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Temperature Control of Pulse Heated Specimens in a Kolsky Bar Apparatus Using Microsecond Time-Resolved Pyrometry[1]

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Analysis of machining processes is important in the understanding and improving of manufacturing methods. The modeling of machining processes relies on high-strain-rate, high-temperature material properties. A Split–Hopkinson (or Kolsky) bar has been developed at NIST for this purpose. By heating the material specimen rapidly with a controlled current pulse prior to the mechanical impact of the bar, structural changes in the specimen are inhibited, thus better simulating conditions during machining. A stress-strain relationship can be determined at various temperatures for a range of materials. For the elevated temperature Kolsky experiments it is essential for the specimen to be maintained at a constant and uniform temperature prior to dynamic loading. The development and implementation of a near-infrared micro-pyrometer (NIMPY) for the precision control of the Kolsky specimen temperature by using a pulse heating system preceding the mechanical impact are described. The pulse-heating system can be operated either in the transient mode, where the current to the specimen is switched off at a preset temperature or time; or in the brief steady-state mode, where the specimen is heated rapidly to achieve the preset temperature (in the range from 400 to 1300 K) in a short time (about 200 ms)

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and then held isothermally for a brief period (< 2 s). A brief description of a model of the pulse heating process is provided, and the predicted specimen temperature history is compared with measured temperature data.

KEY WORDS: Kolsky bar apparatus; PID control; pulse heating; pyrometry; temperature control.

1. INTRODUCTION

The prediction and measurement of rapidly changing temperatures near the cutting tool tip have been long-term goals for machining research. Modern analytical tools such as the finite element analysis (FEA) method are being used to model machining processes in an attempt to provide a predictive capability for parameters such as cutting temperature and forces. However, efforts to use the FEA method to model machining processes have been hampered by the lack of adequate material properties for the high strain rates and rapid heating encountered in modern machining processes. During machining of metals, rapid heating occurs (on the order of 5×10^4 K$\cdot$s^{-1}) up to temperatures on the order of 1300 K, as well as very high strain rates (in the range of 10^3 to 10^6 s^{-1} [1]). A new experimental apparatus called the pulse heated Kolsky bar apparatus has been developed at the National Institute of Standards and Technology (NIST) to produce high rate dynamic loading while simultaneously pulse heating the specimen with electric current. A room temperature Kolsky test typically consists of impacting a sample sandwiched between two long bars with a projectile at a high velocity. By measuring the amplitude of the resultant elastic strain wave produced in the two bars, the stress versus strain function for the specimen material can be calculated by solving the wave equation for uniaxial stress propagation.

Traditionally, the Kolsky bar test is done at room temperature, but to determine a stress-strain function useful for modeling machining processes, high temperature material properties are needed. Therefore, the NIST Kolsky bar apparatus has been integrated with an existing facility that provides a controlled high current pulse. Although methods have been developed for heating specimens prior to testing in a Kolsky bar apparatus [2], there is currently no method for preheating a specimen quickly enough to simulate the conditions that occur during a high-speed machining operation.

The success of the elevated temperature Kolsky experiments is greatly dependent on the reliability and accuracy of the main components of the temperature control system, of which the pyrometer is an important one. A near-infrared micro-pyrometer (NIMPY) has been specifically built to cover the temperature range of interest for steel, i.e., 700 to 1300 K. The

temperature control system, which principally consists of the NIMPY, the field effect transistors (FETs), and a temperature control algorithm, can be run in various control modes depending on the type of control desired. In the "Time + Temperature Control Mode" both a time and a temperature value are preset in the computer program. When the desired temperature is reached, the current to the specimen is switched off unless the system is timed out earlier. A more advanced mode of operation for temperature control is the "Isothermal Control Mode," where the plateau temperature and time are preset. The process is based on rapid resistive heating of the specimen up to the preset temperature in a short time (~ 500 ms) and maintaining the specimen at this temperature under steady-state conditions for a brief period (50 to 2000 ms) before switching off the current to the specimen. The operational characteristics of the control system are described in more detail in the subsequent sections.

