Dynamic Properties for Modeling and Simulation of Machining: An Update of Results from the NIST Pulse-Heated Kolsky Bar

T. J. Burns[1*], S.P. Mates[1], R. L. Rhorer[1], E. P. Whitenton[1], D. Basak[2]
[1]National Institute of Standards and Technology[**], Gaithersburg, MD, USA
[2]Orbital Sciences Corporation, Dulles, VA, USA
[*]timothy.burns@nist.gov

Abstract
The Pulse-Heated Kolsky Bar Laboratory at the National Institute of Standards and Technology (NIST) has been developed for the measurement of dynamic properties of metals. Because high-speed machining processes can lead to extremely rapid heating of a material, followed by rapid cooling, our research program has been directed in part at studying the influence on flow stress of the heating rate and the time-at-temperature prior to impact in rapid compression tests on carbon steels. The unique pulse heating capability of the NIST Kolsky bar system enables rapid uniform pre-heating of an experimental test sample from room temperature to several hundred degrees C in less than a second, prior to a Kolsky bar test. We present new results on AISI 1075 steel, which demonstrate constitutive response behavior that cannot be predicted by the Johnson-Cook flow stress model that is widely used in simulations of high-speed machining processes.

1 INTRODUCTION

Prediction of the best machining parameters for a particular process and work material continues to be a challenge in manufacturing. The fundamental problem that needs to be modeled is chip formation. During chip formation, the work piece interacts with a cutting tool under extreme conditions of pressure and temperature, and large plastic deformation takes place at a very high rate of strain, both in the thin primary shear zone, and in the secondary shear zone along the tool/work interface, as the newly cut material slides up the rake face of the tool (see Figure 1). In some materials, the temperature during high-speed cutting can rise to a significant percentage of the melting temperature [1],[2],[3],[4].

Even though great strides have been made in modeling and simulation capabilities in the last few decades, due in large part to the development of user friendly finite element software packages, such as Abaqus [5], DEFORM [6], and AdvantEdge [7], there continues to be a need for higher precision and reliability in the

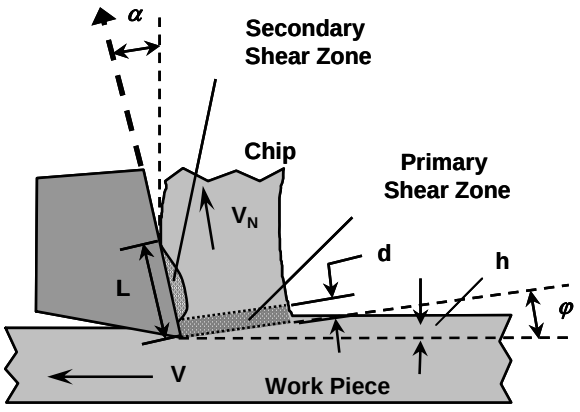

Figure 1: Schematic illustration of orthogonal cutting.

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modeling and simulation of machining processes [8],[4],[9]. One of the challenges to improved modeling and simulation is the determination of an appropriate material description, i.e., constitutive response model, for the flow stress in the work piece [4],[10]. In this paper, we provide an update on some ongoing research in the NIST Pulse-Heated Kolsky Bar Laboratory [11], an experimental facility which has been developed for obtaining constitutive response data for application to machining studies as well as for other applications.

It is instructive to begin by providing an estimate of just how extreme the plastic deformation conditions are in a routine high-speed machining operation. We do this by reviewing an example of the modeling of orthogonal cutting considered by Tlusty. Following this, we discuss the limitations on reproducing machining conditions by current material testing capabilities. This is the subject of Section 2. In Section 3, we provide a brief description of the current status of our Kolsky Bar Laboratory, with an emphasis on its unique pulse-heating capabilities for rapidly pre-heating a sample, and then holding it at a prescribed temperature for up to several seconds, prior to performing a compression test. In addition, we outline some of our current experimental work in the laboratory that is aimed at providing improved stress-strain data for machining applications. This research program is based on a combination of pulse heating, followed by impact testing, and finally by post-test metallurgical analysis of a sample. In Section 4, we present some recent experimental results on AISI 1075 steel that we have obtained, as part of some ongoing research on the dependence of the flow stress in carbon steels as a function of the heating rate and time at temperature of the material. We also discuss the challenge these data pose to the development of a constitutive model for the flow stress of this material. We finish the paper with some discussion and conclusions in Section 5.

