Recent Results from the NIST Pulse-Heated Kolsky Bar

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ABSTRACT

A Kolsky bar laboratory for measuring dynamic material properties, in support of improved finite-element modeling of high-speed machining processes, has been developed at the National Institute of Standards and Technology (NIST). The NIST split-Hopkinson pressure bar has the capability of electrically pulse heating a test sample to a temperature on the order of 1000 ºC in less than a second, then holding the sample at a fixed high temperature for several seconds (if desired), followed by loading of the sample in a dynamic compression test. Recent advances in temperature measurement and control capabilities are discussed, together with recent results on the constitutive response of AISI 1045 steel. The goal of the work is to study the influence of the rate of heating and time at high temperature on the stress-strain response of the material, which depends upon the dynamic evolution of the material's microstructure.

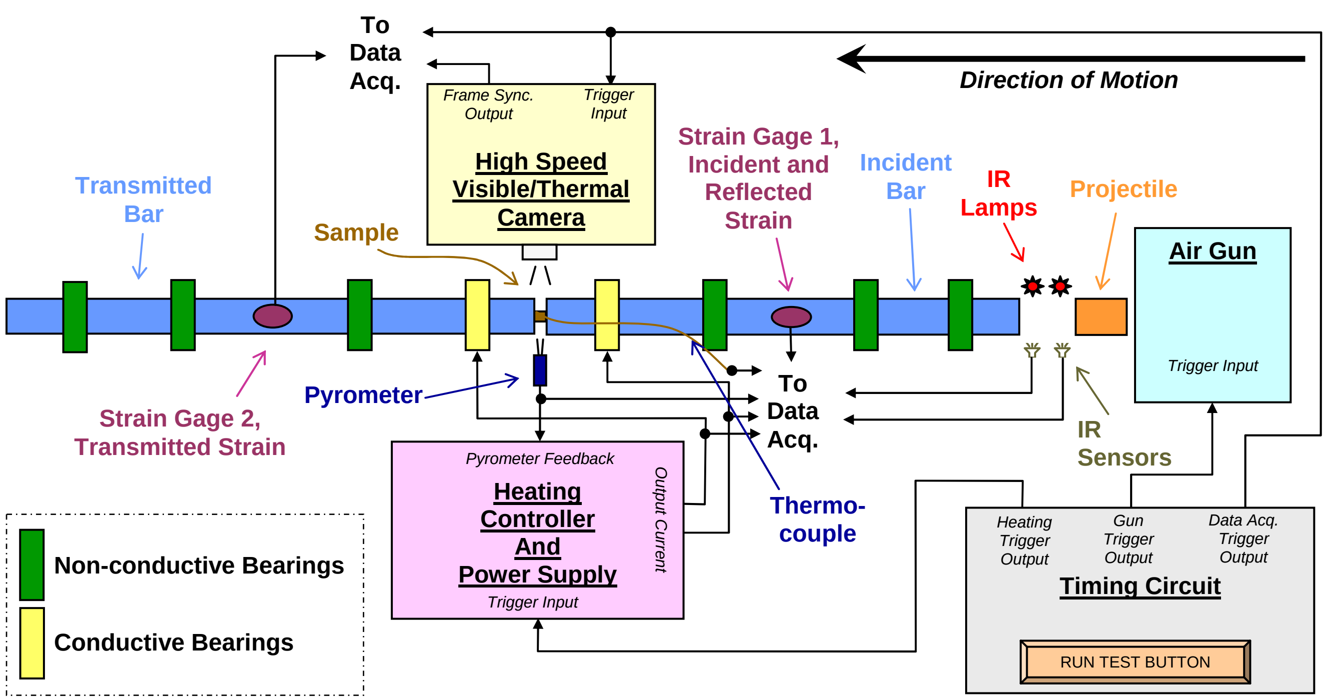

Figure 1. Schematic diagram of NIST pulse-heated Kolsky bar apparatus.

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Introduction

Over the past few decades, a number of studies have appeared regarding the use of finite element software to simulate rapid material removal processes [1]. Evidently, a large-scale computational approach is emerging as a potentially useful aid for the design and optimization of high-speed machining processes. Unlike older analytical approaches to the scientific study of metal-cutting operations, state of the art finite-element simulations performed on modern computer workstations provide realistic looking visualizations of material fields such as stress, strain, and temperature during rapid plastic deformation in the vicinity of the tool-chip interface, even in three-dimensional settings that cannot be approximated as plane strain.

