MODELING OF THE TEMPERATURE FIELD IN THE CHIP AND IN THE TOOL IN HIGH-SPEED MACHINING OF A CARBON STEEL: EFFECT OF PEARLITE TO AUSTENITE PHASE TRANSITION IN AISI 1075

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

[1]National Institute of Standards and Technology[†], Gaithersburg, MD, USA
[2]Orbital Sciences Corporation, Dulles, VA, USA
[3]St. Olaf College, Northfield, MN, USA

ABSTRACT: A one-dimensional transient finite-difference model for the temperature distribution in orthogonal metal cutting, which was originally developed by Boothroyd, and then improved upon by Tlusty, is used to calculate the temperature field in the chip and in the tool in orthogonal cutting of AISI 1075 steel. In a series of compression tests using the NIST pulse-heated Kolsky bar, a phase transformation from pearlite to austenite was observed to take place within a few seconds near the eutectoid temperature (723 ºC) of the material. At temperatures above the transformation temperature in this material, which had been heat treated so that it had uniform pearlitic microstructure prior to testing, a large decrease in flow stress of approximately 50 % was observed. It is shown how the predicted peak temperature along the chip-tool interface on the rake face decreases when this decrease in material strength is incorporated into a Johnson-Cook constitutive response model for the material.

KEYWORDS: high-speed machining, modeling, Johnson-Cook, AISI 1075 steel

1 INTRODUCTION

High-speed metal machining processes can cause extremely rapid heating of the work material. If this material is a carbon steel, a small region of the workpiece is deformed plastically in the primary shear zone to a strain on the order of 200 %, at a strain rate on the order of 10^4 s^{-1}, on a time interval on the order of ten microseconds. In this region, the work material undergoes a change in temperature from ambient (~ 20 ºC) to a maximum on the order of magnitude of several hundred degrees Celsius. Subsequently, for a time on the order of a millisecond, the highly compressed material rubs along the interface between the tool and the work piece, with the result that it undergoes additional large plastic deformation, accompanied by a further large increase in temperature due to friction. Peak temperature of the work material along the tool rake face can approach 1000 ºC, which is a significant fraction of the melting temperature of the material (see, e.g., Tlusty [1]). Thus, in a fairly routine cutting operation on a modern machining center, a heating rate on the order of one million degrees Celsius per second is not uncommon for iron-carbon alloys of interest in manufacturing.

These extreme conditions pose a challenge for the measurement and modeling of the constitutive response of such materials for use in computer simulations of machining operations, and there continues to be a need for improved models. An important point that has been emphasized by Childs [2] is that, during high-speed metal machining, there is insufficient time for the microstructure of the work material to reach thermal equilibrium. Practically speaking, this means that it is unlikely that there is sufficient time for thermal softening mechanisms to have much effect in the primary shear zone, so that the material is likely to have a stiffer response than is predicted using standard constitutive response measurement techniques (Figure 1).

A well-established apparatus for the testing of materials at high strain rates is the split-Hopkinson pressure bar (SHPB), also called the Kolsky bar (see, e.g., [3,4]). To study the mechanical response of metals at high temperatures, a number of techniques have been developed for pre-heating a sample prior to impact testing in a Kolsky bar. At the National Institute of Standards and Technology (NIST), a unique SHPB facility has been in operation for several years, in which the strength of metals can be measured under conditions of rapid DC pulse-heating, followed by rapid loading. The flow stress can be measured in samples that have

* Corresponding author: Mail Stop 8910, 100 Bureau Drive, Gaithersburg, MD 20899-8910, USA, Phone: 301-975-3806, Fax: 301-975-3553, email: burns@nist.gov

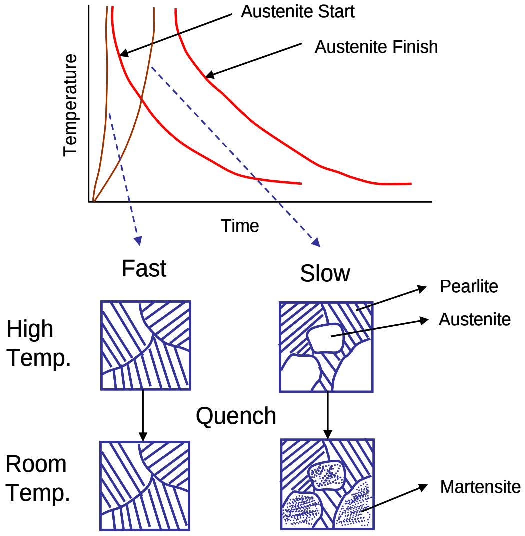

***Figure 1**: The mechanical properties of carbon steel at high temperature depend upon the rate of heating and the time at temperature, because the metallurgical phases present in the microstructure depend upon the heat treatment history; less austenite is present at high temperature when heating is sufficiently rapid*

been pre-heated to uniform temperatures of up to 1200 ºC, at heating rates of up to 6000 ºC s^{-1}, and then dynamically loaded at strain rates up to the order of 10^4 s^{-1} (Mates, et al. [3]).

