QUANTITATIVE INFRARED THERMOGRAPHY FOR MEASUREMENT OF TEMPERATURE-DEPENDENT MATERIAL PROPERTIES

by E.A. Fuchs, P. Hughett and D.C. MacMillan

Surface temperature measurements are required for many applications in mechanical engineering, aerodynamics, electronics, and other fields. Contact thermometers can be used but suffer some disadvantages. First, they provide point measurements only; temperatures at points between thermometers must be estimated by interpolation. Second, thermometers may be detached by thermal or mechanical stress. Third, they may distort the temperature distribution being measured. Fourth, they may not survive a harsh test environment.

Surface temperature may also be determined remotely by measuring the infrared radiation emitted from a specimen. The radiance depends on the temperature, material, and viewing angle and can be measured with a radiometer. If a scanning radiometer is used, a temperature image can be generated which shows the temperature at any visible point. Reported applications of infrared thermography include studies in the deformation of stainless steel,[1] laser heat treatment,[2] hypersonic wind tunnel experiments,[3] thermal management of electronic modules,[4,5] impact testing of polymer foams,[6] arc welding,[7] and constitutive modeling of nylon.[8]

In order to develop and validate material models that can accurately represent coupled thermal and mechanical behavior, it is necessary to measure material properties as a function of temperature. In general, both temporal and spatial resolution are needed to define the development of the temperature field during a test. Because of the drawbacks of spot detectors and the need to obtain continuous full-field data, we used an imaging infrared radiometer to measure the temperature of stainless steel undergoing tensile deformation. This technique provides accurate, full-field surface temperature measurements without contacting the specimen. A full-field temperature image as well as the point and time of strain localization can be easily recorded during a test. The data are stored on videotape and temperatures are calculated after the experiment with the Video Digital Analysis System (VDAS). The temperature at a given point can also be calculated in real time by VDAS and used by the Program for Adaptive Control (PAC) to control the specimen temperature during the tests.

In the tests reported here, solid cylindrical samples of 304L stainless steel were pulled at a constant rate using a servo-controlled axial test machine. First, quasi-static tensile loading at varying temperatures was used to provide data for the material constitutive model. Then, tensile loading, with two temperature changes during the test, was used as a preliminary step in validating the model. A feature of our results is that we obtain full-field temperature measurements that can be directly correlated to stress and strain measurements. It is important to combine temperature measurements with the mechanical measurements because the flow stress of 304L stainless steel is strongly temperature dependent. This dependence must be accurately represented in the constitutive model.

EXPERIMENTAL METHOD

Thermography

The temperature of a specimen can be determined from its infrared radiance provided that the specimen emissivity and ambient radiance are determined. One approach is to estimate or measure specimen emissivity and ambient radiance and then to compute the temperature from the equations given by Bruno et al.,[9] Cetas,[10] Orlove,[11] or Hughett and Fuchs.[12] The emissivity of the surface must be known but the determination of trustworthy emissivity values is a difficult problem. Spectral or effective, rather than total, emissivity values are required but are not often found in the literature. In addition, the emissivity of metals depends strongly

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on temperature and surface roughness.

Another technique is to coat the specimen with powder, tape, paint, etc., with high emissivity.[9,11] This method is successful in many applications but does not work in all cases. A coating must be selected which will not decompose or react with the specimen and which has a constant high emissivity over the temperature range expected. Some of the problems encountered are that: (1) the coating may debond under thermal or mechanical stress; (2) ablation or mechanical distortion of the specimen will expose a new uncoated surface; (3) the coating changes the thermal characteristics of the specimen and may disturb the temperature distribution.

A third method called the specimen calibration method[12] was used. We prepared a calibration curve relating observed radiance and temperature for the 304L stainless steel under the actual experimental conditions. Once the calibration curve is known, the temperature can be measured accurately without attaching a thermometer or coating the specimen.

