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DESIGN AND PERFORMANCE OF
A MICROWAVE STRAIN MEASURING
SYSTEM FOR MATERIALS TESTS

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T. Roger Billeter and L. D. Blackburn

December, 1975

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T. Roger Billeter and L. D. Blackburn

ABSTRACT

Excellent sensitivity and accuracy in the measurement of deformation occurring in materials tests have been achieved with a newly developed microwave frequency sensor and instrumentation system. The strain sensor comprises a microwave cavity resonating in the circular TE₁₁₃ and TM₁₁₀ modes. Detection of axial strain occurs due to the changes of resonant frequency incurred by cavity length changes. Axial strain sensitivity for the TE₁₁₃ mode was 6×10^{-6} per MHz, whereas radial dimensions of the cavity were related to frequency of the TM₁₁₀ mode. Aperture coupling of the cavity to the end wall of K_a band waveguide provided signal excitation of the two monitored modes. Phase locked frequency stability enabled digital count/display of resonant frequencies to within 70 kHz at 35 GHz. Room temperature tension test results demonstrate a strain measuring sensitivity ($\pm 1 \times 10^{-6}$) and accuracy (± 1 percent of the measured value) equivalent to those of electrical resistance strain gages. The system yields accurate measurements of elastic strains as well as small departures from elastic response and hysteresis behavior during unloading and reloading. Creep test results confirm that measurement sensitivity and accuracy are retained in elevated temperature tests. Strain response on loading, subsequent creep deformation and creep recovery after unloading can all be measured in detail. Stability of microwave sensor calibration after exposure for 22×10^6 seconds at temperatures from 728°K to 866°K is shown to be excellent.

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INTRODUCTION

Microwave cavity resonators for use as the sensor element of measurement instrumentation have been developed for a number of applications.⁽¹⁻⁴⁾ Use of such devices often depends on a variation of resonator frequency with changes either in sensor length and diameter or in the dielectric and magnetic properties of material contained within the sensor. Experience gained in past applications provided impetus to consider the development of microwave sensors to monitor deformation occurring in materials tests. Such sensors offer a potential for high sensitivity, resolution and accuracy. In addition, they can operate directly across a relatively short section of a test specimen, thus minimizing extraneous movement in the total measuring system which could cause errors in the measured deformation. This feature of microwave strain sensors is very attractive as one of our potential applications uses the sensors for mechanical tests performed inside nuclear reactors. Experimental assemblies for such tests typically require large distances between the test specimen and external control and recording equipment; therefore a measuring system which minimizes effects of extraneous mechanical motion becomes a strong candidate for such applications.

As a first step in evaluating the potential of microwave cavities for deformation measurements, the present work included the development of a microwave sensor and associated instrumentation and tests to demonstrate the capability for measuring deformation. Operational characteristics of the microwave system were demonstrated in two common laboratory tests--the tension test and the creep test. The tension test, conducted at room temperature, compared microwave sensor measurements with electrical resistance strain gage measurements, the latter serving as a standard. Subsequently, performance of the creep test demonstrated capabilities of the microwave system for elevated temperature measurements.

THEORY, EQUIPMENT AND PROCEDURES

Theory of Microwave Resonators

Use of a microwave resonator as a strain sensor is based on the dependence of resonator frequency upon length, diameter, and the dielectric and

magnetic properties of material contained within the sensor. A particular cavity can absorb microwave energy at a multiplicity of frequencies, each associated with a mode of resonance and each having a characteristic frequency variation with changes of size or interior dielectric and magnetic properties. These modes of resonance can be excited in the cavity with use of a single wide-bandwidth exciting source of microwave energy. For a hollow right circular cylinder, the theoretical resonant frequency, f_0 , is given by⁽⁵⁾

$$f_0 = \frac{1}{4\mu\epsilon} \sqrt{\left(\frac{n}{L}\right)^2 + \left(\frac{X_{\ell,m}}{\pi a}\right)^2} \quad (1)$$

