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EFFECT ON FLOW STRESS OF A RAPID PHASE TRANSITION IN AISI 1045 STEEL

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ABSTRACT
New experimental data on AISI 1045 steel from the NIST pulse-heated Kolsky Bar Laboratory are presented. The material is shown to exhibit a nonequilibrium phase transformation at high strain rate. An interesting feature of these data is that the material has a stiffer response to compressive loading when it has been preheated to a testing temperature that is below the eutectoid temperature using pulse-heating than it does when it has been preheated using a slower heating method. On the other hand, when the material has been pulse-heated to a temperature that exceeds the eutectoid temperature prior to compressive loading on the Kolsky bar, it is shown to exhibit a significant loss of strength. A consequence of this behavior is that fixed-parameter constitutive models, such as the well-known Johnson-Cook model, cannot be used to describe this constitutive response behavior. An argument is made that the phase transition does not occur during high-speed machining operations, and suggestions are made as to how to modify the Johnson-Cook model of Jaspers and Dauzenberg for this material in order to obtain improved temperature predictions in finite-element simulations of high-speed machining processes.

INTRODUCTION
In a high-speed machining operation on a carbon steel such as AISI 1045, a small region of thickness on the order of magnitude of 10 µm is deformed plastically in the primary shear zone at a strain rate of the order of magnitude of 10,000 s^{-1}, to a true strain on the order of 100 %, 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 that is typically less than 1 ms. During this very short cutting time, the work material is sheared so rapidly that it undergoes an increase in temperature of the order of magnitude of 1000 ºC. Thus, plastic working by rapid shear in two thin material layers induces a heating rate on the order of magnitude of one million degrees per second (see, e.g., Tlusty [1]). Under such extreme dynamic loading conditions, there is insufficient time for thermally-activated processes that take place on significantly longer time scales to cause significant changes in the material's microstructure (see, e.g., Childs [2]). On the other hand, unique non-equilibrium superheated microstructural states can be present during high-speed machining operations. As a result, the material flow stress in a high-speed machining process can differ significantly from that which is measured experimentally under equilibrium high-temperature conditions. This presents unique difficulties for both experimental measurement and constitutive response modeling of the flow stress in these materials for use in finite-element simulations of high-speed machining processes [2].

In this paper, new experimental data on AISI 1045 steel from the NIST pulse-heated Kolsky Bar Laboratory are presented. These data were obtained as part of a program on material response measurement and modeling for application to high-speed machining simulations. The AISI 1045 is shown to exhibit a nonequilibrium phase transformation at high strain rate, that is similar to the phase transformation that has recently been observed to take place in AISI 1075 steel [3]. An interesting feature of both of these data sets is that the material has a stiffer response to compressive loading when it has been preheated using pulse-heating to a testing temperature that is below the eutectoid temperature, than it does when it has been preheated using a slower heating method. On the other hand, in both cases, when the material has been pulse-heated to a temperature that exceeds the eutectoid temperature prior to compressive loading on the Kolsky bar, it is shown to exhibit a significant loss of strength. A consequence of this behavior is that fixed-parameter constitutive models, such as the well-known Johnson-Cook model [4], which is frequently used in finite-element simulations of high-strain-rate deformation processes, cannot be used to describe this constitutive response behavior. An argument is given, based on computer simulations of high-speed machining of AISI 1045, that the phase transition does not occur during high-speed machining operations, and suggestions are made as to how to modify the often-cited Johnson-Cook model of Jaspers and Dauzenberg for AISI 1045 steel [5], in order to obtain improved temperature predictions in finite-element simulations of high-speed machining processes.

JOHNSON-COOK CONSTITUTIVE MODEL

The constitutive response model of Johnson and Cook [4] is a purely phenomenological, five-parameter mathematical formula for calculating the effective true flow stress in a material as a function of the effective true strain, true strain rate, and temperature. It is widely used in finite-element codes, because it is relatively easy to fit. It is given as a product of three terms, that separate, respectively, the strain-hardening, strain-rate-hardening, and thermal-softening material response behaviors of a metal, with five material constants *A, B, C, m,* and *n*,

$$\bar{\sigma}\left(\bar{\varepsilon},\dot{\bar{\varepsilon}},T\right)=\left(A+B\bar{\varepsilon}^{n}\right)\left(1+C\ln\dot{\bar{\varepsilon}}\right)\left(1-T^{*m}\right) \tag{1}$$