2 CHIP FORMATION

2.1 Orthogonal Machining of Carbon Steel

Following Tlusty [2], consider chip formation during orthogonal machining of AISI 1035 steel, with the following parameters: uncut chip thickness h = 0.2 mm, chip width b = 6 mm, shear zone thickness d = 0.02 mm, cutting speed V = 3 m/s, rake angle α = 10º, and shear plane angle φ = 28º; see Figure 1. Because plastic deformation in non-porous metals conserves volume, the normal speed of the work material as it flows through the primary shear zone has the constant value $V_N = V\sin\varphi$ = 1.41 m/s. The corresponding shearing speed of the material entering the primary shear zone is given by $V_S = V\cos\alpha / \cos(\varphi-\alpha)$ = 3.11 m/s. The corresponding chip speed, which is the speed at which the chip moves relative to the tool along the tool face can be shown to be $V_C = V\sin\varphi / \cos(\varphi-\alpha)$ = 1.48 m/s. Using a method due to Piispanen [12], the shear strain in the primary shear zone may be estimated by $\gamma = V_S / V_N = \cos\alpha / [\sin\varphi \cos(\varphi-\alpha)]$ = 2.21, which is very large. The corresponding average shear strain rate can then be estimated by $\dot{\gamma} = \gamma / \Delta t_1$, where $\Delta t_1 = d / V_N = 1.42\times10^{-5}$ s is the time interval required to deform an element of the work material into a corresponding element of the chip; this gives $\dot{\gamma} = 1.56\times10^{5}$ s^{-1}, which is also very large. At the slower cutting speed of 2 m/s, Tlusty estimates the temperature near the chip/tool interface to be about 900 ºC. This is consistent with the temperature measured in AISI 1045 steel at 3.2 m/s by Davies, et al. [3],[4]. The chip remains in contact with the tool over a contact length that we estimate, following Tlusty again, to be four times the undeformed chip thickness, L = 4×h = 0.8 mm, so that d « L. If the uncut material entering the primary shear zone is at room temperature T_0 = 25 ºC, this gives a huge thermal gradient of approximately (900 - T_0) / L = 1.09×10^{6} ºC/m. If we estimate the time required for the deformation in the secondary shear zone to take place by $\Delta t_2 = L / V_C$, then $\Delta t_2 = 5.41\times10^{-4}$ s. Using Δt_2 as an estimate of the time required to heat the work material from room temperature up to the maximum temperature, this gives an average heating rate of (900 - T_0) / Δt_2 = 1.62×10^{6} ºC/s, which is very high.

2.2 Constitutive Response Data

Ideally, a carefully designed orthogonal cutting operation could be used for the determination of material constitutive properties for the modeling of machining processes. During continuous chip formation, the process is steady state, and the strain, strain rate, and temperature are of the correct orders of magnitude for machining. Although considerable progress has been made in the measurement of aspects of orthogonal metal cutting, the best attempts to date to identify constitutive parameters using this method still require a considerable amount of analytical modeling; see, e.g., [13]. Thus, this approach cannot yet be viewed entirely as one of making improved experimental measure-

ments. There are also questions about the uniqueness of the constitutive model parameters that are obtained using this method [14].

The most common experimental method that is currently used for obtaining constitutive response data for finite-element modeling of machining, as well as for more general purposes, is the split-Hopkinson pressure bar (SHPB) [15]. This instrument is also known as the Kolsky bar, after the man who made a number of improvements to Hopkinson's experimental design [16]. Using this method, the constitutive response data required for the deformation processes modeled by these sophisticated software packages are obtained under conditions that do not approach those that occur during high-speed machining; see, e.g., [17]. In particular, the maximum strain rates that are typically attained in a Kolsky bar test are ~1×10^4 s^{-1}. There are also methods for loading the sample in tension [18] and in torsion [19] to approximately the same strain rates, on the Kolsky bar. Typical maximum strains obtained with a compressional Kolsky bar are ~50 %; larger strains, ~2, can be obtained with the torsional bar test. Thus, with these methods, the strain rate is an order of magnitude smaller than is routinely observed in machining. Additionally, when the influence of thermal softening on material strength is measured during a Kolsky bar test, the usual method, in the case of the compression test, is to preheat the sample slowly in an oven, away from the bar, and then to insert the sample between the bars immediately prior to a test. This heating method is not used in a torsional Kolsky bar test, because of the difficulty with clamping the specimen in this configuration.