2. MEASUREMENT AND CONTROL METHOD

The "Time + Temperature Control Mode" is a transient technique where the amplified temperature signal from the pyrometer is acquired by the control computer and processed by the control algorithm with a cycle time of 0.7 ms. When the desired temperature is reached, the current is switched off automatically. While this mode is suitable for some applications, elevated temperature Kolsky tests done in this mode have the disadvantage that the mechanical impact may take place when the temperature is rapidly increasing or decreasing, thus affecting the repeatability of the impact temperature.

The "Isothermal Control Mode" combines the transient and the brief steady-state techniques. The specimen is maintained at an essentially constant temperature with the feedback control system which controls the current through the specimen. The computer-controlled feedback system operates a solid-state switch composed of the FETs. The sensing signal for the FETs is provided by NIMPY. Such solid-state switches are ideal for switching high currents on and off in millisecond-resolution pulse heating tests, as developed and described by Matsumoto and Ono [3]. Applications of solid-state switches for pulse heating applications have been discussed by Matsumoto et al. [4, 5].

Figure 1 is a schematic diagram showing the temperature vs. time trace for a Kolsky specimen controlled with the feedback control technique. The specimen undergoes initial rapid heating from room temperature, T_0, to a preset high temperature, T_i, in period A, followed by a brief steady-state period B, and a final cool-down period C. When the temperature of the specimen reaches the preset plateau temperature, the proportional, integral,

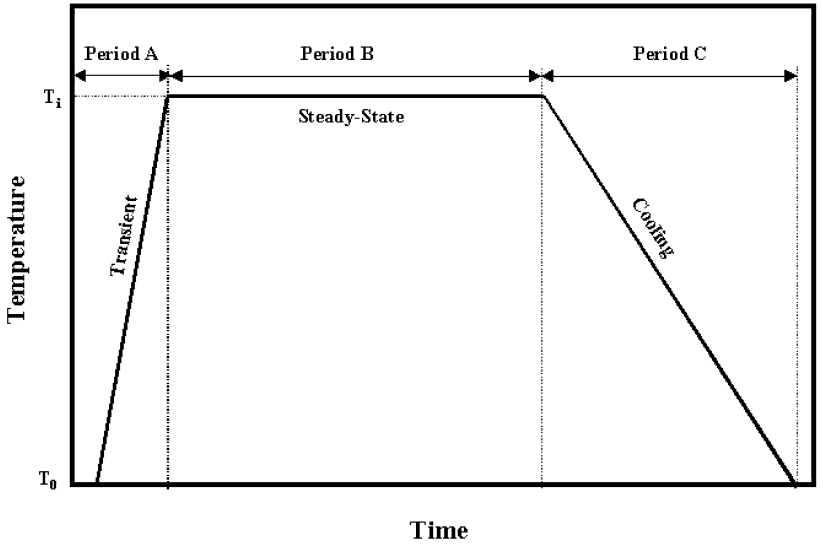

Fig. 1. Schematic diagram showing the temperature as a function of time for a typical isothermal test.

and differential (PID) algorithm in the computer program takes over the control and adjusts the current instantaneously with a high time resolution in an effort to balance the imparted electrical power to the specimen with the total power loss from the specimen, resulting in the temperature arrest, period B. The duration of periods A and B are varied depending on the requirements of the experiment. Period A can be varied by changing the imparted power to the specimen and the electrical resistance of the pulse-heating circuit, while period B can be varied by entering its value in the feedback control program.

3. MEASUREMENT AND CONTROL SYSTEM

A schematic diagram of the measurement and control system for the Kolsky bar apparatus is shown in Fig. 2. Temperature signals from the specimen were measured and recorded for each test. A single-channel spot pyrometer (NIMPY) was used for the measurement of temperature, whereas an imaging pyrometer was used to map the temperature distribution of the specimen during heating. Tests were performed on cylindrical specimens of 304 stainless steel with the following dimensions: 4 mm diameter and 2 mm length.