Typically, 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 [2]. Whether the data that are currently available can be extrapolated reliably to the high heating rates and high temperature conditions that can occur during a machining process is questionable [3]. These can be on the order of 10^4 ºCs^{-1} and 1000 ºC, respectively [4]. An effort is underway at NIST to begin to address these issues experimentally.

A split-Hopkinson pressure bar (SHPB) system (see Figures 1 and 2) [5], originally developed by Kolsky [6], has been combined with an existing controlled resistive-heating facility, the NIST Subsecond Thermophysics Laboratory (see Figure 3) [7]. This metallurgical facility had been developed for the precise measurement of physical properties at high temperature, such as the critical point at melting of a pure metal, using rapid resistive heating and non-contact thermometry. The heating system power source consists of a bank of twenty-four two-volt submarine batteries. Depending upon test requirements, all of the batteries or a specified subset can be connected in series. The total power capacity of this DC electrical system is sufficient to increase the temperature of a sample from room temperature to above 1000 °C in less than 500 ms. The computer-controlled switching system consists of twenty field effect transistors (FET) in parallel, which can be operated in either a time-control or a temperature-control mode. The current through the sample is controlled by the number of batteries included in the circuit, and by a variable resistor. This current is measured by means of a voltage across a calibrated standard resistor.

Figure 2. NIST Kolsky Bar Laboratory.

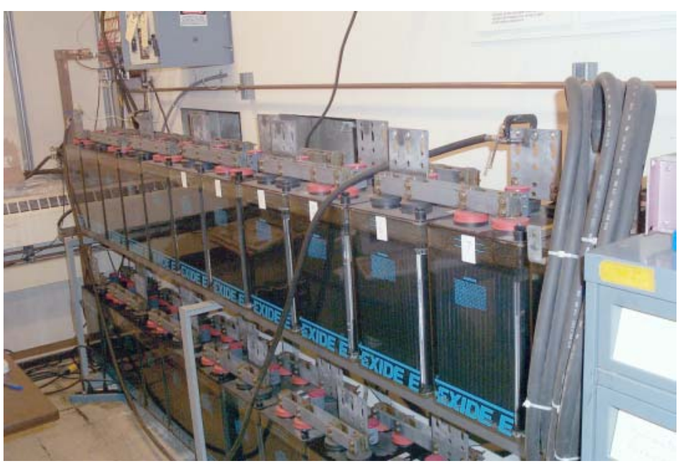

Figure 3. Subsecond Thermophysics Laboratory power supply. FET switches are located at top left.

The two split-Hopkinson maraging steel bars are each 1.5 m long, with a diameter of 15 mm. In order to combine the two systems, rather than install metal bearings to support the steel bars on the SHPB, non-conducting bearings made from acetal plastic (Delrin) have been used at all of the supports except for the two nearest the interior ends of the bars, where the test sample is inserted. Here, two custom-made metal sleeves lined with graphite have been used. The support posts for the center two bearings have been isolated electrically from the base structure, and connected to the DC electrical circuit with heavy-duty welding cables; see Figure 4. By means of this design, the input and transmitter bars can be used to conduct a rapid, controlled DC electrical pulse through a sample.

The standard sample size used in the NIST apparatus is 2 mm thick and 4 mm in diameter, which is considerably smaller than the typical size for a system of this scale (see, e.g., Gray [8]), in order to ensure a much higher current density in the sample than in the bars. Because the sample is heated so rapidly, in addition to the need for lubrication along the contact surfaces between the sample and bars, a material is required that will enable current to pass through the sample, as well as prevent the sample from welding to the bars. After several materials such as high-temperature greases were tried, flexible graphite disks were chosen for the task. These disks are cut with a hole punch from thin sheets of the commercial product Grafoil, and have thickness 0.127 mm and diameter 6.35 mm. This flexible graphite product is manufactured from pure graphite, without a binder, and has density of about 50% that of elemental graphite. Recently, a method has been developed to compensate for the mechanical response of the Grafoil when determining the stress-strain response of the sample material in the Kolsky bar; see Mates, et al. [9].

