-material contact region of length L, indicated in purple.

TLUSTY'S MODEL

What is interesting is that a simplified two-dimensional transient fast convection-slow diffusion model of the temperature field,

---

[*]Corresponding author. Email: burns@nist.gov**.**
[†]Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

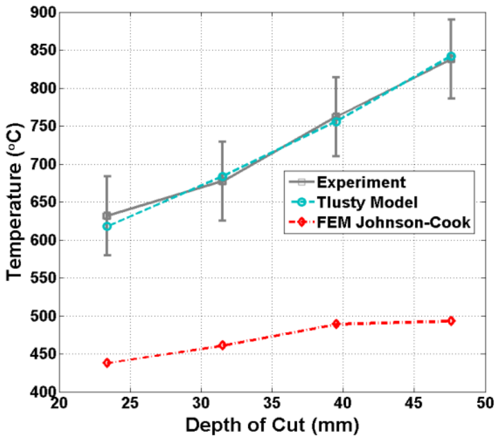

Figure 2 Comparison finite-difference prediction of peak temperature along tool-chip interface (circles) and finite-element prediction using Johnson-Cook model (diamonds) with experimental measurements (squares).

$$\frac{\partial T}{\partial t}+\frac{\partial T}{\partial x}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right),\qquad \alpha=\frac{k}{V_c\rho c L},\qquad \alpha<<1, \qquad (1)$$

due to Tlusty [1], with appropriate initial and boundary values, has been shown to give much better predictions of the peak temperature along the tool-workpiece interface in AISI 1045 steel [4]; see Figure 2. This model builds on earlier work of a number of researchers, in particular Weiner [5], Rapier [6], Boothroyd [7], and Yellowley and co-workers [8]. Here, k is the thermal conductivity, ρ is the density, and c is the specific heat; the x-axis corresponds to the secondary shear line in Figure 1, and the y-axis corresponds the the primary shear line. Tlusty ignored the strain hardening, strain-rate hardening, and thermal softening in the material, and instead made the simplifying assumption that the temperature on the primary shear plane is a constant, T_s, that is determined by the friction angle, the shear plane angle, and the specific cutting energy K_s, of the AISI 1045 steel, but is independent of the cutting speed, at least to a first approximation. In the secondary shear zone, Tlusty assumed that the friction power can be modeled by a constant value in a sticking region over a distance of half of the uncut chip thickness b from the tooltip. This constant value also depends on the specific cutting energy K_s and the friction angle, but not on the strain, strain rate, or temperature in the material. The friction power over the remainder of the contact length L, which Tlusty set equal to four times the uncut chip thickness b, was then assumed to decrease linearly to zero.

DISCUSSION

An analysis of Tlusty's model suggests the following hypothesis. It outperformed the finite-element simulations using the Johnson-Cook material model for AISI 1045 of Jaspers and Dautzenberg, because the material has a stiffer response, i.e., less thermal softening, than was measured by Jaspers and Dautzenberg using their experimental testing system, in which the material sample was pre-heated to the testing temperature much more slowly than occurs during a high-speed machining operation, prior to rapid loading of the sample in compression. Thus, for the experimental measurements that were used by Jaspers and Dautzenberg to fit their Johnson-Cook model, there was enough time for significant microstructural changes to occur in the material, leading to considerable thermal softening. On the other hand, during a high-speed machining operation on AISI 1045 steel, the time spent in the primary and secondary shear zones is insufficient for as much internal structural change to occur in this material, so that it does not exhibit as much thermal-softening behavior under the extreme deformation conditions which are present. Recently, we have reported on some new experimental data on AISI 1045 and AISI 1075 steel, from the NIST Pulse-Heated Kolsky Bar Laboratory [9], that support this hypothesis; see [10,11]. In these tests, the material sample was pre-heated to high temperature much more rapidly, prior to compression, than it was in the tests performed by Jaspers and Dautzenberg [3].

References

[1] Tlusty, J.: Manufacturing Processes and Equipment, Prentice-Hall, Upper Saddle River, NJ, 2000.

[2] Davies, M. A., Cao, Q., Cooke, A. L., and Ivester, R.: On the Measurement and Prediction of Temperature Fields in Machining AISI 1045 Steel, Annals of the CIRP **52**/1:77-80, 2003.

[3] Jaspers, S. P. F. C., and Dautzenberg, J. H.: Material Behaviour in Conditions Similar to Metal Cutting: Flow Stress in the Primary Shear Zone, Journal of Materials Processing Technology, **122**: 322-330, 2002.

[4] Davies, M. A., Yoon, H., Schmitz, T. L., Burns, T. J., and Kennedy, M. D.: Calibrated Thermal Microscopy of the Tool-Chip Interface in Machining, Machining Science & Technology **7**/2:166-190, 2003.

[5] Weiner, J.H.: Shear Plane Temperature Distribution in Orthogonal Cutting, Trans. ASME, **77**:1331-1341, 1955.

[6] Rapier, A.C.: A Theoretical Investigation of the Temperature Distribution in the Metal Cutting Process, British J. Appl. Physics, **5**/11:400-405, 1954.

[7] Boothroyd, G.: Temperatures in Orthogonal Metal Cutting, Proc. IME, **177**/29:789-802, 1963.

[8] Buryta, D., Sowerby, R., Yellowley, I.: Stress Distributions on the Rake Face During Orthogonal Machining, Int. J. Mach. Tools Manufact., **345**:721-739, 1994.

[9] Mates, S. P., Rhorer, R. L., Whitenton, E. P., Burns, T. J., and Basak, D.: A Pulse-Heated Kolsky Bar Technique for Measuring Flow Stress of Metals Subjected to High Loading and Heating Rates, Experimental Mechanics, **48**:799-807, 2008.

[10] Burns, T. J., Mates, S. P., Rhorer, R. L., Whitenton, E. P., and Basak, D.: Dynamic Properties for Modeling and Simulation of Machining: Effect of Pearlite to Austenite Phase Transition on Flow Stress in AISI 1075 Steel, Machining Science & Technology, **15**:1–20, 2011.

[11] Burns, T. J., Mates, S. P., Rhorer, R. L., Whitenton, E. P., and Basak, D.: On Modeling the Peak Temperature on the Tool-Chip Interface during High-Speed Machining of AISI 1045 Steel, submitted for publication.