The specimen was held between the bars by friction only. This is necessary to enable free expansion of the specimen during impact, to facilitate

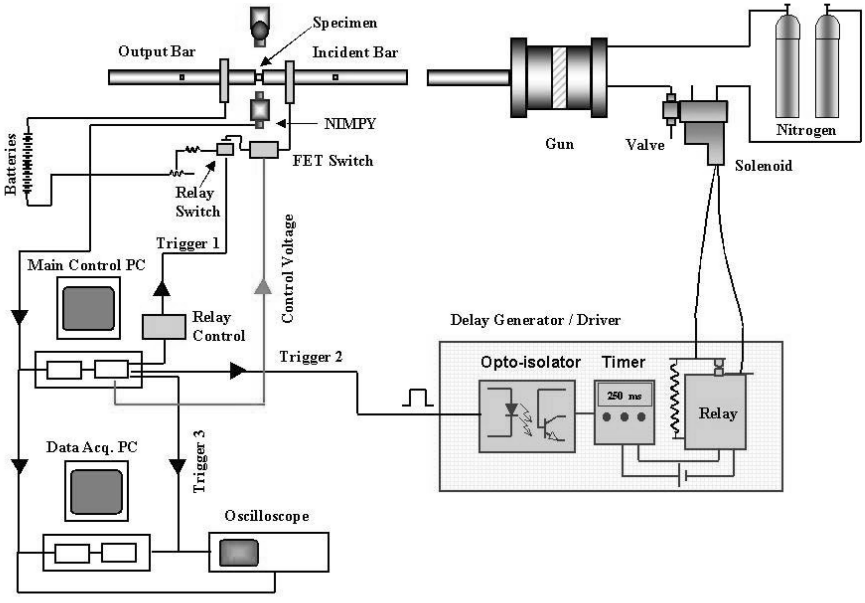

Fig. 2. Schematic diagram of the measurement and control system for the Kolsky bar apparatus.

one-dimensional wave propagation within the sample. A flexible foil of graphite (Grafoil®) with a thickness of 0.2 mm was attached to each of the bars to enable better electrical contact between the specimen and the bars. The use of the Grafoil® eliminated hot spots on the specimen, resulted in better uniformity in the specimen temperature, and eliminated sparks between the bars and the specimen during heating. The electrical pulse heating circuit consists of the Kolsky specimen sandwiched between two bars, connected in series with a battery bank, a standard resistor, a variable resistor, and a computer-controlled high-speed FET switch. Details of the pulse heating system are discussed by Basak et al. [6]. A constant flow of argon gas is maintained to form an inert atmosphere around the specimen. The main elements of the feedback control system are the pyrometer (NIMPY), the FET switch, and the control algorithm. These elements are described below in more detail.

A typical elevated temperature Kolsky experiment is initiated by sending simultaneous trigger pulses to multiple devices (see Fig. 2). The mechanical safety relay switch is first closed. The high control voltage is then sent to the gate of the FETs, which allows a controlled high current to flow through the specimen. This results in the rapid temperature rise, followed by a temperature arrest. At the same time, a trigger is sent to the

"Delay Generator and Driver Unit," where a preset delay is entered. This delay (150 to 350 ms) is comparable to the time it takes for the specimen to heat from room temperature and stabilize at the desired high temperature, minus the time required by the mechanical system to fire the projectile. This timing arrangement ensures that the mechanical impact to the specimen occurs after the specimen has reached a steady-state condition. Trigger pulses are also sent simultaneously to all the recording instruments, which acquire the data with a high resolution.