where L and a are the internal length and radius; ℓ , m , n are integer mode designators; μ and ϵ are the permeability and permittivity of the medium contained in the hollow cavity resonator; and $X_{\ell,m}$ is the argument for which the Bessel function is zero. Physically, the mode designators have simple meanings: ℓ is the number of full-period variations (of electromagnetic field) around the circumference, m is the number of half-period variations with respect to the radius, and n is the number of half-period variations along the axis of the cylindrical cavity. For TM (transverse magnetic) modes, $X_{\ell,m}$ is given by the zeros of the ℓ^{th} order Bessel function of the first kind, $J_{\ell}(X_{\ell,m}) = 0$; while for TE (transverse electric) modes, $X_{\ell,m}$ is found from $J'_{\ell}(X_{\ell,m}) = 0$, the prime indicating a first spatial derivative.

Measurement of deformation in mechanical test specimens is based on variation of absorption frequency with sensor length. The sensor used in this study exhibited four modes of resonance within the frequency band from 33.0 to 37.5 GHz, as shown in Table I. A single assemblage of microwave instrumentation for excitation and readout can be used to monitor any of the resonances, a typical display appearing in Figure 1. As shown, the upper horizontal trace represents total energy absorption. The cavity is efficiently coupled to the input waveguide at the frequencies of resonance and absorbs a large fraction of the incident microwave signal; the absorption frequencies are therefore identifiable by strong absorption of microwave energy at those specific frequencies.

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FIGURE 1. Typical Display of the Four Modes of Resonance Exhibited by Microwave Sensor. Photo No. 745602-2

TABLE I
THEORETICAL RESONANT FREQUENCIES OF CYLINDRICAL SENSORS

<u>Mode</u>	<u>Resonant Frequency (GHz)</u>	<u>Sensitivity $\left(\frac{\text{GHz}}{\text{in.}}\right)$ with Length</u>
TM110	33.4	0
TE212	34.2	34.83
TE011	34.9	10.11
TE113	36.0	58.68

Cavity Characteristics: $\mu = \mu_0$ L (length) = 13.9 mm
 $\epsilon = \epsilon_0$ $2a$ (diameter) = 10.95 mm

The theoretical variation of absorption frequency with sensor length is given by

$$\frac{\partial f_0}{\partial L} = - \frac{n^2}{L^3} \left[\frac{\left(\frac{n}{L}\right)^2 + \left(\frac{\chi_{\ell,m}}{\pi a}\right)^2}{4\mu\epsilon} \right]^{-1/2} \quad (2)$$

where the symbols are as defined for Equation (1). The relationship between mode resonant frequency and cavity length is obviously non-linear, but for very small changes in length the sensitivity remains nearly constant, as subsequent discussions of sensor calibration will demonstrate. Each of these resonant modes for the cavity exhibits a different frequency sensitivity with length changes, as each mode has a different value of n . Consequently, the cavity may be employed as a sensor to measure very small axial strain by monitoring the most sensitive TE113 mode response or very large strains with use of the least sensitive TE011 mode response. Additionally, the sensor diameter can be measured nearly independent of length with measurements of the TM110 frequency. In the present work, we chose the TE113 and TM110 mode frequencies for our measurements.

The microwave signal propagating along the hollow rectangular waveguide must excite the cavity into resonance. Effective coupling of the electromagnetic

signal between the waveguide and cavity requires an aperture located at a position of common electromagnetic fields on either side of the metal wall separating the two microwave components.⁽⁵⁾ An approximate location of the aperture can be determined by considering the wall currents which flow due to electromagnetic fields in the cavity and in the waveguide. The aperture in the cavity must be placed at a position where the magnitude and direction of magnetic field components, and thus the wall currents, correspond closely with those in the waveguide.