Although improvements on the heating rate prior to testing in a Kolsky bar have been made by the development of an induction method for in situ pre-heating in the dynamic tensile test [20] and by our own method of in situ resistive pre-heating in the compression test [11], as far as we know there is currently no experimental method which can simultaneously produce the high heating rates and high temperature conditions that frequently occur during modern machining operations, and also accurately measure the dynamic stress-strain response of a material. It follows that when constitutive models fit with these data are used to predict material response for machining simulations, the results of these calculations are subject to the criticism that they are based on extrapolations to much larger strains, strain rates, and heating rates than the experimental data on which the models are based. Thus, there is still a considerable need for improvements in experimental methods for the determination of constitutive response data for the modeling and simulation of high-speed machining operations [8]. In the next section, we describe our current method for the measurement of flow stress at high temperature and high strain rate.

3 THE NIST KOLSKY BAR LABORATORY

3.1 Split-Hopkinson Pressure Bar

The NIST Kolsky Bar is a precision engineered split-Hopkinson pressure bar [21]. Two high strength maraging steel bars, each of 1.5 m length and 15 mm diameter, are mounted on bearings to enable easy sliding of the bars in the axial direction and to resist bending in other directions. A cylindrical sample of the material to be tested is inserted between the two long bars, carefully aligned for axial symmetry, so that, ignoring radial effects, the data can be analyzed using one-dimensional wave theory. One of the long bars, called the incident bar, is impacted by a striker, launched by an air gun. The striker is a much shorter bar made from the same maraging steel, with the same diameter, as the two long bars.

In this way, the sample is rapidly loaded by a compressive wave. Because there is an impedance mismatch at the sample, and because the system can be modeled fairly accurately by one-dimensional linear elastic wave theory, when the compressive wave arrives at the bar/sample interface, the difference in impedance between the bar and the sample results in a splitting of the input wave into a tensile wave that is reflected back into the incident bar, and a wave that compresses the smaller-diameter

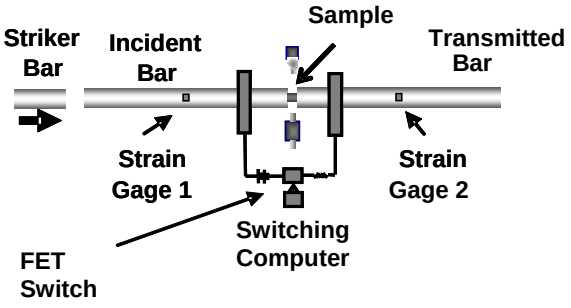

Figure 2. Schematic drawing of the NIST Kolsky Bar with DC current pulse-heating capability.

sample sufficiently that it is rapidly and permanently deformed plastically. This compressive wave then propagates into the second long bar, called the transmitted bar. The system is designed so that the only plastic deformation occurs in the sample. By means of strain gauges mounted at the midpoints of the input and transmitted bars and one-dimensional elastic wave analysis, the stress vs. strain response of the sample can be obtained.

3.2 Subsecond Thermophysics Laboratory

What makes the NIST apparatus unique is the fact that it has been combined with an existing controlled resistive-heating facility, the NIST Subsecond Thermophysics Laboratory [22]. This Laboratory was originally developed to measure physical properties of metals at high temperature, such as the critical point at melting of a pure metal, using rapid resistive heating and non-contact thermometry. It has the capability to pre-heat an experimental sample extremely rapidly, in situ, using precisely controlled DC electrical current.

3.3 Combined Pulse-Heated Kolsky Bar

In order to combine the two systems, non-conducting (Delrin® acetal plastic) bearings are used to support the two long bars, with the exception of the bearing at the support at the end of each bar nearest to the sample. At these two interior supports, custom-made graphite-lined metal sleeves are used. Heavy-duty welding cables connect the interior pair of support posts to the DC electrical circuit. The interior support posts are isolated electrically from the surrounding support structure. By means of this design, the incident and transmitter bars can be used to conduct a rapid, controlled DC pulsed electric current of up to several hundred amperes through a metal Kolsky bar sample; see Figure 2. The typical sample size that we use in this system is 2 mm thick and 4 mm in diameter, which is smaller than usual for a 15 mm diameter Kolsky bar system. The reason for using this smaller size is to guarantee that the sample will heat up much more rapidly than the interior ends of the two long elastic bars during a test.

The sample temperature is controlled by means of a fast-response pyrometer. The signal from the pyrometer is used to pulse the heating current sufficiently rapidly that the sample quickly reaches and maintains a pre-selected temperature. Using this method, a sample temperature uniformity of 20 ºC or less can be obtained [11]. The thermal control system shuts off the DC current within a few milliseconds prior to firing the air gun to launch the striker bar into the incident bar. Once the test is over, the sample typically remains compressed between the bars, and it cools rapidly.