3.1. Pyrometer

The high-speed near-infrared micro-pyrometer (NIMPY) was designed using a commercial 5× objective lens (NA 0.14) with a 50% transmission beam-splitter to view the specimen with a 1 mm spot size. Figure 3 shows a schematic of the NIMPY. The detector is a temperature stabilized (248 K) InGaAs photodiode, manufactured by Germanium Power Devices, whose spectral responsivity peaks at 1.5 μm wavelength and can operate at a sampling rate of 1 MHz. The photodiode is used without any spectral filtering. A refractive objective made out of crown and flint glasses is used which enables transmission up to 1.7 μm wavelength. The signal from the photodiode is amplified with an amplifier which has a minimum bandwidth of 800 kHz and operates at a gain of 10^6. The lower threshold temperature for this instrument is about 650 K. Originally set up as a measurement device for the Kolsky bar apparatus, the pyrometer is currently being used

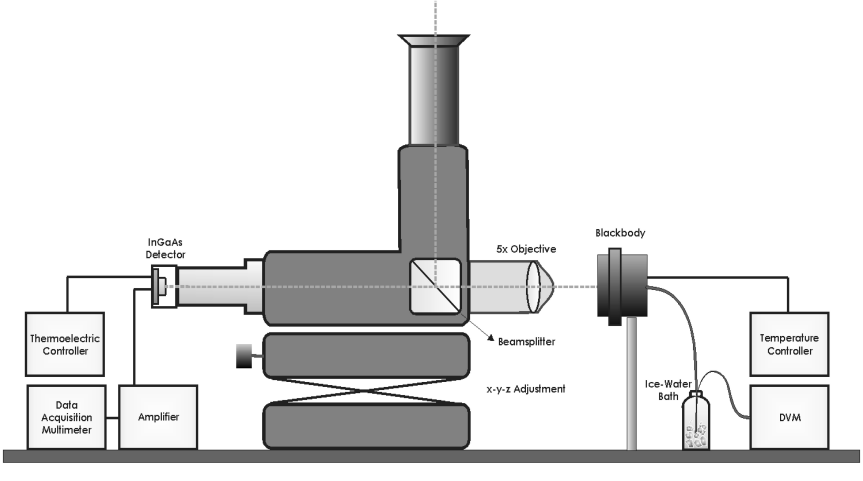

Fig. 3. Schematic of the near-infrared micro-pyrometer (NIMPY) along with calibration instrumentation.

as both a measurement and a control instrument to monitor and control specimen temperature. The pyrometer was calibrated using a blackbody operating at known temperatures and emissivity (0.99 ± 0.005).

Preliminary temperature control tests were done on samples of 304 stainless steel. Hence, the reflectance of this steel was measured in the near-infrared wavelength region along with the spectral power responsivity of the InGaAs detector. The reflectance of the polished steel sample was measured at room temperature in the NIST IR Spectral Reflectivity Facility using an FT-IR spectrometer [7]. The spectral power responsivity was measured at the NIST Spectral Comparator Facility. The detector scale is traceable to an electrical substitution radiometer. The spectral reflectance was weighted by the spectral power responsivity to obtain a single band-weighted reflectance value (0.52), and the corresponding emissivity (0.48) was determined from the measured reflectance using Kirchhoff's law for opaque bodies,

$$\varepsilon_\lambda = 1 - r_\lambda \tag{1}$$

where ε_λ is the spectral emissivity and r_λ is the spectral reflectivity. The thermodynamic temperature was determined using the radiance temperatures obtained from the pyrometer calibration function and the corresponding emissivities, at room temperature. For the preliminary tests done in this study room temperature emissivity was used to calculate true temperature for the entire range, but tests are planned for the future to measure specimen reflectivity at elevated temperatures. It is also worth noting that since the measurement of specimen temperature is performed at the short wavelength region of the Planck radiation law, the sensitivity to changes in the emissivity is minimized [8].

