ON MODELING THE PEAK TEMPERATURE ON THE TOOL-CHIP INTERFACE DURING HIGH-SPEED MACHINING OF AISI 1045 STEEL

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Abstract: New experimental data on AISI 1045 steel from the NIST pulse-heated Kolsky Bar Laboratory is presented. The material is shown to exhibit a stiffer response to compressive loading when it has been rapidly preheated than it does when it has been heated using a slower preheating method to a testing temperature that is below the eutectoid temperature. Suggestions are made as to how to modify the well-known Johnson-Cook constitutive model of Jaspers and Dautzenberg for this material to achieve improved temperature predictions.

Keywords: high-speed machining, thermal modeling, AISI 1045 steel, Kolsky bar

1 INTRODUCTION

High-speed machining processes can cause extremely rapid plastic deformation and heating of the work material. If this material is a carbon steel, a small region of thickness on the order of 10 µm is deformed plastically in the primary shear zone, to a strain on the order of 100 %, at a strain rate on the order of 10,000 s^{-1}, on a time interval on the order of 10 µs. Subsequently, the material is subjected to additional large plastic strain in the secondary shear zone for a time on the order of 1 ms. During this small cutting time, the work material undergoes a change in temperature on the order of magnitude of 1000 ºC. Thus, a heating rate on the order of one million degrees Celsius per second is not uncommon for iron-carbon alloys of interest in manufacturing (see, e.g., [Tlusty, 2000]). Under such extreme conditions, there can be insufficient time for thermally-activated processes such as solid-solid phase transformations, dislocation annealing, and grain growth to produce changes in the microstructure of the material that occur on significantly longer time scales. This means that unique non-equilibrium superheated microstructural states can be present during high-speed machining operations, with the result that the material flow stress can differ significantly from that which is measured under equilibrium high-temperature conditions. This poses a challenge for modeling the constitutive response of these materials for use in finite-element simulations of rapid machining operations; see, e.g., [Childs, et al., 2000].

In a series of steady-state orthogonal cutting experiments on AISI 1045 steel that were performed at NIST [Davies, et al., 2003a], the temperature field along the tool-chip interface was measured. In four sets of these experiments, all of the cutting parameters were kept the same, except for the uncut chip thickness. Assuming conditions of plane strain and material incompressibility, the chip velocity was calculated, and then the net thermal flux Φ that exited a control volume surrounding the cutting region was estimated for each of the four sets of experiments. Assuming that the net thermal energy flux was equal to the total mechanical power led to an estimate for the specific cutting energy K_s in the system, $\Phi = F_c v_c = K_s\, h b v_c$. Here, F_c is the cutting force, v_c is the cutting speed, and h and b are the uncut chip thickness and chip width, respectively. For the four different uncut chip thicknesses, it was found that the specific cutting energy was nearly constant, with $K_s \approx 2400$ N/mm^2.

In the same study, a transient advection-diffusion model for the temperature distribution in orthogonal metal cutting, which was originally developed by Boothroyd [Boothroyd, 1963], and subsequently improved upon by Tlusty [Tlusty, 2000], was used to calculate the temperature field in the chip and in the tool for the same four sets of orthogonal cutting parameters, using a finite-difference numerical method. The stress in this model is determined directly from the specific cutting energy, and it does not depend upon the temperature. While this model did not accurately reproduce the temperature contours measured in the cutting experiments, it gave remarkably good predictions of the peak temperature along the tool-chip interface. In a subsequent study, [Davies, et al., 2003b], a commercial finite-element software package [ABAQUS, 2003] was used to model the temperature in these experiments. Using both the Johnson-Cook and the Zerilli-Armstrong material response models for AISI 1045 that had been developed specifically for computer simulations of metal-cutting operations by Jaspers (see [Jaspers and Dautzenberg, 2002]), it was found that the simulations underpredicted the peak tool-chip interface temperature by hundreds of degrees Centigrade.