Testing a metallic specimen at elevated temperature

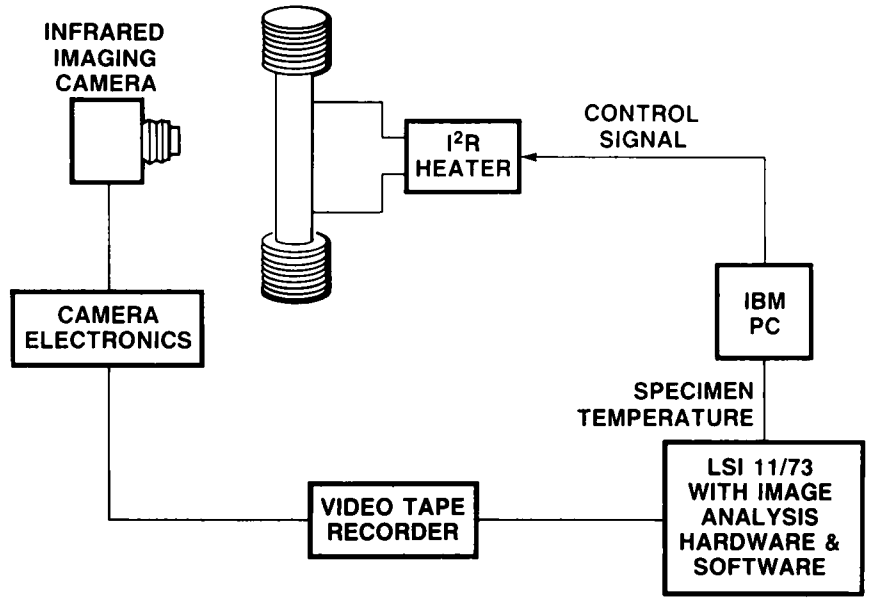

Fig. 1—*Experimental test set-up*

Image Analysis

Infrared imagery in the 8-12 μm band was obtained with an Inframetrics 525 thermal imaging camera with the 8-bit option. The tests were run in the full image mode yielding a 30-Hz sample rate. The information was stored on a videotape recorder and post-processed as described in Fig. 1. The video image was digitized by an Imaging Technology model IP512 image-processing board set installed in a PDP-11/73 host computer. The IP512 provides four frame memories, each one of which is 512 pixels square and is 8 bits deep. Output video is three-channel RGB processed through color look-up tables and is compatible with standard video equipment.

The most accurate temperature measurements using VDAS require the preparation of a calibration curve for the specific specimen design and environmental conditions. To determine this curve, a platinum resistance thermometer was attached by a thermally isolated screw to the surface of a specimen of the material being tested. A layer of silicone heat sink material was placed between the specimen and the thermometer to ensure good thermal contact. VDAS automatically collects and reduces the data.

Program for Adaptive Control

The program for adaptive control (PAC) was designed to control the temperature of a metallic specimen.[13] PAC is part of a closed-loop system that includes the ability to start and stop a servo-hydraulic test machine. The system also includes a video synchronizer which looks at the video signal and initiates the test when the top of the video frame is detected. A vertical line 3 pixels wide is written on the video to allow the temperature and mechanical data to be synchronized. In the calibration mode, the control temperature signal is derived from a resistance thermometer. In the test mode, a digital signal is received from VDAS.

PAC was written for an IBM PC with digital and analog interface capabilities. The optimum controller design depended strongly on the specimen design because the power (or heat) generated in the specimen is a function of the cross-sectional area and the resistivity of the specimen. During a test the specimen will change dimension as it is pulled, resulting in a smaller cross-sectional area. As the specimen is heated, the resistivity goes up. In addition, the specimen design could change radically between tests. For these reasons the control program was redesigned as an adaptive controller.

An adaptive controller easily accommodates wide variations in the specimen and test equipment characteristics. PAC consists of an estimator, a controller designer and the controller. The estimator is a least-squares estimator similar to one suggested by Goodman.[14] It estimates the parameters based on past estimates, past control effort, and the difference between the estimated present temperature and the actual present temperature. The control designer uses these new estimates and the desired closed-loop performance to derive new parameters for the control algorithm. The controller uses the present temperature error and produces new control effort commands. This process repeats continuously for the duration of the test. It takes less than 90 seconds for PAC to reach a desired temperature and stabilize within ± 1 percent.

TEST PROCEDURE

The tests were run in three stages. In order to calibrate, a resistance thermome-

ter (RTD) was attached to the specimen. This RTD served as the feedback to PAC. The infrared imaging camera measured the radiance data from the same area as the RTD. VDAS then calculated the temperature of this spot on the specimen and compared it to the temperature measured by the RTD. The specimen was stepped through a series of temperatures, typically six to ten different temperatures, in the range of interest. Data were acquired after the temperature had stabilized to reduce transient effects. As a final step in the calibration, a new specimen was inserted in the fixture and the same calibration was run to check the accuracy of the calibration curve. The second step was to run an actual test using the infrared imaging camera with VDAS to provide feedback to PAC and to record the full-field temperature data on a video tape recorder, Fig. 1. The third step was to analyze the temperature data using the information recorded on the video tape.