At the end wall of the rectangular waveguide, the magnetic field is transverse to the direction of propagation and directed parallel to the wide dimension of the waveguide (Figure 2). Consequently, end wall currents flow from bottom to top directed parallel to the narrow rectangle direction with a maximum amplitude at the center at $x = W/2$. In the cavity only the magnetic field components H_r and H_θ which cause end wall currents must be analyzed. Using the particular characteristic value for the TE₁₁₃ mode, magnetic fields at the end wall expressed in a cylindrical coordinate system are

$$H_r = \frac{\frac{3\pi}{L}}{\left[\left(\frac{3\pi}{L}\right)^2 + \left(\frac{X_{11}}{a}\right)^2\right]^{1/2}} J_1' \left(\frac{X_{11} r}{a} \right) \cos \theta$$

$$H_\theta = \frac{\frac{3\pi}{L}}{\left[\left(\frac{3\pi}{L}\right)^2 + \left(\frac{X_{11}}{a}\right)^2\right]^{1/2}} \frac{J_1 \left(\frac{X_{11} r}{a} \right)}{\frac{X_{11} r}{a}} \sin \theta$$

where J_1 is a Bessel function of the first kind; r is the radial distance from the sensor axis; and the other quantities are as previously defined. Radial magnetic field components are maximum at the cavity center and decrease to a minimum at the outer edge ($r = a$) with a variation determined by the Bessel function or its spatial derivative. Positioning of a slot aperture radially outward from the center of the end cap couples the waveguide vertically-oriented and the cavity circumferentially-oriented wall currents.

FIGURE 2. Schematic Illustration of Magnetic Field Lines at:
 (a) Terminal End of Waveguide and (b) End Wall
 of Cylindrical Sensor. Photo No. L-225-3

The slot size and off-set radial position must be determined experimentally to provide optimum signal coupling. The schematic of the sensor/waveguide junction (Figure 3) illustrates relative positions of these two components.

Digital Measurement of Microwave Frequency

Excitation of the microwave cavity and readout of its resonant frequency is accomplished ⁽⁶⁾ with the circuit depicted in block diagram in Figure 4. The cavity sensor connects to external instrumentation via 3.56 mm by 7.11 mm rectangular waveguide (K_a band). External equipment includes the microwave signal source (backward wave oscillator) and two auxiliary RF instrument loops--one to maintain the oscillator output frequency in coincidence with the sensor resonant frequency using a lock-in amplifier, the other a digital frequency counting scheme. Phase lock of the signal source to the selected

POSITION OF COUPLING SLOT RELATIVE TO RECTANGULAR WAVEGUIDE AND TO CYLINDRICAL SENSOR

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FIGURE 3. Position of Coupling Slot Relative to Rectangular Waveguide and to Cylindrical Sensor. Photo No. L-225-3

mode of resonance of the sensor results by frequency modulation of the master oscillator with a 1000 Hz reference signal from the lock-in amplifier. The amplitude of modulation is adjusted manually to obtain a frequency deviation of ± 5 MHz about the center frequency of the master oscillator. Frequency coincidence of the master oscillator and the sensor resonance causes a detected signal with a 2000 Hz frequency component to be input to the lock-in amplifier. Within the amplifier, detection synchronous with the 1000 Hz reference signal restricts the effective amplifier bandwidth so only signals within several hertz of the reference frequency are amplified. Consequently, a d-c error signal is output from the lock-in amplifier only when the sensor and microwave oscillator are not frequency coincident, a condition which causes the detected signal to contain a 1000 Hz component. A d-c error signal of amplitude just sufficient to maintain frequency coincidence of the sensor and microwave oscillator exists as the output of the lock-in amplifier.

FIGURE 4. Block Diagram of Microwave Frequency Measurement System.

The helix of the master oscillator, the control element adjusting the output frequency, responds to both the error signal and the 1000 Hz reference modulation signal, combined in an operational (summing) amplifier.

A small fraction of the incident signal, diverted to a mixer crystal, combines with a harmonic of the local oscillator. Through operation of the synchronizer, the local oscillator emits an output signal frequency which is a subharmonic of the master oscillator frequency. Digital readout of the local oscillator frequency occurs by frequency down conversion in the transfer oscillator; this down converted signal being displayed on a digital counter. Ultimately, the accuracy of determining the source output frequency, identical to the sensor frequency, depends upon a 20 MHz crystal oscillator contained within the synchronizer unit. This crystal oscillator has a 24-hour stability of $2 \text{ in } 10^6$ parts per 24-hour period. The digital frequency measurement scheme, as opposed to other common methods of microwave frequency determination, provides required measurement resolution of at least 1 MHz out of 35,000 MHz.