In Equation 1, $\bar{\varepsilon}$, $\dot{\bar{\varepsilon}}$, and T^* are the effective true plastic strain, effective true plastic strain rate, and the homologous temperature, respectively. The homologous temperature is given by the nondimensional formula $T^* = (T - T_r) / (T_f - T_r)$, where T is the temperature of the material in degrees Celsius, T_r = 20 ºC is the reference temperature, and T_f is the melting temperature of the material. The parameters in each of the three terms are usually determined independently using experimental data. The first term, corresponding to the strain hardening, is determined from quasi-static, room-temperature data. The second term is determined from room-temperature dynamic split-Hopkinson pressure bar (SHPB) compression data taken at two different strain rates. The third term, the thermal-softening response, is also usually determined using dynamic (SHPB) data, in which the samples have been pre-heated using some kind of heating device, such as a small in-situ oven [5], or an in-situ magnetic induction system [6]. Because of the way the homologous temperature appears in the third term in Equation 1, it turns out that a larger value of m corresponds to *less* thermal softening in a material.

The parameters for the Johnson-Cook constitutive model for AISI 1045 steel that was fit in the paper of Jaspers and Dautzenberg [5] were determined in part using data from a SHPB 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. Typically, the fastest of these methods preheats the sample in a time on the order of magnitude of one minute (see, e.g., [7,8]).

At the National Institute of Standards and Technology, a unique SHPB facility has been in operation for several years. This laboratory combines a precision-engineered SHPB (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} [9]. In the next two sections, results from the NIST Kolsky Bar Laboratory on two carbon steels are discussed.

PULSE-HEATED AISI 1075 DATA

In [3], new 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, the eutectoid temperature 723 ºC, among the carbon steels.

In these tests, which were performed at a nominal strain rate of approximately 3600 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. 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 Equation 1, it was shown that the AISI 1075 experimental results could conveniently be summarized by the following expression for the effective true stress vs. the temperature,

$$\bar{\sigma}\left(T\right)=1140\times\left(1-T^{*m}\right)\ \text{MPa} \tag{2}$$

with a melting temperature of the material given by T_f = 1490 ºC. 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 2 to the data. 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 2 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.

PULSE-HEATED AISI 1045 DATA

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, with $m>1$ for temperatures below the eutectoid, and $m<1$ for temperatures above the eutectoid, instead of a response with a single value of the thermal-softening parameter given by $m=1$, as was reported for AISI 1045 by Jaspers and Dautzenberg [5]. It turns out that this is indeed the case.

In Figure 1, the square in the upper left-hand region of the plot corresponds to the stress predicted by the Johnson-Cook model of Jaspers and Dautzenberg for AISI 1045, at room-temperature (20 ºC), a true strain of 0.1, and a true strain rate of 4000 s^{-1}. The diamond-shaped data plotted in Figure 1 give the true stress at a true strain of 0.1 in a set of pulse-heated Kolsky bar experiments that were performed on AISI 1045 steel, at dynamic strain rates on the order of magnitude of 4000 s^{-1}. Since this material was shown by Jaspers and Dautzenberg to have small strain-rate-sensitivity, it is reasonable to compare the two data sets in this way. Keeping the strain and strain-rate values fixed at 0.1 and 4000 s^{-1}, respectively, in this model, leads to an expression, similar to Equation 2, for the true stress in AISI 1045, that depends only on the temperature and the thermal-softening behavior of the material,

$$\bar{\sigma}(T) = 1004 \times \left(1 - T^{*m}\right) \text{ MPa} \tag{3}$$

The homologous temperature T^* has already been defined above; here, the melting temperature of the material is given by T_f = 1460 ºC. For experiments in which the sample had been preheated to a temperature below the eutectoid, a value of $m=2$ was found to provide a good fit of the model in Equation 3 to the data. This is twice the value for m that was found by Jaspers and Dautzenberg for samples that had been pre-heated by means of a slower heating method to a test temperature that was below the eutectoid temperature of 723 ºC. On the other hand, for experiments in which the sample had been preheated to a temperature above the eutectoid, a value of $m=0.75$ was found to provide a good fit of the model in Equation 3 to the data.

In the next section, some earlier work on the measurement and modeling of the temperature along the tool-chip interface during high-speed machining of AISI 1045 is reviewed. Based on this work, an argument is presented that the phase transformation is unlikely to be observed during high-speed machining of this material, and that the thermal-softening value of $m=2$ is a better value for use in finite-element (FEA) simulations of machining processes in this material than the value of $m=1$ that is given in [5].

