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Laser-Based Strain Measurements For High Temperature Applications

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SUMMARY

The Instrumentation and Control Technology Division at NASA Lewis Research Center has developed a high performance optical strain measurement system for high temperature applications using wires and fibers. The system is based on Yamaguchi's two-beam speckle-shift strain measurement technique. The system automatically calculates surface strains at a rate of 5 Hz using a digital signal processor in a high speed micro-computer. The system is fully automated, and can be operated remotely.

This report describes the speckle-shift technique and the latest NASA system design. It also shows low temperature strain test results obtained from small diameter tungsten, silicon carbide, and sapphire specimens. These specimens are of interest due to their roles in composite materials research at NASA Lewis.

INTRODUCTION

The NASA Lewis Research Center has been engaged in an ongoing effort to develop a non-contacting optical strain measurement system. This measurement system is intended for use on test specimens subject to hostile environments, such as those found in earth-to-orbit propulsion systems.

This effort has developed systems that can measure strains along one or two principal axes at a point on a flat test specimen, at high specimen temperatures. Both one-dimensional and two-dimensional strains have been measured beyond 750°C.[1-2] The systems are based on the laser speckle-shift strain measurement technique of Yamaguchi,[3] which utilizes the linear relationship between surface strain and laser speckle shifts in the Fraunhofer diffraction plane. This technique accurately measures surface strains in the presence of rigid body motions of the specimen, and requires no surface preparation. The optical system is very stable and requires no periodic adjustment once initially aligned.

A feasibility study investigated theoretical aspects of using the system on small diameter wires and fibers at high temperatures.[4] Interest in fiber and wire materials research for the development of high temperature composites has led to the current focus of this effort, which is to make real-time uniaxial strain measurements on small diameter specimens.

The current effort advances the state-of-the-art of Lewis' optical strain measurement system, and demonstrates the successful application of the speckle-shift technique to small diameter wire and fiber specimens. Although the system is certainly not restricted to making measurements on wires and fibers, the testing emphasized these specimens to demonstrate measurements on a traditionally difficult application. In the past, strain measurements on these specimens have been made using extensometers, or even visual observation of the movement of flags on the specimen surface. These techniques have suffered from either a long gage length and/or low strain resolution. The optical technique described here features a short gage length (< 1 mm) and a strain resolution of about 15 $\mu\varepsilon$. It requires no surface preparation, and can make measurements at very high temperatures. It is estimated that measurements are feasible on specimens as hot as 2000 °C, under controlled conditions.

The low strain measurement rate of the previous speckle-shift systems (on the order of 0.1 Hz) limited the response time of the tests. The previous systems were limited to making strain measurements under strictly static conditions. Higher sampling rates and, therefore, higher computation rates were desired to allow continuous loading of the specimen at higher strain rates. This paper describes a system designed to provide high performance at low cost. The system has achieved a performance increase of nearly two orders of magnitude over the previous system, using modular, off-the-shelf components at a relatively low price.

A high speed digital signal processor (DSP) performs the strain calculations with near-real-time results. The use of a two-dimensional charge-coupled device (CCD) for the detector provides the flexibility of a standard video interface, and reduces decorrelation errors due to rigid body motions when using a two-dimensional specimen.

Theory

Objective laser speckle patterns, generated by spatially coherent illumination of a rough specimen surface, shift when the surface is strained or when the specimen undergoes rigid body motion. The speckle patterns are recorded on a sensor array, and cross-correlations of the patterns before and after they move are calculated to determine the amount of shift between them (the peak position of the cross-correlation indicates the number of picture elements (pixels) the particular speckle pattern moved). Figure 1 is a schematic of the optical setup. The figure shows a dual beam configuration, which allows automatic cancellation of rigid body motion. By taking the difference in shifts of the speckle patterns generated independently by two laser beams incident on the specimen from equal but opposite angles, error terms due to rigid body motion are canceled.