Although sensor frequency was the observed output variable for the experiments described, the specimen length could be indicated directly with use of a proportioning unit to automatically convert frequency to sensor (or specimen) length. Likewise, the instrumentation could be adapted for automatic data acquisition to provide further versatility.

Microwave Sensors and Test Specimens

The microwave sensor consists of a hollow cylindrical body and a mating solid metal piston (Figures 5a and 5b). Insertion of the piston into the body forms a cylindrical cavity of variable length. The hollow body was fabricated of oxygen-free high-conductivity copper and press fit into an outer jacket of Type 304 stainless steel. The maximum outside diameter of the hollow cylinder is 25.4 mm, the nominal inside diameter is 10.95 mm, and the overall length is 31.62 mm. The rectangular coupling hole in the end wall is nominally 2.73 mm in length by 0.83 mm wide. The piston is made of Type 304 stainless steel and is about 62 mm long by 10.71 mm diameter. Dimensions of the hollow cylinder and piston are controlled to provide an annulus

FIGURE 5. Components of the Microwave Sensor: (a) Cylindrical Body Mounted in Attachment Arm and (b) Piston Mounted in Attachment Arm.

of 0.10-0.13 mm when centerlines are coincident, thus permitting the piston to move freely in the cylinder.

Two cylinders and two pistons are press fit into split attachment arms of Type 304 stainless steel for clamping the sensors to the test specimen. A machined groove in the attachment arms is fabricated to mate with ridges on the test specimen to prevent slippage of the sensors on the specimen (see Figure 6a). The test specimen is 8.6 mm in diameter, and the reduced gage section between attachment ridges is 76.2 mm long. The circumferential ridges are triangular in cross-section with a base of 1.5 mm and a height of about 1.3 mm. The tension test specimen and creep test specimen were fabricated from mill-annealed Type 304 stainless steel and 20% cold worked Type 316 stainless steel, respectively. This dual sensor arrangement (see Figure 6b) provides an averaging system which minimizes errors associated with specimen bending during test. All motion contributing to the measured strain occurs between the ridges defining the gage length. In an elevated temperature test, the microwave sensors operate at the specimen test temperature obviating the need to mechanically translate specimen motion over long distances to reach a sensing element located outside the hot zone.

Strain Gages

Electrical resistance strain gages used in the tensile test were Micro-Measurements EA-09-062Ak-120; the manufacturer's specification for the gage factor of these gages was ± 1 percent. Strain values were determined from the average of readings from four strain gages equally-spaced around the specimen circumference and located at the specimen mid-length.

Microwave Sensor Calibration

Microwave sensors were calibrated by measuring absorption frequencies at selected piston displacements imposed through a precision micrometer. All calibrations were performed in air at ambient temperature ($\sim 295^\circ\text{K}$). Calibration results reported are strain values obtained by dividing piston displacement by the test specimen gage length. The accuracy of input calibration strain was about $\pm 7 \times 10^{-6}$. Four microwave sensors were used in this study. For the two sensors used in the tension test, calibration results

FIGURE 6. Components of the Microwave Sensor: (a) Partial Assembly of Dual Sensor System on Test Specimen and (b) Complete Assembly on Test Specimen.

were applied by determining an average sensitivity (i.e., strain change per unit frequency change) over the selected calibration displacement increments. For the two sensors used in the creep test, calibration displacement data were fit to a third order polynomial in frequency. The standard errors for calibration strain were 4×10^{-6} and 6×10^{-6} for the two sensors, and the maximum deviations were 8×10^{-6} and 12×10^{-6} .

Mechanical Testing

A room temperature tension test was conducted on a hard beam tensile machine. Use of manual readout and recording for the microwave sensors and strain gages precluded operating the test machine at a fixed cross-head speed, so the machine was operated on manual load control with step changes in load followed by hold periods to record strain data. At high loads, the specimen continued to strain during the hold periods, and the strain rates eventually became high enough to preclude accurate manual reading of strain data immediately following the load changes.