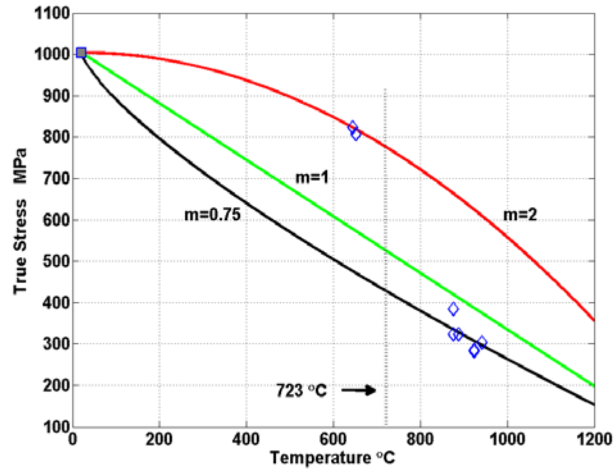

Figure 1 : The square in the upper left-hand region of the plot corresponds to the stress predicted by the Johnson-Cook model of Jaspers and Dautzenberg, (2002) for AISI 1045, at room-temperature (20 ºC), a true strain of 0.1, and a true strain rate of 4000 s^{-1}; the diamonds correspond to the true stress at a true strain of 0.1 in a set of pulse-heated Kolsky bar experiments that were performed on AISI 1045 steel, at dynamic strain rates on the order of magnitude of 4000 s^{-1}.

MEASUREMENT AND MODELING OF TEMPERATURE FIELD IN MACHINING EXPERIMENTS ON AISI 1045

As part of a program in the measurement and modeling of high-speed machining operations at NIST, a series of four high-speed, steady-state orthogonal cutting experiments were performed on AISI 1045 steel [10]. In each of these four sets of tests, all of the cutting parameters were kept the same, except for the uncut chip thickness. Careful non-contact thermometric measurements were made of the temperature field along interface between the chip and the tool. In a subsequent study by Davies, et al. [11], a commercial finite-element software package [12] 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 [5]), it was found that the simulations underpredicted the peak tool-chip interface temperature by hundreds of degrees.

In [10], by making the usual assumptions of plane strain and material incompressibility, the velocity of the chip was calculated, and then an estimate was made of the net thermal flux Φ that exited a control volume surrounding the cutting region. Making the assumption that the net flux of thermal energy was equal to the total mechanical power, the specific cutting energy K_s in the system was calculated as follows,

$$\Phi = F_c v_c = K_s\, hbv_c \quad (4)$$

where F_c is the cutting force, v_c is the cutting speed, and h and b, respectively, are the uncut chip thickness and chip width. It was found that, for the four different chip widths, the specific cutting energy remained nearly constant, with the value of $K_s \approx$ 2400 N/mm^2.

As part of the same study [10], a transient model for the temperature distribution in orthogonal cutting, developed by Tlusty [1], was used to calculate the temperature field in the chip and in the tool for the same four sets of orthogonal cutting parameters, by means of 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.

The model for the tool-work material interface temperature, as presented in [1], 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,

$$hbv_c \rho c\left(T_s - T_r\right) = P_s = F_s v_s \quad (5)$$

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; T_r = 20 ºC is the reference temperature; F_s is the shearing force; and v_s is the shearing speed. The second source of heating is the friction power, P_f, which is generated by friction along the tool-chip interface in the secondary shear zone; this is also modeled as a planar surface. The model for P_f is based on experimental tool pressure measurements, and the friction angle. 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.

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,

$$F_s = \tau_s L_s b \quad (6)$$

In Equation 6, 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. Tlusty's model also 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. This is the basis for the peak temperature prediction along the tool-chip interface.

Now, 600 ºC is considerably less than 723 ºC, the lowest eutectoid temperature for an iron-carbon system. This suggests the following explanation for why Tlusty's model outperformed the finite-element simulations using the two material models for AISI 1045 of Jaspers and Dautzenberg that were reported by Davies, et al. [11]: the material has a stiffer response than was measured by Jaspers and Dautzenberg using their SHPB system. Thus, the material does not exhibit the thermal-softening behavior expressed by the middle, straight-line curve corresponding to the value of m=1 in Figure 1, corresponding to the Jaspers-Dautzenberg [5] fit to their data, nor does it exhibit the more extreme thermal-softening behavior expressed in the lowest curve in Figure 1, corresponding to m=0.75. Instead, the material has the stiffer response to an increase in temperature corresponding to m=2, as depicted in the upper curve in Figure 1.

In Figure 2, the solid curve corresponds to 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}; this corresponds to one of the data points along the upper curve in Figure 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 (dashed) curve, and m=2 in the upper (dot-dashed) curve. It is clear that the case with m=2 provides a better fit to the experimental data.