The combined FEA and finite-difference results support the hypothesis that there is insufficient time for thermal softening mechanisms to have much effect on the work material in the cutting region during high-speed machining, so that the material has a stiffer response than is predicted using standard constitutive models. In the present study, suggestions are made as to how to modify the constitutive model to achieve improved temperature predictions. In the next section, a brief discussion is given of Tlusty's model. The third section presents some relevant NIST pulse-heated Kolsky bar data to provide a possible explanation for why the Jaspers and Dautzenberg model underpredicts the temperature in the machining simulations, and then the final section uses this data to discuss a possible modification of the Johnson-Cook model for application to high-speed machining processes.

2 TLUSTY'S ADVECTION-DIFFUSION MODEL

The model for the tool-work material interface temperature, as presented in [Tlusty, 2000], assumes that there are two heat sources, and that heat is transported by conduction in the direction normal to the tool-chip interface, and by mass transfer along with the work material in the direction of chip flow along the tool face. The first source of heating is represented by the shearing power, P_s, which arises from rapid dissipation by plastic deformation in the primary shear zone; this zone is modeled as a planar surface. This surface is assumed to be at a constant, uniform temperature, T_s. This temperature can be calculated using the following expression,

$$hbv_c\rho c(T_s - T_r) = P_s = F_s v_s \,. \qquad (1)$$

Here, 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 experimental tool pressure measurements. Assuming that the orthogonal cutting parameters are known, including the friction angle, the friction power P_f can be determined once F_s is known. Thus, Tlusty's model predicts the tool-chip interface temperature by using the conditions on the primary shear plane, together with a model for the pressure along the tool chip interface. Furthermore, Tlusty's model predicts a shear plane temperature of approximately 600 ºC in AISI 1045 steel, and to a first approximation, this is independent of h, b, and v_c.

Now, suppose that the specific cutting energy for the material, K_s, is unknown. Then another method to calculate the shear force on the primary shear plane is to use the shear flow stress,

$$F_s = \tau_s L_s b \,. \qquad (2)$$

In Equation 2, τ_s is the nominal shear stress on the primary shear plane, L_s is the length of the primary shear plane, and b is the chip width. Thus, given the orthogonal cutting parameters, if there is a good constitutive response model available for the stress in the work material, the cutting forces and temperatures of interest can be predicted using this simple model. An experimental method for the determination of τ_s is discussed in the next section.

3 NIST PULSE-HEATED KOLSKY BAR DATA

The split-Hopkinson pressure bar (SHPB), which is also called the Kolsky bar, is an experimental system that is widely used to determine the constitutive response of materials under conditions of rapid plastic deformation. A number of techniques have been developed for preheating a sample prior to impact testing in a Kolsky bar. The parameters for the Johnson-Cook constitutive model for AISI 1045 steel that was fit in the paper of Jaspers and Dautzenberg were determined in part using data from a Kolsky bar apparatus, in which the samples were pre-heated in situ using a gas furnace, to a temperature of up to 600 ºC, prior to loading in compression. At the National Institute of Standards and Technology (NIST), a unique SHPB facility has been in operation for several years. This laboratory combines a precision-engineered Kolsky bar and a controlled electrical pulse-heating system. The flow stress can be measured in samples that have been rapidly pre-heated to temperatures on the order of 1000 ºC, in a time on the order of one second, at heating rates of up to 6,000 ºC s^{-1}, and then rapidly loaded in compression at strain rates up to 10^4 s^{-1} [Mates, et al., 2008].

3.1 AISI 1075

In recent work [Burns et al., 2009], pulse-heated compression test results on AISI 1075 steel were reported. The purpose of the experimental study was to investigate the magnitude of the difference in material strength that occurs in a carbon steel due to a transformation from the stronger bcc pearlitic structure to a structure that includes the less-strong fcc austentitic structure. The test samples had been carefully heat treated prior to testing, so that they had a uniform pearlitic microstructure. The particular alloy AISI 1075 was chosen for this study because it has the lowest austenization temperature, 723 ºC, among the carbon steels. In these tests, which were performed at a nominal strain rate of 3500 s^{-1}, 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 austenization temperature (723 ºC) of the material, a nonequilibrium phase transformation from pearlite to austenite was observed to take place [Burns, et al., to appear]. At temperatures below the transformation temperature in this material, it was found that the material exhibited a stiffer response than is typically found in carbon steels. By fixing the value of the strain at 0.1, and the strain rate at 3500 s^{-1} in the Johnson-Cook model, it was shown that the experimental results could conveniently be summarized by the following expression for the effective true stress vs. the temperature,