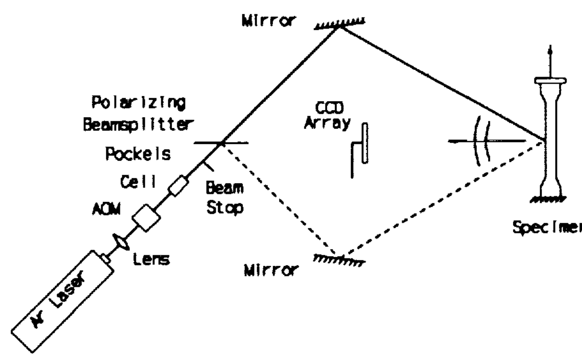

Figure 1: *Optical schematic*

The current system measures one-dimensional strain in near real-time on small diameter wires and fibers, as well as extended flat specimens, by using a digital signal processor (DSP) for the calculation intensive cross-correlations. Rigid body motion constraints and decorrelations are reduced by using a two-dimensional CCD array to record an extended speckle pattern. A two-dimensional extended pattern allows off-axis speckle shifts to be tracked dynamically, without irrecoverable decorrelation. While this is important when

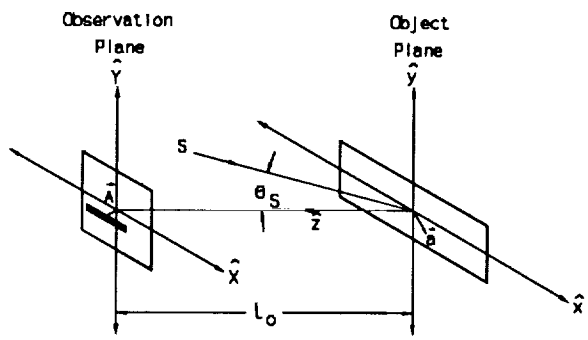

Figure 2: *Simplified coordinate system*

using flat specimens, however, tests showed that for quasi-one-dimensional specimens (defined roughly as specimens much narrower than the laser spot diameter, such as wires or fibers) the correlations are relatively insensitive to transverse speckle shifts.

Figure 2 shows the simplified geometry of the coordinate system. The specimen is in the x,y plane, and the sensor is defined to lie in the X,Y plane. The x,y and X,Y planes are separated by a distance L_0 along the z axis. Deformation of object points on the specimen surface are described by vector a(x,y), and the resulting shifts of the speckle pattern are given by vector A(X,Y). The shaded rectangle in the figure indicates a one-dimensional reference slice of the speckle pattern (one line of the 2-D CCD array) shifted from the origin by A(X,Y). The x,z plane is the plane of the incident laser beam, which comes from source point S.

After rigid body motion terms are canceled out of the simplified speckle-shift equations, the surface strain ε_{xx} in the x direction can be calculated by the relation

$$\varepsilon_{xx}=\frac{-\Delta A_X}{2L_o\sin(\theta)} \tag{1}$$

where the incident angle $\theta = |\theta_S|$, and ΔA_X is the difference between speckle shifts from the two beams

$$\Delta A_X=A_X(\theta_S)-A_X(-\theta_S). \tag{2}$$

The value of L_o is 577 mm, and θ=30° in equation 1.

SYSTEM DESIGN

The optical system uses a switched single beam design, for compactness, following the schematic in Figure 1. The argon ion laser beam is diverted into the beam stop by the acousto-optic modulator (AOM) between tests and exposures. The Pockels cell and polarizing beamsplitter form an optical switch, in order to provide two beam paths for the error cancellation. The Pockels cell rotates the polarization of the beam by $\pi/2$ radians when a high voltage is applied across it; this allows the beam to either pass through the polarizing beamsplitter, or be reflected to the other beam leg. A waist positioning achromatic lens provides a planar wavefront at the specimen surface, in order to maximize error cancellation.[2,3]