A lever arm creep machine with dead weight loading was used for the creep test. The test was conducted in a gas mixture of 94 percent helium - 6 percent hydrogen to prevent oxidation of the interior walls (copper) of the microwave sensors. Temperature variation during the test was controlled to within $\pm 1^\circ\text{K}$. The single specimen was tested for about 7.2×10^6 seconds at each of a series of progressively higher temperatures (728°K , 811°K , and 866°K). For the first loading at each temperature, the stress level was increased in increments of about 15.3 MPa to determine the strain response during loading. About 360 seconds was required for these loadings. During subsequent isothermal portions of the test, several step changes in load were made by removing or adding weight to the load pan as rapidly as possible (i.e., ~ 15 seconds). Only the total strain associated with the stress change was measured in these cases.

RESULTS AND DISCUSSION

Sensor Calibration

Calibration curves for two microwave sensors are shown in Figure 7. The frequency range for these calibrations extends well beyond the range

FIGURE 7. Calibration Results for Two Microwave Sensors.

actually used in subsequent mechanical tests. The nominal strain sensitivity obtained from a linear frequency-strain relation in Figure 7 is about 6×10^{-6} per MHz for these sensors operating in the TE₁₁₃ mode. With our frequency measurement stability of at least 2 in 10^6 parts at an operating frequency of about 35 GHz, a strain resolution of about 0.4×10^{-6} can be attained. Actually, the calibration curves in Figure 7 are slightly concave down, so the strain sensitivity decreases slowly as strain increases. We found that a third order polynomial in frequency gave a better correlation of the calibration strain results than did a linear relation.

The variation of absorption frequency with length changes in the calibration of a microwave sensor does not coincide exactly with the variations predicted theoretically assuming an ideal cylindrical cavity resonator, as illustrated in Figure 8. Deviation can be mainly attributed to the requirement for coupling (via a hole or slot in the cavity) of the sensor to the waveguide. Coupling to an external medium necessarily causes electromagnetic field perturbations within the sensor, thereby influencing both the resonator absorption frequency spectrum and the variation of sensor frequency with size changes. This is a plausible explanation of the gradual departure of the theoretically predicted strain from the input calibration strain up to a strain value of 0.017 in Figure 8. The irregular behavior observed at higher strains in Figure 8 arises from mode interferences when the absorption frequencies of two different modes become very nearly coincident. The dashed lines in Figure 8 indicate the percentage error incurred in using theoretical equations to predict calibration results. At low strains the error is about 3 percent and gradually decreases to less than 1.5 percent at higher strains. For some applications, the accuracy afforded by the theoretical equations may be adequate and extensive experimental calibration can then be avoided.

One of the microwave sensors used in the elevated temperature creep test was calibrated both before and after the experiment. A comparison of pre- and post-test calibrations shows that, for a given frequency change, slightly larger strains were observed in the post-test calibration, as indicated by the results in Table II. The maximum difference between calibration strains is about 1 percent, demonstrating that drift in sensor calibration as a result

FIGURE 8. Comparison of Theoretically Predicted Strain with Input Calibration Strain for a Microwave Sensor.

TABLE II

COMPARISON OF PRE- AND POST-CREEP TEST CALIBRATION OF MICROWAVE SENSOR

<u>Post-Test Input Strain</u>	<u>Predicted Strain Using Pre-Test Calibration</u>	<u>Per Cent Difference</u>
0	0	0
0.001667	0.001661	0.36
0.003333	0.003304	0.88
0.005000	0.004955	0.91
0.006667	0.006599	1.03
0.008333	0.008251	0.99
0.010000	0.009922	0.79
0.011667	0.011593	0.64
0.013333	0.013262	0.54

of elevated temperature exposure is small. The absorption frequency of the TM110 mode, sensitive only to changes in the inside diameter of the sensor, increased by about 13 MHz from pre- to post-test calibration. This small frequency change, indicating a diameter decrease of about 0.03 percent, demonstrates good dimensional stability of the microwave sensors.