The specimens used in the present test series were tensile specimens with bulky ends to approximate adiabatic end conditions and to allow the leads from the DC power supply to be easily attached as shown in Fig. 2. The tests at constant temperature (300°C, 500°C and 700°C) and constant quasi-static crosshead rate (.254 mm/s) were run to provide data for the material model constants under isothermal conditions. Because PAC was used to control the temperature in these tests, the specimen temperature remained essentially constant for the entire test.

The tests performed as a preliminary step in validating the material model were also performed at a constant crosshead rate of .254 mm/s, with temperature changes introduced during the test. The tests consisted of five steps: (1) bring the specimen to the desired temperature T_1 and then pull at a constant crosshead rate for a set time t_1; (2) hold the deformation constant while heating the specimen to a new temperature T_2; (3) maintain T_2 while pulling at a constant crosshead rate for a set time t_2; (4) hold the deformation constant while bringing the specimen to a new temperature T_3; (5) pull the specimen at a constant crosshead rate to failure while maintaining T_3. Table 1 summarizes these test parameters. The tests were run on an MTS 880 tension/compression servo hydraulic machine.

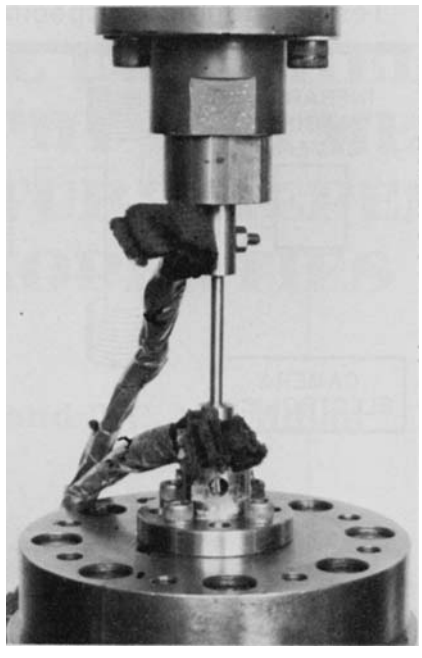

Fig. 2—*Photograph of the specimen mounted in the test frame. The gage length of the specimen is 50.8 mm. The diameter is 6.4 mm. The bulky cables attached to the ends of the specimen carry the current*

TABLE 1—

Test Parameter	Test 1	Test 2
T_1 (°C)	50	500
t_1 (s)	400	375
T_2 (°C)	200	300
t_2 (s)	120	120
T_3 (°C)	300	500

RESULTS

When a material is deformed beyond its elastic range, a temperature increase can occur which is thermodynamically coupled to the non-recoverable work of deformation. Nevertheless, inelastic deformation can take place isothermally when the material has a high thermal conductivity and/or the deformation rates are low enough to ensure thermal equilibrium. In these tests, because of the slow rate and the controlled heating, the tests were isothermal until the strain localizes in the last second of testing. A typical curve illustrating the temperature distribution along the reduced section of the specimen is shown in Fig. 3. These localization data are not shown on Fig. 4 because the clip-gage data (used for strain measurement) appeared unreliable.

Figure 5a shows the true stress versus true strain curves for the temperature change Test 1. Figure 5b is the true stress versus true strain curve for a temperature change Test 2. A future paper will discuss the comparison of the data with the model predictions.

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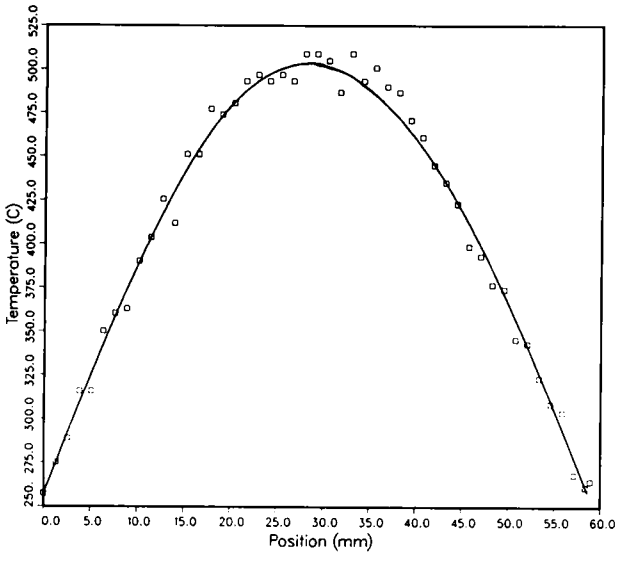