By combining the thermophysics laboratory with a Kolsky bar, we now have a facility for high strain rate testing of metal samples that have been pulse-heated prior to stress loading. With the heating rates and temperature control capabilities of this system, together with non-contact thermal measurements, we can now reliably introduce a uniform temperature into a sample extremely rapidly. In its present configuration, the NIST Kolsky Bar facility can measure the flow stress of metals at heating rates of up to 6×10^3 ºC/s. While this heating rate is still orders of magnitude smaller than the ~1×10^6 ºC/s that is routinely observed in high-speed machining processes, as discussed in the example in the preceding section, it is much more rapid than the rates at which material samples are pre-heated using more traditional methods.

In the next section, we present new data from pulse-heated high strain rate Kolsky bar experiments that we have performed on AISI 1075 steel in the neighborhood of the austenite formation temperature, 723 °C. As discussed in Section 2, this is certainly within the minimum and maximum range of temperatures that routinely occur during high-speed machining of carbon steels.

4 APPLICATION TO AISI 1075 STEEL

4.1 Discussion of Microstructure

During a high-speed machining operation on a carbon steel, the material undergoes rapid heating. Furthermore, because the resulting chip is quickly exposed to air or to a cooling fluid, upon separation from the tool, the work material is rapidly quenched. It follows that it undergoes a rapid heating-cooling cycle, much like one of our pulse-heated Kolsky bar samples. Although the Kolsky bar heating rate is not as rapid as in machining, it is still fast enough to study some interesting dependence of the flow stress on the rate of heating and the time at temperature.

At room temperature, an iron-carbon alloy such as AISI 1075 is typically a solid mixture of two body-centered-cubic (bcc) crystalline materials, ferrite (iron) and cementite (iron carbide) [23]. The steel used in our tests was heat treated to

obtain a uniform initial microstructure of 100 % fine pearlite. In this microstructure, the ferrite and cementite particles form into thin lamellae, or plates, which alternate within the structure. With 0.75 % Carbon content, AISI 1075 steel is near the eutectoid composition, and its eutectoid temperature is 723 ºC, which is the lowest among the carbon steels.

When heated to a temperature exceeding the eutectoid temperature, and then maintained isothermally, pearlite undergoes a phase transformation into homogeneous austenite, a face-centered cubic solid solution, also called the γ-phase, which is unstable at temperatures below the eutectoid. This phase transformation results from the diffusion of carbon into solid solution with the iron. What this means from the point of view of the present discussion is that, under isothermal heating conditions, this material transforms to austenite (100 % γ-phase), a face-centered-cubic structure (fcc), at the lowest temperature of the carbon steels. Because of this property, due to its location on the iron-carbon phase diagram, this particular alloy allows us to measure most easily the strength difference that occurs with its transformation from one single-phase bcc material (pearlite) that is very strong, to another single phase fcc material (austenite) that is less strong.

Like all diffusion processes, a sufficient amount of time is required for equilibrium to be attained. If the time at temperature is too short, the original pearlite will not have time to transform into austenite. As the time at temperature increases, an increasing percentage of the pearlite will transform into austenite, so there will be a nonequilibrium solid solution consisting partially of austenite. When austenite is cooled very rapidly, it transforms into martensite. Thus, by using metallurgical techniques to measure the percentage of martensite in the material after a rapid heating-cooling cycle, the percentage of austenite that was present during the rapid heating phase can be determined.

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4.2 Kolsky Bar Data

As we have already discussed, the samples were heat treated prior to testing, in order to ensure that the initial microstructure was uniformly fine pearlitic. This was done to make sure that the strength loss due to austenitization would be a maximum, because we were unaware of any published estimates of the magnitude of this difference in measured flow stress, depending on the heating rate and the time at temperature of the test material. We performed a series of Kolsky bar tests on samples of this heat-treated AISI 1075 steel, at room temperature and also on pulse-heated samples. The flow stress and the true strain rate measured in one of the room-temperature tests are shown in Figure 3. Pulse-heated tests were performed at temperatures considerably below and above the eutectoid temperature, and at a sequence of temperatures at smaller increments on either side of the transition temperature. In these tests, each 1075 sample was pulse-heated to the test temperature within 2 seconds, held at temperature for a further 2.5 seconds, and then mechanically deformed to 25 % - 35 % true strain within the next 100 µs. The true strain rate in all of these tests was approximately 3500 s^{-1}. For the heated tests, Figure 4 gives the flow stress at 10 % true strain vs. the measured test temperature. The uncertainty in the temperature measurement is discussed in Mates, et al. [11].