3.2. Switch

The solid-state switching system consists of 20 FETs connected in parallel with a total of 80 protective resistors, 0.1 Ω each. The specifications of the FETs are given in Table I. The switch is controlled by a control voltage (gate-source voltage) which is in the range from 0 to 10 V. In principle, current through an individual FET may be approximated by a quadratic function of the control voltage,

$$I_{sw} = K_c(V_c - V_t)^2 \qquad (V_c \geqslant V_t) \tag{2}$$

where I_{sw} is the current through the switch, K_c is the gain of the current, V_c is the control voltage, and V_t is the threshold voltage. The control

Table I. Specifications for Individual FETs and the Overall Switch Used for Temperature Control

Experimental parameters	FET	Switch
Maximum continuous current (A)	145	2900
Maximum heat dissipation (W)	500	10
Maximum response time (ns)	340	340
Control Voltage, V_c (V)	0 to 20	0 to 20
Threshold Voltage, V_t (V)	3.6	3.6
Resistance (mΩ)	11	1.8
Gain, K_c ($A \cdot V^{-2}$)	27	530

voltage is transferred from the computer to the FETs by a control unit which is essentially a differential amplifier of unity gain.

3.3. Feedback Control Algorithm

The PID feedback control technique is widely used in laboratory and industrial applications. The details of this theory can be found elsewhere [4, 9]. The feedback temperature control was performed using a dedicated personal computer with analog-to-digital (A/D) and digital-to-analog (D/A) converters with 12-bit resolution. The basic equation used in the PID control algorithm is given by

$$u = K_p e + K_d \frac{de}{dt} + \frac{1}{K_i} \int e \, dt \tag{3}$$

where u is the normalized control output ($-1 \leqslant u \leqslant 1$), t is the time, K_p, K_i, and K_d, are the proportional, integral, and differential constants, respectively, and e is the control error given by

$$e = (T_i - T_r) \tag{4}$$

where T_i is the desired or set temperature and T_r is the measured temperature. The normalized control output is related to the control voltage of the switch by

$$V_c = (u+1)(V_{max} - V_t)/2 + V_t \tag{5}$$

where V_{max} is the maximum control voltage, which is approximately 10 V.

The steps involved in a single loop of control include the following:

(i) Output voltage from the pyrometer (NIMPY) is sampled by the A/D converter.

(ii) A radiance temperature is calculated from the output voltage.

(iii) A corresponding control voltage is computed using Eqs. (3), (4), and (5).

(iv) The digital value of the control voltage is converted to real voltage by the D/A converter.

(v) The control voltage is transferred to the gate of the FET switch through the differential amplifier.

(vi) The current flowing through the FETs is adjusted according to Eq. (2).

The stability and convergence of the control system are strongly dependent on the values of the three constants, K_p, K_i, and K_d. Several tests were conducted by varying the values of these constants to optimize the system for a given set of conditions. These constants are especially sensitive to the specimen resistance, contact resistance between the specimen and bars, desired specimen temperature, ambient temperature, and argon flow rate.

Tests were also conducted with a simplified proportional and differential (PD) control method which ignores the integral component, K_i. An advantage of the PD control mode is the simplicity of calculation resulting in smaller loop time and lesser sensitivity to varied operational conditions. However, it does have the disadvantage that the temperature offset from the set-point could be larger. All results presented in the next section are based on the PD control mode.

4. RESULTS

Figure 4 shows the temperature vs. time trace of a test conducted in the "Time + Temperature Control Mode." For this test, the preset specimen temperature was 1060 K and the actual maximum temperature was 1065 K. The 5 K overshoot was largely due to the fact that the grafoil, which has a higher resistivity than the sample and bars, heats significantly during the test and continues to conduct heat to the specimen for a few milliseconds after the current is switched off. This has been observed with the high speed imaging pyrometer.