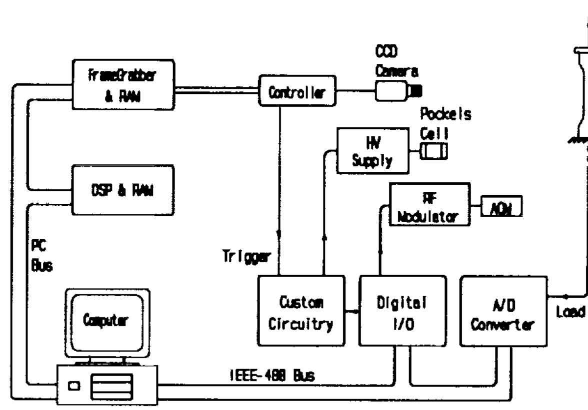

Figure 3: *Block diagram of system*

The data acquisition system is based on a high performance personal computer (Intel 80486 CPU), with a VGA graphics adapter using a graphics co-processor. This PC is the system controller, synchronizing the video and load data acquisition with the strain calculations. Figure 3 shows a block representation of the system control paths. The image processing system components (frame grabber and DSP board) plug into the computer's 16-bit I/O bus (ISA PC bus). The computer controls the data acquisition and graphics display while the DSP board correlates the speckle patterns. A simple, custom digital circuit switches the Pockels cell in synchronization with the camera. This synchronization circuit is basically a flip-flop, driven by the RS-170 even/odd field signal supplied by the CCD camera circuitry (labeled "trigger"). The exposures for the two beams are timed for successive video frames, 1/30 second apart. The output of the custom circuit is a line driver that toggles the state of the Pockels cell. The computer has an IEEE-488 bus (GPIB), to which is connected a digital I/O unit, and an analog-to-digital converter (A/D converter). The digital I/O unit controls the state of the acousto-optic modulator by turning on or off the RF signal to the crystal. The A/D converter digitizes the voltage across a load cell connected to the specimen mount.

The fibers and wires are mounted in a custom load rig. The load cell is connected to the fixed specimen grip in the rig. A stepping motor with a fine pitch lead screw moves the other grip along rails, applying a load to the specimen. The resolution of the stepping motor is much finer than the resolution of the load cell, so the loading is essentially continuous.

RESULTS

Tests of the system demonstrated the performance of the real-time speckle tracking technique, and showed that accurate strain measurements can be made on small diameter specimens. Rigid body motion tests showed that residual error was below the resolution of the system for static tests. The system measured strains at a rate of 5 Hz, which included speckle data acquisition, image transfer from the frame-grabber to the DSP board, calculation of strain, and updates to the graphics displays.

Figure 4 shows a plot of stress versus strain for a 150 µm (6 mil) diameter sapphire fiber (Saphikon). The solid line indicates a least-squares linear regression of the data. The dashed line indicates the theoretical stress-strain data whose slope represents the published value of Young's modulus for this

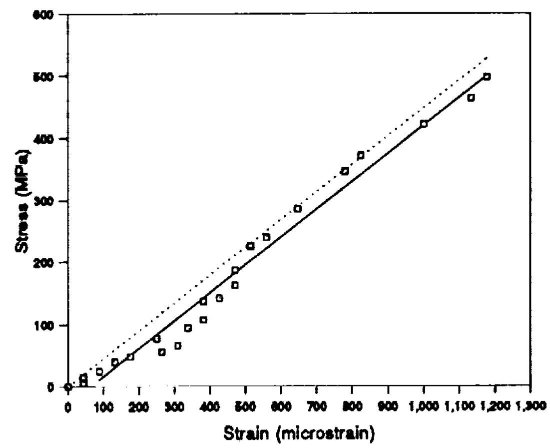

Figure 4: *Stress-strain plot for 150 µm diameter Saphikon, at room temperature*

material. The measured modulus is 450 GPa (65 Msi), which agrees with the handbook value of modulus to within two significant figures. The RMS deviation of the strain