$$\bar{\sigma}(T) = 1140 \times \left[1 - T^{*m}\right] \text{ MPa}, \qquad (3)$$

where $T^* = (T - T_r)/(T_f - T_r)$ is the homologous temperature, T is the temperature, T_r = 20 ºC is the reference temperature, and T_f = 1490 ºC is the melting temperature of the material. What is interesting about these data is that, for experiments in which the material had been preheated to a temperature below the eutectoid temperature, a value of m=1.6 was found to provide a good fit of the model in Equation 3 to the data. This contrasts with the fact that typically, for carbon steels, SHPB tests in which the sample has been preheated more slowly prior to loading in compression, it is found that m=1.0 (see, e.g., [Johnson and Cook, 1983],[Jaspers and Dautzenberg, 2002]). Furthermore, for experiments in which the sample had been preheated to a temperature above the eutectoid, a value of m=0.7 was found to provide a good fit of the model in Equation 3 to the data. Thus, a Johnson-Cook type of model was found to be too simplistic to provide an overall good fit to the data. In addition, for the data on tests which were performed with preheating to a temperature below the eutectoid, a value of the thermal-softening parameter m greater than one is very interesting, because it supports the hypothesis that thermal-softening effects are less than would be expected to be found in experiments performed with a slower method of preheating the sample.

3.2 AISI 1045

Iron alloys with a smaller percentage of carbon, such as AISI 1045 steel, are used much more frequently than a spring steel like AISI 1075 in manufacturing processes that involve high-speed machining operations. Furthermore, the material is not typically carefully prepared to have a uniform microstructure prior to its being formed by machining. Therefore, it is of interest to investigate whether or not a series of dynamic tests on samples of this material, prepared from commercial bar stock, which have been rapidly preheated, exhibit a response similar to that described by Equation 3. This will be the subject of a subsequent paper. In the remainder of this section, the following question is addressed. As discussed in Section 2, Tlusty's model predicts a shear plane temperature of approximately 600 ºC, which is below the lowest eutectoid temperature for an iron-carbon system. Could the reason be that Tlusty's model outperformed the finite-element simulations in [Davies, et al., 2003b], in particular using the Jaspers-Dautzenberg fit to the Johnson-Cook model for AISI 1045, because the actual material has a stiffer response than was measured by Jaspers and Dautzenberg using their SHPB system? In other words, just as was described for AISI 1075 in the preceding section, does a value of the thermal-softening parameter m in the Johnson-Cook model that is greater than one provide a better fit to the pulse-heated experimental data than the value m=1 reported in [Jaspers and Dautzenberg, 2002]? Figure 1(a) gives a plot of the true effective stress vs. true effective strain data from a pulse-heated Kolsky bar test that was performed at a nominal strain rate of 3600 s^{-1}. In this test, the sample was heated to a temperature of 645 ºC in approximately one second, and then it was held at that temperature for approximately 6.2 s prior to compressive loading. Also shown in the figure are two additional plots, both using the model of Jaspers and Dautzenberg at the same strain rate and temperature, but with m=1 in the lower curve, and m=2 in the upper curve. It is clear that the case with m=2 provides a better fit to the experimental data.