Figure 5 shows test results for three tests conducted in the "Isothermal Control Mode." The average plateau temperatures obtained for these tests

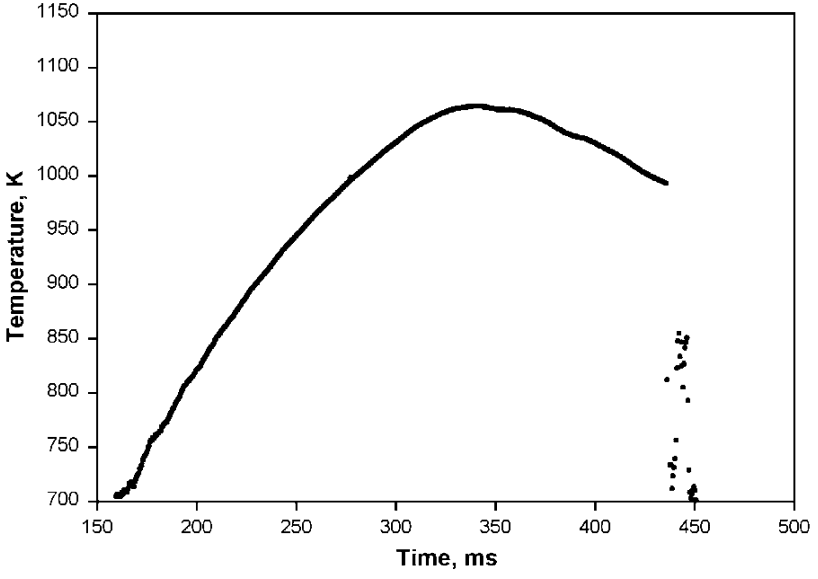

Fig. 4. Results of a temperature control test conducted in the transient (Time + Temperature Control) mode.

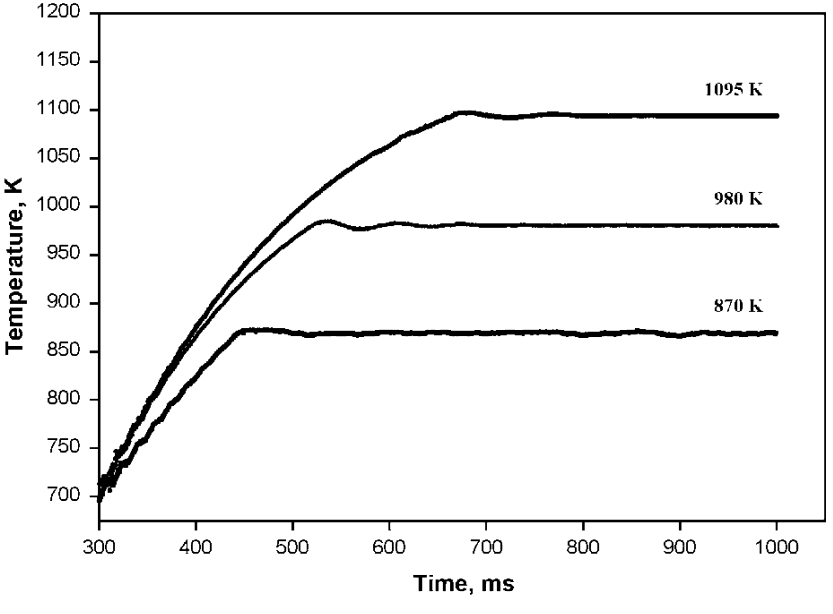

Fig. 5. Results of temperature control tests conducted at three temperature levels, in the transient plus brief steady-state (Isothermal Control) mode.