Tension Test

The stress-strain curves of Figure 9 illustrate the results from the room temperature tension test. Agreement between the resistance strain gage and microwave sensor strain measurements was excellent. At strains less than 0.003, strain values agreed to within $\pm 3 \times 10^{-6}$ for 38 of 49 measurements, and the maximum difference was 12×10^{-6} . At higher strains, the two measurements agreed within ± 1 percent or better, with one exception where agreement was about 5 percent. This latter measurement was made when the strain rate was changing rapidly, making it impossible to obtain all manual readings rapidly enough for good accuracy. The test was continued to strain levels beyond those plotted in Figure 9, but data from the microwave system were not obtained in this range. All four strain gages failed at a strain level of about 0.02, and the specimen was then unloaded. Microwave sensors indicated a total strain of 0.019931 and subsequent direct micrometer measurement of the ridge-to-ridge distance on the specimen gave a strain value of 0.02033, only 2 percent higher than indicated by the microwave system.

Tension test results demonstrate that the strain measurement sensitivity ($\sim 1 \times 10^{-6}$) and accuracy (± 1 percent of the measured value) of the microwave system is comparable to that of electrical resistance strain gages at low strain levels. The system is capable of accurate measurement of the elastic strain response on loading as well as small deviations from elastic behavior, as illustrated in Figure 9. In addition, the hysteresis loop shown in Figure 8 confirms that the system can monitor details of behavior during unloading and reloading.

Creep Test

Results obtained in the creep test portray the elevated temperature performance of the microwave sensor system. Results first presented were

FIGURE 9. Stress-Strain Curves for Room Temperature Tension Test Showing Comparison of Microwave Sensor System Results and Electrical Resistance Strain Gage Results.

obtained from load change experiments interspersed throughout the test, followed by results obtained during hold times at constant load, and finally results for the temperature change portions of the test.

The measured strain responses for all loadings and unloadings are summarized in Table III. At the two lower temperatures, the observed linear stress-strain response during the first incremental loadings confirmed completely elastic behavior and were in excellent agreement (i.e., within 1 percent) with the results of Garafalo, et al.⁽⁷⁾ The total elastic strain value obtained on initial loading was reproduced to within about 1 percent at all subsequent load changes. Reproducibility of this elastic strain value confirms that calibration of the microwave sensors does not drift significantly during the test.

At 866°K, some non-elastic strain ($\sim 18 \times 10^{-6}$) was observed at the higher stress levels during initial incremental loading. We attribute this non-elastic strain to creep deformation during the short hold times required to read microwave sensor frequencies. The experimental value of Young's modulus determined from the linear portion of the stress-strain curve is about 4 percent lower than the average value obtained by Garafalo, et al.⁽⁷⁾ Results in Table III show apparent elastic extensions on loading which are about 1 percent larger than apparent elastic contractions on unloading. As we shall show later, this effect appears to be real, suggesting that additional non-elastic effects are present in the measurements. Furthermore, the apparent extensions and contractions are reproducible, again confirming the stability of the microwave sensor calibration over this portion of the test.

The creep curves in Figure 10 summarize strain measurements obtained during constant load portions of the test. Strain and time values were re-zeroed after each temperature change for convenience in plotting Figure 10. In addition, all strain contributions at load changes were subtracted out in constructing the figure; these predominately elastic loading strains were somewhat greater than the full-scale of Figure 10. The resulting curves show excellent creep measurement sensitivity and resolution for the microwave sensor system for the test duration. To illustrate, a fourth order polynomial in $t^{0.15}$ fit to the strain data at 728°K over the initial 3.6×10^6 seconds of