DISCUSSION AND CONCLUSIONS

Experimental data on AISI 1045 steel have been presented, which show that the material exhibits a rapid phase transformation, similar to that which has been observed in AISI 1075 steel, when it has been rapidly preheated to a temperature above its eutectoid temperature, prior to loading in a Kolsky bar compression test [3]. An argument has been given, based on a finite-difference model for the temperature field along the tool-chip interface in high-speed machining, for why the phase transition should not be expected to take place during a high-speed machining operation.

Furthermore, the AISI 1045 has been shown to have a stiffer response when it has been pulse-heated, rather than preheated using a slower method, to a temperature below the

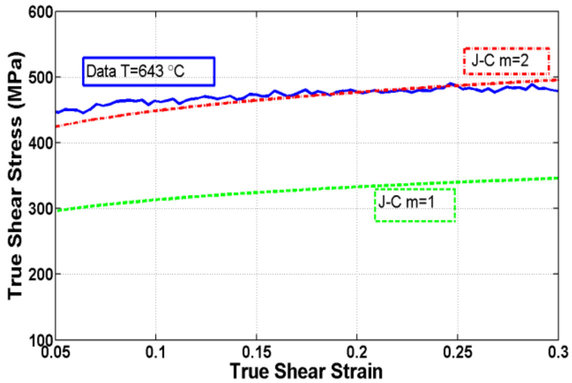

Figure 2; Data (solid curve) from pulse-heated compression test of an AISI 1045 steel sample that had been preheated to 643 ºC, and then plastically deformed at a true strain rate of 3600 s^{-1}, and corresponding values of the Johnson-Cook model for AISI 1045 of Jaspers and Dautzenberg; in the upper (dot-dashed), and lower (dashed) curves, *m*=2 and *m*=1, respectively.

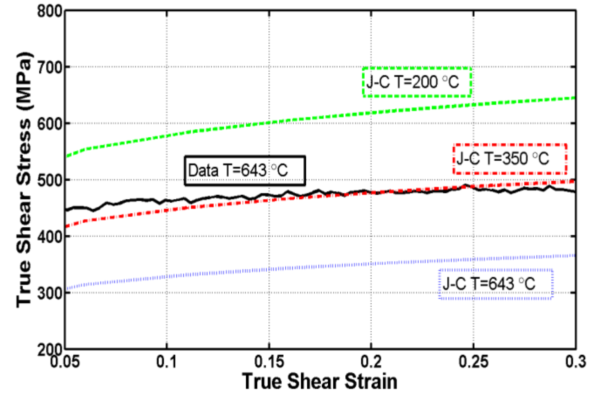

Figure 3: Data (solid curve) from pulse-heated compression test of an AISI 1045 steel sample that had been preheated to 643 ºC, and then plastically deformed at a true strain rate of 3600 s^{-1} (solid curve), and corresponding values of the Johnson-Cook model for AISI 1045 of Jaspers and Dautzenberg, with *m*=1, at three different temperatures, as indicated.

eutectoid, prior to loading in a dynamic compression test, and it has been proposed that this provides an explanation for why the finite-element simulations of orthogonal cutting tests on this material were found by Davies, et al. [11] to underpredict the peak temperatures measured in corresponding orthogonal cutting experiments.

We conclude with the following remarks. In the machining experiments of Davies, et al. [10], the AISI 1045 workpiece was in the shape of a hollow tube, one end of which had been mounted onto a rotating disk. Orthogonal cutting was performed by removing material from the opposite flat surface of the tube, using a sharp tool insert that had been mounted onto a rigid tool post. After it had been machined, the temperature of the surface of the workpiece exiting the cutting region was found to be on the order of 500 ºC. When this portion of the surface returned to the cutting region, its temperature was still as high as 350 ºC. In Figure 3, the experimentally measured stress vs. strain response data of the pulse-heated AISI 1045 material at a testing temperature of 643 ºC, that have already been given in Figure 2, are plotted again (solid curve). Also plotted in the figure are three additional curves, corresponding to the Jaspers-Dautzenberg fit to the Johnson-Cook model, Equation 1, with *m*=1, at a true strain rate of 3600 s^{-1}, for three different values of the temperature: 200 ºC (dashed curve), 350 ºC (dot-dashed curve), and 643 ºC (dotted curve). The best fit to the data among the three values of the temperature is clearly given by the curve corresponding to 350 ºC. This suggests the following hypothesis. During the few hundred microseconds during which high-speed machining takes place, the microstructure of the AISI 1045 has insufficient time to react to the huge thermal gradients in the primary and secondary shear zones. Therefore, any significant temperature-dependent changes in the material's microstructure must take place prior to the entry of material into the region of cutting. Much additional experimental work is necessary to confirm this hypothesis.

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