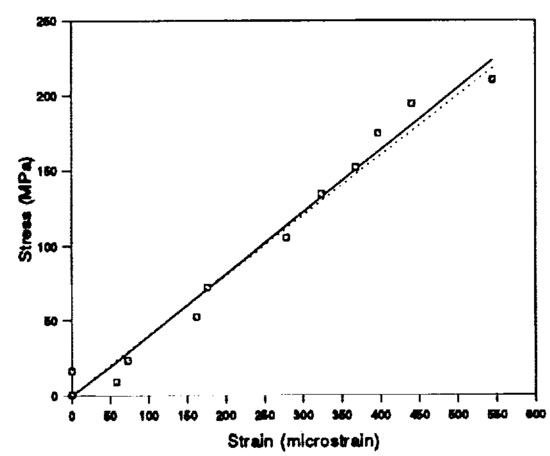

Figure 5: *Stress-strain plot for 140 µm diameter SiC fiber, at room temperature*

points from the fit is 50 με. The correlation coefficient of the linear fit is 0.99.

Similarly, figure 5 shows a stress-strain plot of a 140 μm diameter silicon carbide fiber (Textron SCS-6). The measured modulus is 410 GPa (60 Msi) and the handbook value is 400 GPa (58 Msi). The RMS deviation of the strain from the fit is 25 με. The correlation coefficient of the fit is 0.99.

Figure 6 shows a plot of the stress-strain values measured on a 76 μm (3.0 mil) diameter tungsten-3% rhenium wire specimen. The

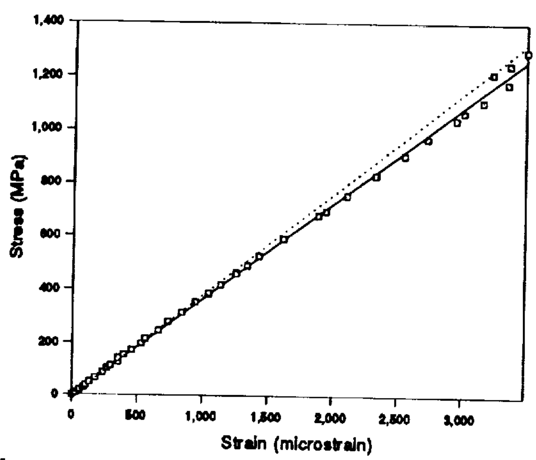

Figure 6: *Stress-strain plot for 76 μm diameter W-3% Re wire, at room temperature*

value of Young's modulus given by a fit of the measured data is 360 GPa (52 Msi) and the handbook value is 380 GPa (55 Msi). The discontinuity in the data at 1200 MPa was caused by a false correlation, such as discussed in the error analysis section, which offset the subsequent strain values by about 170 με. The RMS deviation of the corrected strain data from the fit is about 22 με. The correlation coefficient of the fit is 1.0.

CONCLUSIONS

There are two critical changes implemented in the speckle-shift strain measurement technique that, combined, create a speckle tracking system that greatly increases the usefulness of the technique. A two-dimensional CCD array camera prevents most off-axis speckle shifts from causing decorrelation, and a DSP-based processing system allows strain to be calculated at a rate near the data acquisition rate. The system has also demonstrated the ability to measure strains on small diameter wires and fibers, with no strain resolution penalty for having very short gage lengths.

REFERENCES

1. Lant, C.T., Qaqish, W.: "Optical Strain Measurement System Development - Phase I," (Sverdrup Technology, Inc.; NASA Contract NAS3-24105) NASA CR-179619, 1987.

2. Lant, C.T.: "Two-dimensional High Temperature Optical Strain Measurement System - Phase II," (Sverdrup Technology, Inc.; NASA Contract NAS3-24105) NASA CR-185116, 1989.

3. Yamaguchi, I.: "A Laser-speckle Strain Gauge," J. Phys. E. Sci. Instrum., vol. 14, no. 11, Nov. 1981, pp. 1270-1273.

4. Lant, C.T.: "Feasibility Study for the Advanced One-Dimensional High Temperature Optical Strain Measurement System - Phase III," (Sverdrup Technology, Inc.; NASA Contract NAS3-25266) NASA CR-185254, 1990.