TABLE III

RESULTS OF LOAD CHANGE EXPERIMENTS DURING CREEP TEST

Temperature, K	Total Elapsed Time, s	Initial Stress, MPa	Final Stress, MPa	Elastic Strain, 10^{-6}	Constants Obtained from		
					$\sigma = E\epsilon + \sigma_0^{(a)}$		
					E , MPa	σ_0 , MPa	S , MPa ⁽⁶⁾
728	0	1.5	137.9	+ 804.2	16.9×10^4	1.9	0.3
	3.71×10^6	137.9	1.5	- 798.0			
	4.75×10^6	1.5	137.9	+ 795.1			
	5.96×10^6	137.9	62.8	- 438.8			
	7.17×10^6	62.8	1.5	- 360.6			
811	7.34×10^6	1.5	137.9	+ 851.3	16.0×10^4	2.2	0.5
	10.80×10^6	137.9	1.5	- 847.6			
	11.66×10^6	1.5	137.9	+ 850.0			
	13.91×10^6	137.9	1.5	- 851.7			
866	15.29×10^6	1.5	137.9	+ 931.9 ^(c)	14.9×10^4	1.8	0.4
	18.84×10^6	137.9	1.5	- 902.1			
	19.87×10^6	1.5	137.9	+ 913.8			
	22.29×10^6	137.9	1.5	- 901.4			

(a) Reference for zero strain is 1.5 MPa

(b) Standard error of estimate of σ (c) Includes non-elastic strain of about 18×10^{-6}

FIGURE 10. Creep Curves Obtained from Microwave Sensor Systems. All strain contributions at load changes have been subtracted out, and strain and time were arbitrarily re-zeroed after each temperature change for convenience in plotting.

test gave a standard error of estimate for creep strain of 1×10^{-6} . The microwave system was thus able to monitor an accumulated creep strain of about 100×10^{-6} with a resolution of the order of 1×10^{-6} . Figure 10 shows that the microwave system is capable of measuring both creep behavior following loading and creep recovery behavior following unloading in considerable detail.

Absorption frequency measurements for the TE₁₁₃ and TM₁₁₀ modes before and after each temperature change yielded results on the thermal characteristics of the test specimen and microwave sensor system. In this experiment, the hollow cylinders and pistons are attached to opposite ends of the 76.2 mm specimen gage length, but the length of the cavity resonator is only about 13.7 mm. Ideally, the thermal expansion of the test specimen is exactly compensated by the expansion of the sensor except over this 13.7 mm segment. The actual effective initial length for thermal expansion is then 13.7 mm, but we have also computed a quantity we will term "apparent specimen thermal strain" which is based on the initial 76.2 mm specimen gage length. Values of apparent specimen thermal strain and mean thermal expansion coefficients of the sensors obtained from the frequency measurements are listed in Table IV. Two different values of apparent specimen thermal strain are given for each temperature range--one based on length changes determined from experimental sensor calibration, and one based on length changes determined from theoretical equations. The values based on theory account for the significant expansion or contraction in sensor radius and are clearly more accurate on an absolute basis. We use the values based on sensor calibration to obtain an appropriate estimate of the temperature sensitivity of strain measurements for the present experiment; the results in Table IV give a value of about 4×10^{-6} per °K for the temperature sensitivity of strain as determined from the microwave system. Both sets of specimen thermal strain values indicate a net specimen contraction on heating from 292°K to 866°K and cooling back to 295°K. This same effect is, of course, observed in the mean thermal expansion coefficients for sensor length--the measured coefficient for heating is smaller than that for cooling. Thermal expansion coefficients for sensor radius, however, indicate that expansion and contraction are essentially identical in magnitude. This suggests that the apparent net contraction is

TABLE IV

THERMAL CHARACTERISTICS OF SPECIMEN AND MICROWAVE SENSORS
DURING HEATING AND COOLING

Temperature Interval, K	Apparent Specimen Thermal Strain, 10^{-6}		Microwave Sensor			
			Mean Thermal Expansion Coefficient, $10^{-6}/K$			
			Radius		Length	
	<u>Calibration</u>	<u>Theory</u>	<u>Sensor 1G</u>	<u>Sensor 2G</u>	<u>Sensor 1G</u>	<u>Sensor 2G</u>
295 - 728	1748.5	1371.7	17.5	18.2	17.6	17.8
295 - 811	2086.8	1626.3	18.0	18.5	17.1	18.2
295 - 866	2303.7	1774.0	19.3	18.7	17.1	17.6
866 - 295	-2554.3	-2019.8	18.7	18.9	19.4	20.0

a real effect in the test specimen and, indeed, contraction of 20% cold worked Type 316 stainless steel is known to occur as a result of exposure at elevated temperatures.⁽⁸⁾