Fig. 3—*Temperature as a function of position along the reduced section of the specimen*

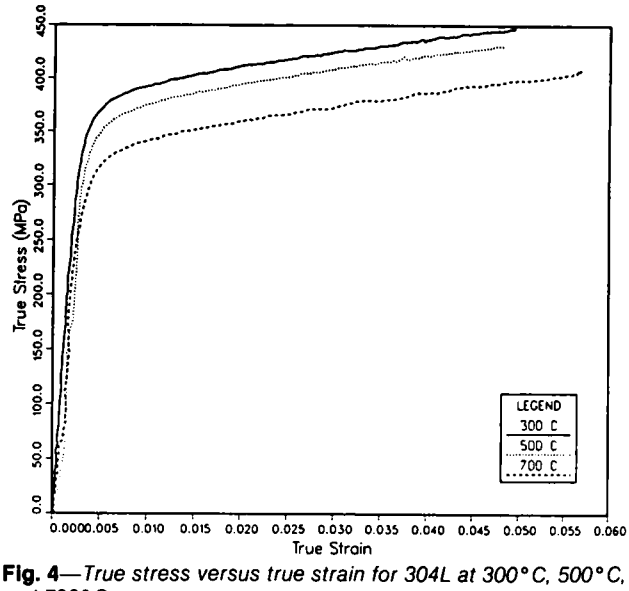

Fig. 4—*True stress versus true strain for 304L at 300°C, 500°C, and 700°C*

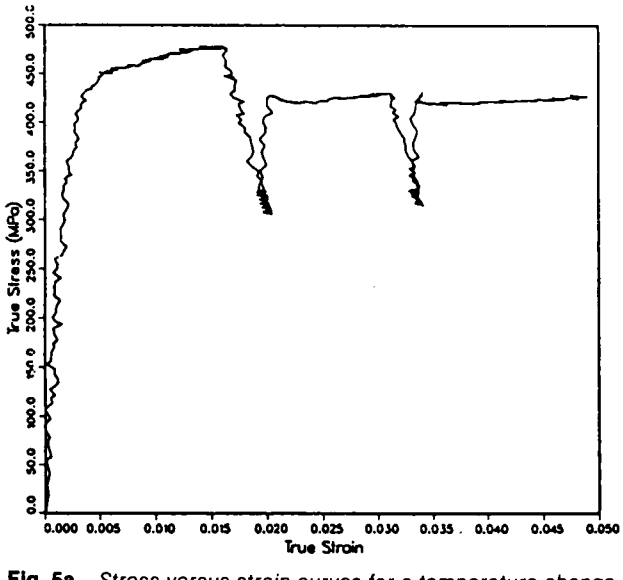

Fig. 5a—*Stress versus strain curves for a temperature change of 50°C, 200°C, and 300°C*

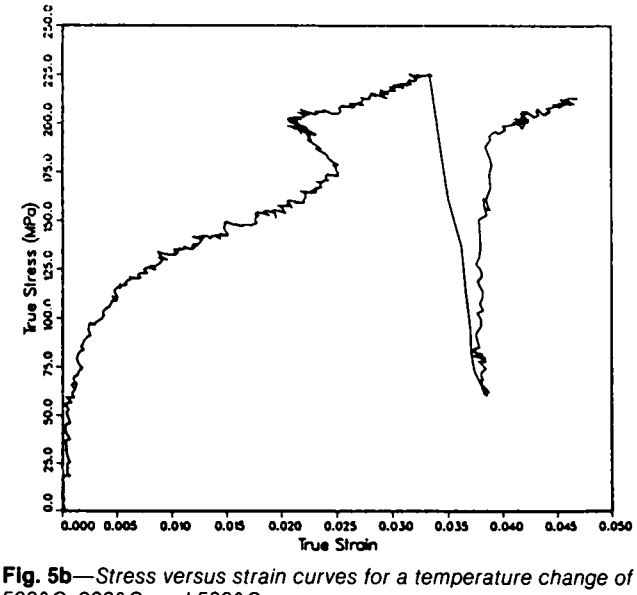

Fig. 5b—*Stress versus strain curves for a temperature change of 500°C, 300°C, and 500°C*

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