In recent work (Burns, et al. [5]), pulse-heated compression test results on AISI 1075 steel were observed, in which a nonequilibrium phase transformation from pearlite to austenite took place within just a few seconds near the austenization temperature (723 ºC) of the material. In these tests, each sample was pulse-heated to the test temperature within 2 s, held at temperature for a further 2.5 s, and then mechanically deformed to a true strain of approximately 0.25 to 0.35 within the next 100 µs. At temperatures above the transformation temperature in this material, which had been heat treated prior to testing so that it had a uniform pearlitic microstructure, a large decrease in flow stress of approximately 50 % was observed; see Figure 2. Since 723 ºC is well within the range of temperatures that have been measured along the tool-material interface in carbon steels during high-speed machining (see, e.g. Davies, et al. [6]), it is worthwhile to study the implications of this loss of strength in developing a constitutive model for AISI 1075 for use in high-speed machining simulations.

Although iron alloys with a smaller percentage of carbon, such as AISI 1035 and AISI 1045 steels, are used more frequently in manufacturing processes that involve high-speed machining operations, the particular alloy AISI 1075 is of important scientific interest, because it has the lowest austenization temperature, 723 ºC, among the carbon steels. Because of this property, this alloy was selected for an experimental study of the strength difference that occurs in a carbon steel due to a transformation from the stronger single-phase bcc pearlitic structure to a structure that includes the less-strong fcc austentitic structure.

In this paper, a model developed by Tlusty [1] is used to study the implications of this rapid loss in material strength for the prediction of the temperature in the chip and in the tool. In the next section, it is shown how the AISI 1075 results can be incorporated into a Johnson-Cook constitutive response model for the material, by adjusting the thermal-softening parameter in the model. In Section 3, a one-dimensional transient finite-difference model developed by Boothroyd, and improved upon by Tlusty, is used to calculate the temperature field in the chip and in the tool in orthogonal cutting of AISI 1075 steel. It is shown that there is a corresponding 33 % decrease in the predicted peak temperature along the tool-material contact region on the rake face of the tool. Following this, based on some earlier experimental work on AISI 1045 steel, it is argued that the effects of the phase transition would not be observed in high-speed machining of AISI 1075.

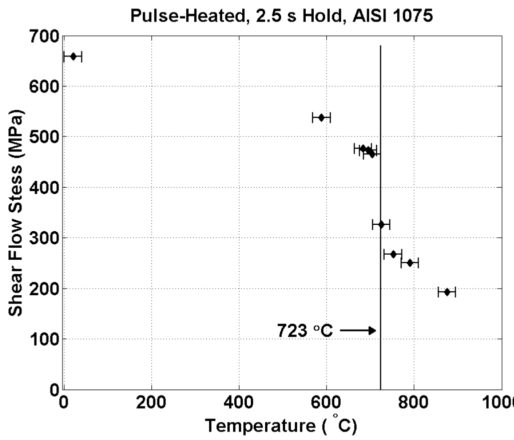

***Figure 2**: Pulse-heated Kolsky bar data on shear flow stress vs. temperature, at a true compressive strain of 0.1, and a true strain rate of 3500 s^{-1} [5]; sample microstructures were a uniform fine pearlite prior to testing; error bars denote 2σ [3]; upper left data point corresponds to room-temperature test in which sample was not pre-heated*

2 JOHNSON-COOK MODEL

The Johnson-Cook model [7] is a constitutive response function with five parameters,

$$\tau = \frac{1}{\sqrt{3}}\left[A + B\left(\frac{\gamma}{\sqrt{3}}\right)^n\right]\left[1 + m\ln\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\right]\left[1 - (T^*)^\nu\right]. \quad (1)$$

Because it separates, respectively, the strain-hardening, strain-rate-hardening, and thermal-softening behavior of a material into a simple product of three terms, this model is often used in finite-element simulations of rapid plastic deformation in metals. Here, τ is the true shear flow stress, γ is the true shear strain, $\dot{\gamma}$ is the true shear strain rate, nondimensionalized using a reference strain rate of $\dot{\gamma}_0 = 1.0$ s^{-1}, $T^* = (T-T_r)/(T_f-T_r)$ is the homologous temperature, T is the temperature, T_r = 20 ºC is the reference temperature, and T_f = 1516 ºC is the melting temperature of the material.