The experimental data show that across the transition temperature, there is a reduction in flow stress of about 50 %. Metallurgical study of the post-test samples, to correlate the material's microstructure with the measured flow stress, is still in progress, and will be discussed elsewhere. However, it appears that there was sufficient time at temperature for a transformation from pearlite to austenite to take place in the samples that were heated above 723 ºC. In the next subsection, the implications of the test results presented in Figures 3 and 4 for the constitutive response modeling of AISI 1075 are discussed.

4.3 Johnson-Cook Flow Stress Model

The Johnson-Cook flow stress model [24] is a commonly used constitutive response function for finite-element simulations of the rapid plastic deformation of metals; see, e.g., [25], [26]. This phenomenological model expresses the von Mises flow stress, σ, as a function of the true strain, true strain rate, and temperature,

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

In Equation 1, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}^{*} = \dot{\bar{\varepsilon}} / \dot{\bar{\varepsilon}}_{0}$ is the dimensionless true strain rate, $\dot{\bar{\varepsilon}}_{0} = 1.0\,\mathrm{s}^{-1}$, and T^{*} is the homologous temperature, a dimensionless quantity that is defined as follows,

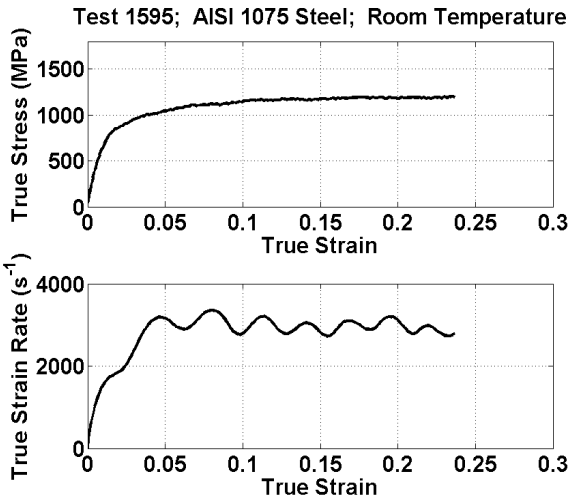

Figure 3: Results of Kolsky bar test on room-temperature sample of AISI 1075 steel. True stress at 10 % true strain is approximately 1140 MPa; true strain rate is approximately 3500 s^{-1}.

$$T^* = \frac{T - T_0}{T_M - T_0}. \qquad (2)$$

Here, T is the temperature in degrees C, T_0 = 25 °C is the initial temperature, and T_M is the melting point of the material in degrees C. A, B, C, n, and m are five material constants that are fit to experimental data. Note that Equation 1 is a product of three power-law expressions, with each term involving only one of the independent variables.

Johnson and Cook fit their model (Equation 1) for a specific material in three steps. First, the parameters in the leading term are determined using quasi-static tension or torsion data; A is the yield strength of the material, and B and n estimate its strain-hardening behavior. Second, the thermal softening fraction K_T is determined by computing the ratio of the stress in a heated test to that in a room-temperature test at the same strain rate. It then follows that m = ln (1-K_T) / ln T*. In the third step, the strain-rate sensitivity coefficient C is determined by using the flow stress values at a fixed strain from two different room temperature tests, performed at two different strain rates. Some authors use optimization methods to determine the best-fit parameter values for sets of data on a given material that have been measured experimentally; see, e.g., [27].

4 4. Johnson-Cook Modeling of AISI 1075 Data

Now, consider the AISI 1075 data given in Figures 3 and 4. All of these experiments were

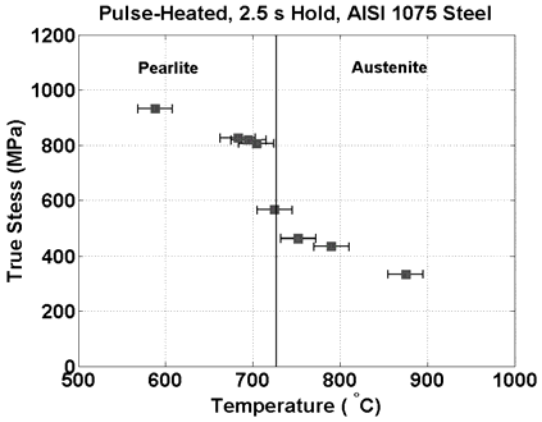

Figure 4: Kolsky bar experimental data on AISI 1075 steel; pearlitic room-temperature samples were pulse-heated and then held at temperature for 2.5 s; vertical line denotes the eutectoid temperature (723 °C); squares denote the flow stress at 10 % true strain; error bars denote 2σ [11].