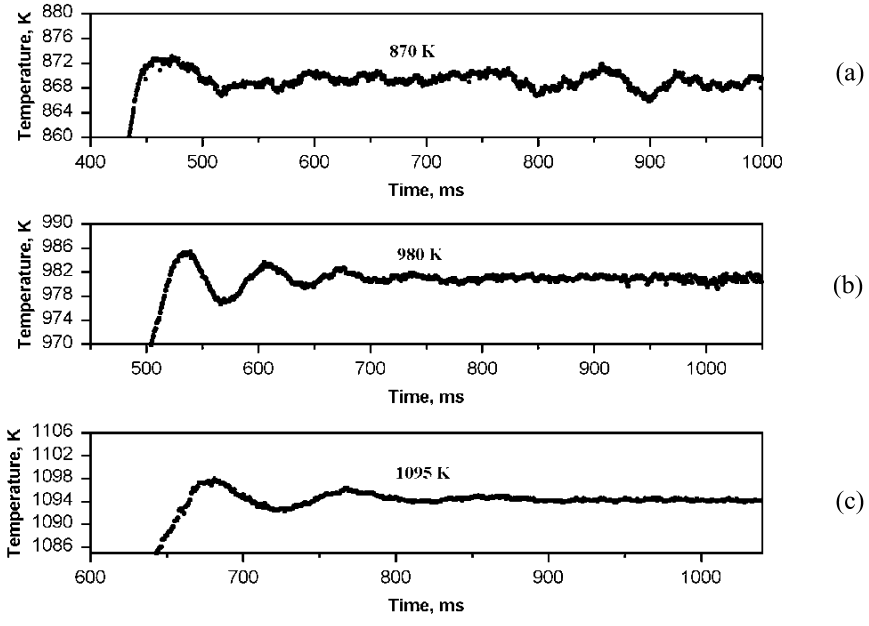

Fig. 6. Results of the temperature control tests shown in Fig. 5, with the plateau region magnified. The average plateau temperature is (a) 870 K, (b) 980 K, and (c) 1095 K.

are 870, 980, and 1095 K. Figure 6a, b, and c shows the individual plots with the plateau region magnified. The details of the tests are given in Table II. Set point temperature (Column 1) is the desired plateau temperature of the specimen, preset through the control software before the start of the test. Average plateau temperature (Column 2) is the average of the actual specimen temperature at the plateau after it has reached a steady state. ΔT (Column 3) is the difference between the set-point temperature and the average plateau temperature. Column 4 is the standard deviation from the mean plateau temperature. Time to plateau (Column 5) is the time

Table II. Details of Isothermal Tests Performed on Kolsky Specimens

Temperature (K)		ΔT	Std. dev.	Time to plateau	Time to stability
Set point	Plateau avg.	(K)	(K)	(ms)	(ms)
869	869.2	0.2	1.1	450	125
982	980.8	−1.2	0.8	525	100
1096	1094.5	−1.5	0.3	670	70

required for the specimen to reach the preset plateau temperature after initially applying power to the specimen. Time to stability (Column 6) has been arbitrarily defined as the time required from the beginning of the plateau until the temperature is stabilized to vary less than ± 2 K from the plateau average.

5. MODELING PULSE HEATING OF THE SPECIMEN

We have developed a one-dimensional thermal model of the pulse heating experiment based on the heat equation with temperature-dependent coefficients, in order to predict the temperature history of the specimen for comparison with the test results. The high dc current I through the circuit causes rapid Joule heating almost entirely within the specimen, because its electrical resistance is much larger than that of the bars due to its smaller diameter. In such a rapidly heated condition, heat losses due to convection, conduction, and radiation are estimated to be insignificant compared to the Joule heating per unit volume V_S of the specimen. Hence, the approximate heating rate of the specimen $\dot{q}(t)$ is given as

$$\dot{q}(t) = I^2(t)\, R_S(t)/V_S = I(t)\, E_S(t)/V_S \tag{6}$$

where R_S and E_S are the resistance and the potential difference across the specimen, respectively. The value of $\dot{q}(t)$ is estimated to be very large because the maximum current in the circuit is on the order of 1000 A, the maximum voltage across the specimen is about 2.5 V, and the specimen volume is small, $2.5 \times 10^{-8}\ \mathrm{m}^3$. Furthermore, since the volume of each of the bars is on the order of 10^3 times greater than that of the specimen, most of the bar material, except for a thin layer on either side of the specimen, remains at its initial temperature during the several hundred millisecond time interval of the test.