4 DISCUSSION AND CONCLUSIONS

Experimental data on AISI 1045 steel has been presented, that shows that the material exhibits a stiffer response when it has been pulse-heated, instead of preheated by a slower method, to a temperature below the eutectoid, prior to a dynamic SHPB compression test. This may help to explain why the finite-element simulations of orthogonal cutting tests on this

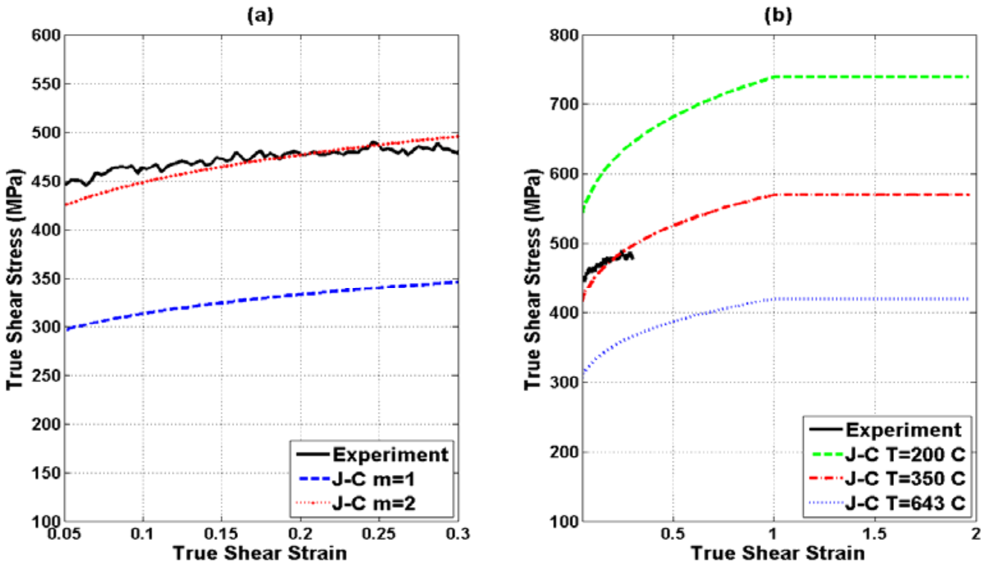

Figure 1; Data from pulse-heated compression test of an AISI 1045 steel sample that had been preheated to 643 ºC, and then plastically deformed at a true strain rate of 3600 s^{-1} (solid curve), and corresponding values of the Johnson-Cook model for AISI 1045 of Jaspers and Dautzenberg: (a) in the upper (dotted), and lower (dashed) curves, m=2 and m=1, respectively; (b) m=1, and the corresponding temperatures are as indicated; for strains greater than 1, n=0 [Childs,et al., 2000].

material were found by [Davies, et al., 2003b] to underpredict the peak temperatures measured in corresponding orthogonal cutting experiments. Of course, this work does nothing to address the issue of path-dependence. Here, the experimental technique involves preheating the sample and then quickly loading the sample. In high-speed machining, however, the rapid heating and rapid plastic deformation do not occur in sequence, but rather they occur simultaneously.

There is another way to think about the fact that the Johnson-Cook model of Jaspers and Dautzenberg for AISI 1045 underpredicts the measured flow stress in Figure 1(a), as well as the temperature along the tool-chip interface that was measured in the orthogonal cutting experiments of [Davies, et al., 2003a]. In the machining experiments just cited, the workpiece was a tube of AISI 1045 steel. After it had been machined, the temperature of the surface of the workpiece exiting the cutting region could be on the order of 500 ºC. When this portion of the surface returned to the cutting region, it was still as hot as 350 ºC. This suggests the following hypothesis. Since all of the machining takes place in a time on the order of a hundred microseconds, there is insufficient time for the microstructure in the workpiece material to react to the huge thermal gradient that is present during the actual cutting operation. Instead, temperature-dependent microstructural changes that influence the material response in the primary and secondary shear zones during high-speed machining must take place prior to the entry of material into the region of cutting. In support of this hypothesis, consider Figure 1(b). The middle, dashed, curve of the Johnson-Cook model that has the approximate temperature of the workpiece material that enters the cutting zone gives a much better approximation to the experimental data than does the lower, dotted, curve, corresponding to the actual testing temperature; note that this latter temperature is close to Tlusty’s estimate of the shear plane temperature. It is clear that much additional experimental work is necessary to confirm this hypothesis.

Figure 1(b) also emphasizes that modeling of high-speed machining operations usually requires large extrapolations from data that have been obtained using currently available experimental methods. Ideally, constitutive data for machining simulations ought to be determined by means of some carefully designed cutting experiments.

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