The data in Figure 2 are given at an effective true strain of 10 %, and a true strain rate of approximately 3500 s^{-1}. Keeping these strain and strain-rate values fixed in Equation (1), and fitting the room-temperature stress data (upper left data point in Figure 2), leads to an expression for the true stress that depends only on the temperature and the thermal-softening behavior of the AISI 1075 (see [5]),

$$\tau = 658.2\left[1-\left(T^*\right)^{\nu}\right]. \qquad (2)$$

In Figure 3, Equation (2) has been plotted using four different values of ν. The case $\nu = \infty$ corresponds to no thermal softening; the reason for including this case will be discussed in Section 4. When $\nu = 1.6$, the expression fits the data at temperatures below the eutectoid fairly well. Similarly, when $\nu = 0.7$, Equation (2) fits the data at temperatures above the eutectoid fairly well. For most carbon steels, it has been found that the thermal softening term $\nu = 1.0$ [4,7]. However, it is apparent in Figure 3 that this value of the parameter provides a poor fit to all but the one data point at the transition temperature. In the next section, the Johnson-Cook model for AISI 1075 in Equation (2) is used to predict the peak temperature in machining the material.

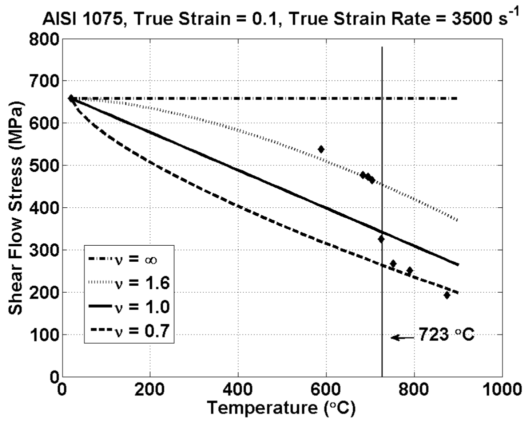

Figure 3: True shear flow stress vs. temperature, plotted using Equation (2), with four different values of ν, as indicated

3 TEMPERATURE PREDICTION

3.1 ONE-DIMENSIONAL CUTTING MODEL

Consider an orthogonal cutting operation on AISI 1075 steel. The objective of this section is to predict the temperature along the interface between the chip and the tool, because the peak temperature along this surface is important for predicting tool life. Rather than use a finite-element code for this purpose, a simplified method first introduced by Boothroyd [8] is used. It turns out that this method, as modified by Tlusty [1], can give a better peak temperature estimate than some finite element simulations [6,9].

The basic model, as presented by Tlusty, assumes that there are two heat sources. The first source of heating is represented by the shearing power, P_s, which arises from rapid dissipation by plastic shearing in the primary shear zone; this zone is modeled as a planar surface, which is assumed to be at a constant, uniform temperature, T_s, calculated using the following expression,

$$hbv_c\rho c\left(T_s - T_r\right) = P_s = F_s v_s, \qquad (3)$$

where h and b are the depth of cut and chip width, respectively; v_c is the cutting speed; ρ and c are the density and specific heat of the workpiece material, respectively; F_s is the shearing force; and v_s is the shearing speed. The second source is the friction power, P_f, which is generated by friction along the chip-tool interface in the secondary shear zone, which is also modeled as a planar surface. The model for P_f is based on tool pressure measurements of Yellowley (see [10]). It is assumed that heat is transferred only by convection in the direction of chip flow (X), and only by conduction into the chip and the tool in the direction parallel to the primary shear plane (Y). The latter assumption allows for heat loss from the chip into the tool. The tool is modeled as a wedge with two layers, one of carbide and one of steel.

3.2 TLUSTY'S ALGORITHM

The key idea of Tlusty's model is to follow a thin slice of material of width ΔX. It enters the primary shear zone at temperature T_r, and is rapidly heated to the shear plane temperature T_s. Some of the heat generated in the primary shear zone is lost to the tool (here assumed to be 20 %; see [6]). As the slice moves along the rake face of the tool, it gains additional heat due to friction. Once the temperature in the chip has been determined for each slice, the temperature field is adjusted by allowing for heat loss by conduction into the tool. For specificity, the following orthogonal machining parameters are assumed: cutting speed v_c = 3 m/s, chip width b = 6 mm, depth of cut h = 0.2 mm, shear plane angle $\varphi = 28°$, friction angle β = 16.7º (tanβ = 0.3), and tool rake angle α = 10º. Following Tlusty, it is also assumed that the chip-tool contact length $L_c = 4h$.