We have assumed that the main system parameter affecting the heat transfer from the specimen to the bars is an interface thermal contact conductance H_C, resulting from imperfect contact between the specimen and bars over the specimen cross-sectional area A_S. Assuming that the contact pressure is on the order of $100\ \mathrm{kN \cdot m^{-2}}$, the approximate range for the contact thermal conductance for steel at room temperature, $\theta_0 \approx 300$ K, is given as 300 to $11000\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ in the literature [10]. H_C generally increases with interface temperature, pressure, and smoothness of the two contact surfaces. Unfortunately, there are not much data available on these variables. Therefore, we have employed an approach in which H_C is treated as a constant parameter and equal for both contacts, and the value of He in the model defined by Eq. (6) that gives the best fit to the measured

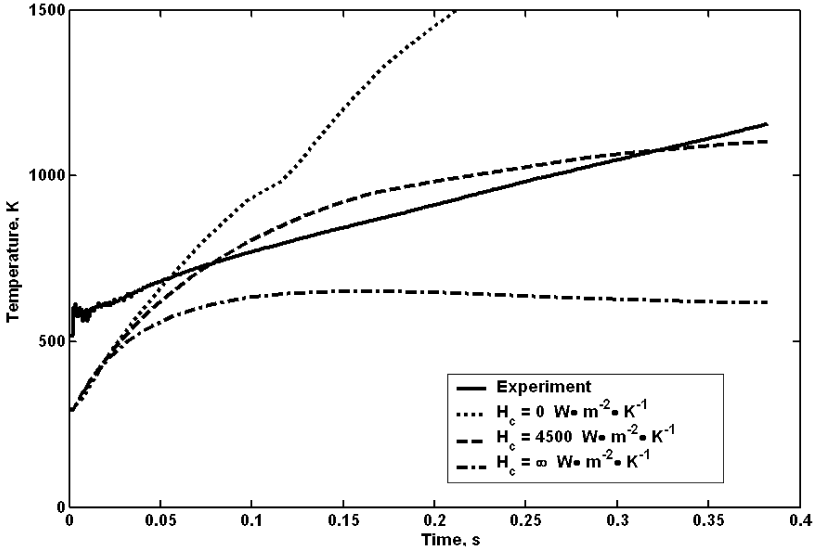

Fig. 7. Temperature history of the specimen as predicted by the model along with measured temperature data.

temperature data is estimated numerically. Using this approach, for the present data we have found that $H_c \approx 4500\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$; see Fig. 7. This result is within the range for this parameter in the literature [10]. It may be noted that at lower temperatures (< 700 K) the discrepancy in the curve between the model and experiment is partly due to the insensitivity of the pyrometer. For comparison, the specimen-center temperature is also shown for the adiabatic case $H_C = 0$ (no heat loss to the bar), and for the case $H_C = \infty$ (bar is an isothermal heat sink at ambient temperature θ_0).

6. DISCUSSION AND CONCLUSION

In general, the current test results under discussion show a rather high degree of temperature control (a maximum 2σ standard deviation of 3 K is obtained). The magnitude of ΔT increases slightly with the increase in plateau temperature, the maximum deviation from the set point being limited to 1.5 K. The standard deviation decreases with an increase in plateau temperature, due to the better signal-to-noise ratio obtained at higher temperatures. The standard uncertainty (2σ) in the measured temperature is 3% under ideal conditions [8]. The quality of the feedback control attained in the discussed experiments is judged adequate for the current application. However, by tuning the system better, it is possible to

obtain temperature stability in a shorter time and to reduce the initial oscillations in temperature. Work is currently in progress to obtain a more optimized system to provide a higher degree of repeatability for the elevated temperature Kolsky experiments.

The calculated result from a one-dimensional model of the pulse heating experiment was found to be consistent with the available data. The bounds for the predicted temperature were also generated for the isothermal and the adiabatic case, which were found to be reasonable.

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