performed at a nominal strain rate of 3500 s^{-1}. Therefore, if we assume that the top curve of the high strain-rate room temperature test has been well-fit by finding the coefficients A, B, C, and n in Equation 1, it follows that the flow stress at 10 % strain and 3500 s^{-1} will approximately be equal to 1140 MPa. Keeping the strain fixed at 10 % and the strain rate fixed at 3500 s^{-1}, Equation 1 can be written as

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

In Figure 5, the isolated circle at T_0 = 25 °C and σ = 1140 MPa is the flow stress at T = T_0, so that T* = 0, also. The pulse-heated data at 10 % strain that are plotted in Figure 4 are re-plotted as rectangles in Figure 5 on both sides of the vertical line that corresponds to the eutectoid temperature of AISI 1075. Using the cold flow stress at T_0 as the initial point, Equation 3 is plotted with m = 1.6 (upper curve), m = 1.0 (center line), and m = 0.7 (lower curve) on the temperature interval [T_0, 1000 °C].

4.5 Discussion

A number of conclusions can be drawn from Figure 5. With the thermal parameter value m = 1.6, Equation 3 predicts the flow stress fairly well at elevated temperatures that are below 723 °C. On the other hand, using the thermal parameter value m = 0.7, Equation 3 predicts the flow stress values above 723 °C fairly well. This is why these two values of m were chosen.

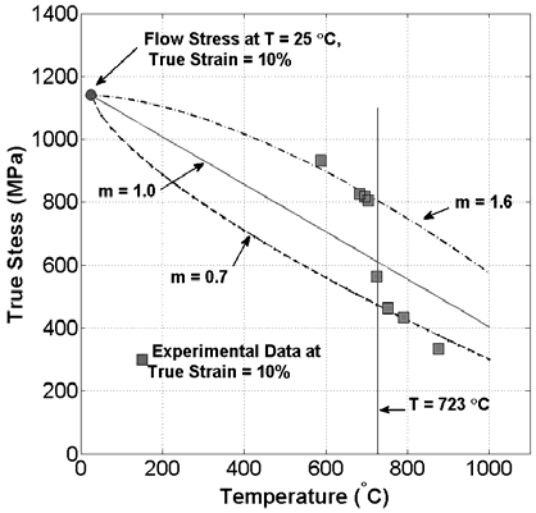

Figure 5: Flow stress at 10 % true strain. Upper (dash-dot) curve: m=1.6; middle (solid) curve: m=1.0; lower (dash) curve: m=0.7. Vertical line denotes eutectoid temperature. Circle is experimental data from room temperature test; squares are experimental data from tests in which the sample was pulse-heated and then held at constant temperature for 2.5 s before impact.

However, for carbon steels, it has been found from experimental data on slowly pre-heated samples by a number of authors that the thermal parameter m = 1.0 [24],[26]. Use of this generally accepted value in Equation 3 provides a poor prediction for all but one of the pulse-heated data points. Overall, the Johnson-Cook model with constant m does a poor job of fitting all of the data in Figure 4, where evidently there is a phase transition in the microstructure at the eutectoid temperature.

5 CONCLUDING REMARKS

We have presented new experimental results on pulse-heated AISI 1075 steel. These data were shown to present a constitutive modeling challenge, because of a phase transformation from pearlite to austenite that took place in the material microstructure when the sample was rapidly pre-heated to a temperature above 723 °C prior to rapid compression testing. In an experimental study of austenite formation in 0.75 % carbon steel using dilatometry, Rose and Strassburg [28] have published heating time-temperature transformation curves that indicate that 2.5 seconds at high temperature are insufficient time for the transformation to austenite to run to completion. Based on this, we expected the flow stress-temperature curve in Figure 5 with m = 1.6 would fit our experimental data on pulse-heated AISI 1075 fairly well. However, this is clearly not the case. Therefore, the data presented here are very interesting, because they show that there is indeed evidence of the phase transformation, even for this relatively short time at high temperature. Metallurgical analysis of post-test samples is currently in progress and will be discussed in a future publication.

DISCLAIMER

Commercial products are identified in order to specify certain procedures or equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the identified products are necessarily the best available for the purpose.

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