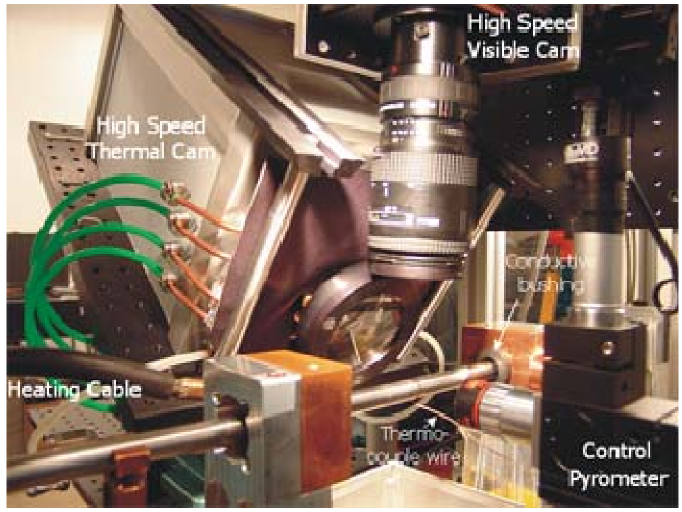

Figure 4. Central region of NIST SHPB, showing instrumentation used to heat sample and to control and measure sample temperature.

The sample temperature is determined using several instruments (Figure 4). A single spot radiance temperature of the sample is provided by a near-infrared micro-pyrometer (NIMPY), which was developed at NIST specifically for the purpose [7], and it this temperature that is used to control the DC current when this is the chosen control mode. The NIMPY consists of a refractive 5x microscope objective with a numerical aperture of 0.14 attached to a traditional microscope body. The thermal measurement is performed with an InGaAs detector with a response time on the order of 1 μs. Due to uncertainties in the emissivity of the dynamically deforming sample, an additional measurement capability has recently been added to the system for the determination of the true temperature. This consists of a thin thermocouple which is spot welded onto the sample surface. Finally, a high-speed infrared thermal camera is used to measure the temperature uniformity across the width of a sample. The thermal camera (a 320 by 256 InSb array) is cryogenically cooled to reduce the dark current, and it is used without any filters, with a 25 mm Si lens and a sapphire window for protection. Thermal images are recorded digitally, and depending upon the selected area of view and the integration time, effective framing rates of over 3000 frames per second can be obtained. These images can be used to evaluate the uniformity of the heating. In a good test, temperature variation across a sample can be as small as 20 ºC.

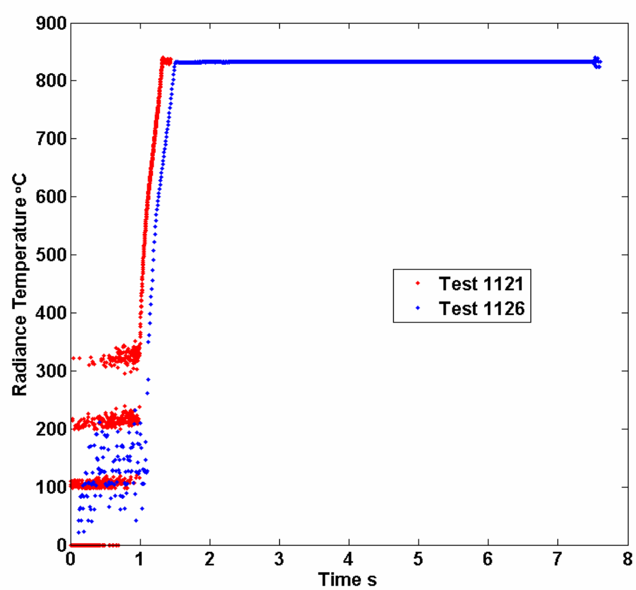

Figure 5. Pyrometer radiance temperature history prior to impact testing in case of "short" (red curve) and "long" (blue curve) rapid heating.

Once the desired temperature has been reached in a few hundred milliseconds, the circuit is quickly de-energized by the control system, or if desired, after rapid continuous heating, the sample can be held at a fixed temperature for up to several seconds prior to shutting off the current in the system, and then the control system quickly fires an air gun to launch a striker bar, initiating a standard pressure bar impact test. In this way, the combined heating and compression systems provide the capability for the determination of dynamic stress-strain curves at controlled heating rates of up to 6000 ºCs^{-1} and precise temperature control for fixed time periods at elevated temperatures. The data reduction procedure for this system has been expedited considerably by the NIST Data PADS software package [10].