The total creep test strain measured by the microwave system is obtained by algebraically summing the elastic strain contributions in Table III, the creep and recovery strain contributions in Figure 10, and the apparent thermal strain contributions in Table IV, yielding a value of 941.9×10^{-6} . Direct measurements of the pre- and post-test ridge-to-ridge distance on the test specimen gave a total strain of $940 \times 10^{-6} \pm 20 \times 10^{-6}$. The excellent agreement between these measurements confirms a high absolute accuracy of strain measurement for the microwave sensor system and further demonstrates that the net extension indicated during nominally elastic loading/unloading at 866°K and the net contraction indicated for the thermal cycle are real effects.

There are several potential sources of error in strain measurement for the creep test, but the following discussion shows such errors are consistent with the agreement between microwave sensor and direct measurements presented above. First, the sensor calibrations were conducted in air and then applied to measurements made in a He-6% H₂ environment. The differences in electric and magnetic properties between these two gas mixtures theoretically produce a slight change in calibration. We measured the change in sensor frequency when the environment was changed from air to He-6% H₂ and used these measurements in the theoretical equations for sensor frequency to estimate that the air calibration gives strain values which are low by about 0.02 percent.

A second source of error is the application of room temperature calibration results at elevated temperature, where thermal expansion of the sensor radius should alter the calibration. We estimated the magnitude of this effect by comparing theoretically-computed strain values based on: (1) the measured sensor radius* at room temperature, and (2) the measured sensor radius* at elevated temperature. This error estimate indicates the room temperature calibration gives strain values which are high by less than 1 percent.

*The radius value computed from the theoretical equation for the measured TM110 frequency.

Finally, the experimental results showed a gradual change in the TM110 frequency during the creep test. This indicated change in sensor radius should further alter the calibration. The measurements indicated a decrease in sensor radius of about 0.1 percent over the total duration of the test. If this effect is real, the theoretical equations predict a strain value about 5 percent higher than that obtained for a constant radius, which is inherently assumed in using calibration data. However, we observed earlier that pre- and post-test calibration measurements indicated a considerably smaller decrease in sensor radius, i.e., 0.03 percent. We attribute this difference to errors in TM110 frequency measurements caused by the perturbing effects of reflections which make up the background of the absorption frequency spectrum. Slightly different experimental arrangements for coupling sensors to the external microwave source led to higher background reflections, and hence potentially greater frequency measurement errors in the creep test. The much higher absorption of the TE113 frequency minimized such problems for the sensor length change measurements. Accepting the smaller radius change obtained in the calibrations as a real effect, the theoretical equations predict a strain value about 2 percent higher than that obtained for a constant sensor radius (or from calibration data). We thus find that the combined error estimate indicates the reported total strain of 941.9×10^{-6} may be too low by about 1 percent, a value which is consistent with the accuracy of ± 2 percent obtained from the comparison of microwave and direct measurements.

SUMMARY AND CONCLUSIONS

The microwave sensor system exhibits a strain measuring sensitivity ($\pm 1 \times 10^{-6}$) and accuracy (± 1 percent of the measured value) equivalent to those of electrical resistance strain gages in room temperature tests. The system is capable of accurate measurements of elastic loading strains as well as small departures from elastic response and hysteresis behavior during unloading and reloading. At elevated temperatures, the microwave system continues to exhibit high strain sensitivity ($\pm 1 \times 10^{-6}$) and accuracy (± 2 percent of the measured value). Strain response on loading, subsequent creep deformation, and creep recovery after unloading can all be monitored in detail. Drift in

microwave sensor calibration after exposure for 22.3×10^6 seconds at temperatures from 728°K to 866°K is small, amounting to differences of 1 percent or less in measured strain values.

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