Now, to connect this model with Equation (2), the force on the primary shear plane is expressed in terms of the shear flow stress,

$$F_s = \tau L_s b. \qquad (4)$$

Here, $L_s = h/\sin\varphi$ is the shear plane length. Using Equation (4) and the assumed cutting conditions, P_s and P_f can be calculated. By starting with the value of τ at ambient temperature $T = T_r$ and iterating, a value for the shear plane temperature T_s is obtained for the four different values of the thermal-softening parameter ν. Applying Tlusty's algorithm for each value of T_s and ν gives four different predictions for the temperature along the chip-tool contact region on the rake face, as shown in Figure 4.

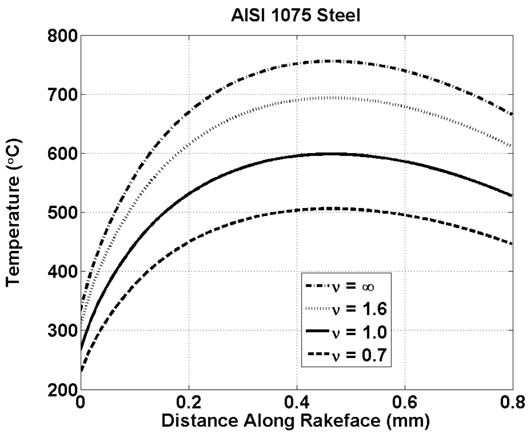

***Figure 4**: Temperature in chip-tool contact region along rake face, as predicted by finite-difference method*

4 CONCLUSIONS

As can be concluded from Figure 4, the predicted peak temperature along the rake face can differ by as much as about 33 % using the method outlined above, depending upon the value of ν chosen for the Johnson-Cook model of AISI 1075 steel. Cutting experiments on this material have not yet been performed, in which the temperature field is also measured. However, it is interesting to speculate upon which value of the thermal-softening parameter will give the best agreement with experiment.

As part of his dissertation work, Jaspers [4] developed a SHPB laboratory with a pre-heating system in which the pressure bars were initially separated. The sample was pre-heated in-situ using a small furnace, and then the bars were quickly brought into contact with the sample, which was rapidly loaded in compression. This method of pre-heating is slower than the pulse-heating method described in Reference [3], and the peak furnace temperature was 600 ºC. When he studied the response of AISI 1045 steel using this apparatus, Jaspers' reported data showed no evidence of a phase transformation. Furthermore, when he fit a Johnson-Cook constitutive law using these data, he concluded that the thermal-softening parameter $\nu = 1$.

However, when FEM simulations were performed to model a series of orthogonal cutting experiments on AISI 1045 of Davies, et al. [6], in which careful measurements were made of the temperature along the tool-chip interface, it was found that Tlusty's method with no thermal softening, i.e., $\nu = \infty$, provided better peak temperature predictions than did the FEM code using Jaspers' Johnson-Cook model [9]. Based on this information, it is likely that Equation (2) with $\nu = \infty$ will give the best peak temperature prediction in AISI 1075.

REFERENCES

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

[2] Childs, T. H. C.: Material property needs in modeling metal machining. Journal of Machining Science and Technology 2(2):303-316, 1998.

[3] Mates, S. P.; Rhorer, R. L.; Whitenton, E. P.; Burns, T. J.; 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.

[4] Jaspers, S. P. F. C.; 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.

[5] Burns, T. J.; Mates, S. P.; Rhorer, R. L.; Whitenton, E. P.; Basak, D.: Dynamic properties for modeling and simulation of machining: an update of results from the NIST pulse-heated Kolsky bar. In: 12th CIRP Conference on Modelling of Machining Operations, 2009. San Sebastian, Spain.

[6] Davies, M. A.; Yoon, H.; Schmitz, T. L.; Burns, T. J.; Kennedy, M. D.: Calibrated thermal microscopy of the tool-chip interface in machining. Journal of Machining Science and Technology 7(2):166-190, 2003.

[7] Johnson, G. R.; Cook, W. H.: A constitutive model and data for metals subjected to large strains, high strain ratesand high temperatures. In: 7th International Symposium on Ballistics, 541-547, 1983. The Hague, Netherlands.

[8] Boothroyd, G.: Temperatures in orthogonal metal cutting. Proceedings of the Institution of the Mechanical Engineers 177(29):789-802, 1963.

[9] Davies, M. A.; Cao, Q.; Cooke, A. L.; Ivester, R.: On the measurement and prediction of temperature fields in machining AISI 1045 steel. Annals of the CIRP 52(1):77-80, 2003.

[10] Buryta, D.; Sowerby, R.; Yellowley, I.: Stress distributions on the rake face during orthogonal machining. International Journal of Mechanical Science 34(5):721-739.