Examples of temperature control using the pyrometer in two Kolsky bar tests on samples of 1045 steel, corresponding to “short” and “long” temperature histories prior to rapid heating, are given in Figure 5. Experience in earlier testing using the apparatus indicated that a two-stage heating process improved the contact between the Grafoil, the sample, and the bars. In the first stage, the sample is heated to a radiance temperature near 300 ºC, where the NIMPY becomes sensitive, but still below a temperature at which significant microstructural changes begin to occur in the test material. This eliminates some issues with electrical sparking and temperature nonuniformity in the sample in some of the rapid-heating tests. The instrument is now being used at NIST to study the dynamic mechanical behavior of several materials of interest, such as carbon steels, aluminum alloys, and pure iron. In addition, as will be discussed in the next section, the rate of heating is sufficiently rapid that non-equilibrium microstructural mechanical effects in carbon steel can be investigated.

Mechanical Testing of AISI 1045 Steel

In a series of carefully designed high-speed machining tests in which material was removed from one end of a thin-walled tube of AISI steel by turning on a lathe, a non-contact thermometry system similar to the one described above, except that it consisted of a planar array of detectors, was used to measure the temperature field during steady-state material removal by rapid plastic deformation arising from the interaction of the steel workpiece material with the carbide cutting tool [11]. In subsequent attempts to model this plane strain deformation process by means of a well-accepted commercial finite-element code, using a Johnson-Cook type constitutive model for the steel that takes into account the effects of strain hardening, thermal softening, and strain-rate sensitivity in the material, it was found that the code systematically and significantly underpredicted the measured temperature in the cutting region.

This has led to the following question, which partially motivates the work in progress described in this section. Since the Johnson-Cook model parameters were determined using a SHPB apparatus in which the samples had been heated slowly in an oven away from the bars, and then inserted between the bars just prior to testing [2], and since the heating rate in the machining operation was orders of magnitude more rapid than in the SHPB tests, could the microstructures of the 1045 steel differ greatly enough that the mechanical response of the material is noticeably different during high-speed machining from that determined in the SHPB tests that were used to fit the constitutive response model for the material that was used in the numerical simulations? In particular, since many microstructural transformations in steel are time-dependent (see, e.g., [12]), could the 1045 steel exhibit a stiffer response immediately following rapid heating than it does following a slow heating process?

Another way to express this question is shown schematically in Figure 6. Prior to a 1045 test, a sample is a mixture of mostly pearlite in a matrix of ferrite. The amount of martensite in a post-test sample is a measure of the amount of prior austenite into which the pearlite has transformed at the high temperature of interest, prior to a rapid quench in the ambient air immediately following impact in the SHPB test. If the larger amount of non-equilibrium austenite that forms during a “long” rapid-heating test is softer than the untransformed pearlite, this could lead to a stiffer material response in the 1045 steel during the machining test compared with that observed in a conventional high-temperature SHPB test. This in turn would cause the finite-element software to underpredict the temperature during a machining test if the conventional Johnson-Cook model is used to simulate the test.

At the present time, work to study this question is just underway. In the two tests whose temperature histories are given in Figure 5, the true strain rate was approximately 4000 s^{-1}. The corresponding stress vs. strain responses, corrected for the effect of the Grafoil used in the tests, are given in Figure 7. While the “short” heating test indicates a somewhat stiffer response, more tests are needed to establish that this behavior is systematic. The post-test samples are currently undergoing a metallographic analysis, in order to compare the microstructures of the two samples.

Discussion and Conclusions

A brief overview of the current status of the NIST Kolsky Bar Apparatus has been presented. The system is now capable of sufficiently rapid controlled uniform heating of the sample that the mechanical behavior of carbon steels of interest in manufacturing can be explored under non-equilibrium conditions. In particular, hypoeutectoid and near-eutectoid steels can be tested in rapid compression under conditions of rapid pre-heating where a substantial percentage of unstable austenite is present in the microstructure. They can also now be tested under conditions such that the temperature pre-heating history does not permit this transformation to austenite to take place. Thus, a comparison can now be made of the stress vs. strain response of the material under these different high-temperature conditions, with the goal of obtaining an improved understanding of the constitutive response of alloys of interest in manufacturing processes.

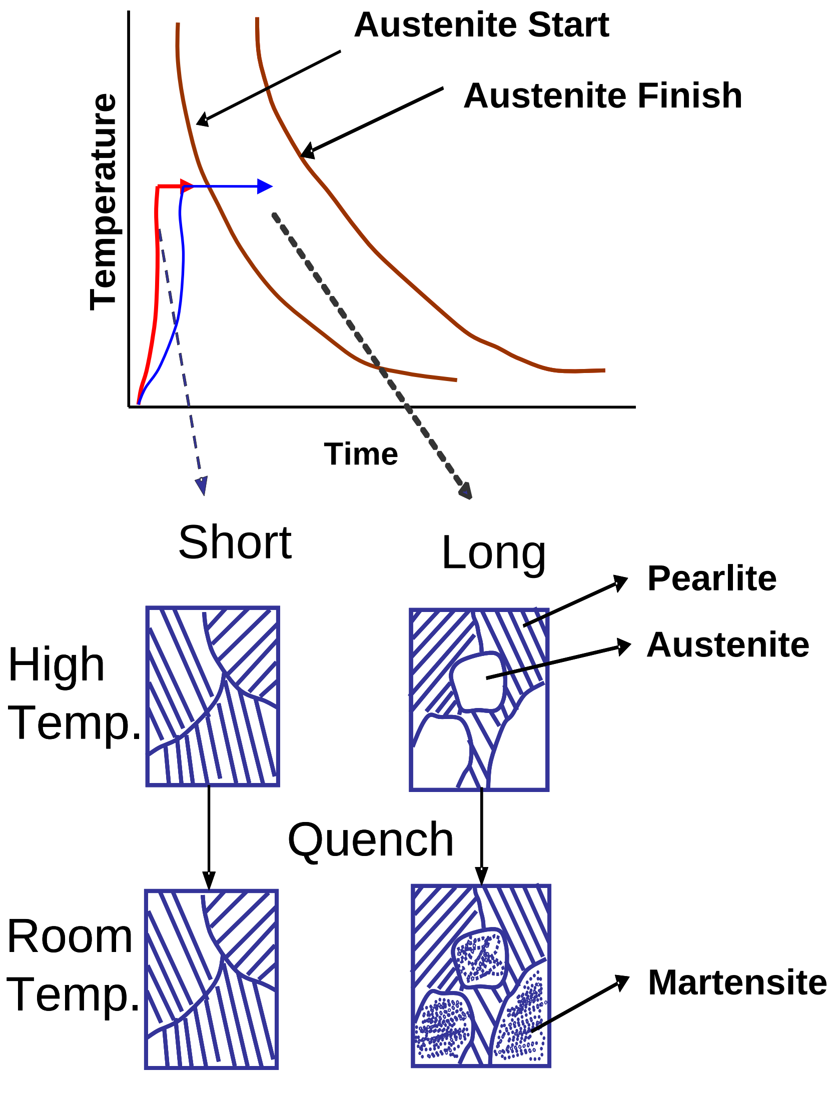

Figure 6. Schematic illustration of microstructural state of AISI 1045 during “short” and “long” rapid heating tests, and after rapid quenching in air immediately following SHPB impact testing.

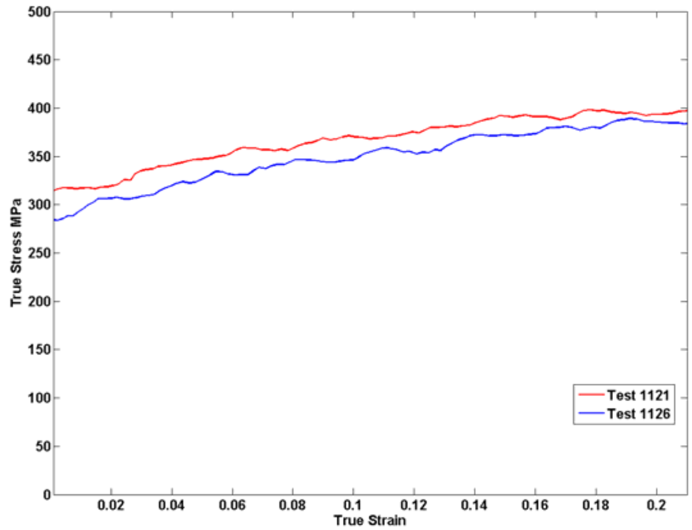

Figure 7. Comparison of true stress vs. true strain in “short” (red curve) and “long” (blue curve) rapid-heating tests corresponding to pyrometer temperature histories in Figure 5.

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