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PIEZORESISTANCE RESPONSE OF YTTERBIUM UNDER STATIC AND DYNAMIC LOADING

Final

April 1982

Technical Report
Covering the Period January 1981 to January 1982

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Prepared for:
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Resistance change measurements in ytterbium foils (encapsulated in a PMMA matric) subjected to quasi-static triaxial (to 0.4 GPa) and shock wave loading (to 1.2 GPa) have been obtained. The use of a solid matrix in the quasi-static experiments is a new feature and ensures consistent comparisons between the two types of experiments. Two sets of gauge orientations, with respect to the matrix stresses, were examined in each type of experiment. Experimental results were analyzed in terms of the recently developed theoretical analysis. Both sets of experimental data confirm the general theoretical framework; an important difference between the static and dynamic measurements can be explained on the basis of the inclusion analysis. Results from these data have pointed out areas in need of refinement in the theoretical work and provided calibration data for lateral stress measurement in uniaxial strain experiments. These necessary theoretical developments, along with a determination of the piezoresistive coefficients, will be examined in the future.

PREFACE

This technical report summarizes work in the past year on the AFOSR contract F49620-81-K0002. The technical monitor was Lt. Col. J. J. Allen.

The following individuals at SRI are sincerely thanked for their contributions: Doug Keough is acknowledged for many helpful discussions regarding the experimental work and his help in coordinating the work towards the end; D. Henley and A. Urweider are acknowledged for their contributions to the experiments; B. Y. Lew is thanked for her help in data analysis.

Mr. Eric Peterson of Terra Tek, Inc., is thanked for his work on the static testing.

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I INTRODUCTION

The response of piezoresistance gauges must be understood to obtain accurate stress measurements in both laboratory and field experiments. These gauges are uniquely suited for most field applications because of their suitable stress and time range and their adaptability to field conditions. However, interpretating the gauge data to infer a particular stress component of interest is difficult. This problem has been discussed at length elsewhere.[1] We have also recently presented a theoretical analysis that can be used to quantitatively model the gauge response.[1] Two aspects of this analysis are noteworthy: (a) development of a phenomenological model for piezoresistance; and (b) development of an analytical method to examine the gauge-matrix interaction, by modeling the gauge as an elastic-plastic inclusion.

In our present work (under AFOSR sponsorship), we are extending the previous work to develop a first principles understanding of piezoresistance gauges and to enable data interpretation in complex loading situations. To achieve this long term objective, we focused on the following specific objectives in the past year: (a) measuring gauge response under triaxial quasi-static loading and shock loading; (b) analysis of these data using our inclusion analysis to determine the validity of the theory and to suggest potential modifications; (c) reconciling the static and dynamic data. An important aspect of our work is an attempt to ensure consistency between experiments by careful material characterization and experimental assembly. Static triaxial experiments of the type reported here have not been done before in piezoresistance studies. We expect these data to be very valuable in understanding and modeling the gauge response. Ytterbium was selected as the material of interest because of its use at low stresses (below 2.5 GPa).[2] PMMA was chosen as the matrix material because it has been well characterized in static[3] and shock studies,[4,5] and is easy to use in experimental assembly.

The present work summarizes the technical results of the past year. Hence, the experimental and analytical methods are not described in any detail: only the main findings of our effort are summarized. After completing some ongoing analysis, we will submit this work for a journal publication. Copies of the manuscript will be submitted to AFOSR.

II EXPERIMENTS

A. Material Characterization

Several foils of ytterbium (3 in. x 3 in. x 0.002 in.) were obtained from a larger cold-rolled foil.* As has been recognized in previous work,[2] the reproducibility of ytterbium (Yb) is a problem. To ensure consistency between all of our dynamic and static experiments, we made resistivity measurements on a small piece from each of the as-received foils. Except for one foil, the resistivity of the foils was within ± 15 percent of the average value. This range of scatter is comparable to measurement errors.† We also measured the resistivity of each gauge before every dynamic and static experiment.

In all of our experiments, the matrix material was PMMA (obtained as sheet stock from Rohm Haas). This particular PMMA has been characterized in both static[3] and dynamic studies.[4,5] The viscoelasticity of PMMA was not expected to pose any problems because we have data quantifying the PMMA behavior at the strain-rates of interest.

B. Dynamic Experiments

Plate impact experiments using a gas-gun[6] were performed to examine the response of piezoresistance gauges along two orientations as shown in Figure 1. Details of sample fabrication and the experimental procedures may be seen in Refs. 1 and 2. A total of 6 experiments were conducted with each experiment consisting of 4 sets of measurements (2 gauges per orientation). The resistance measurements for each of the experiments, before shock loading, are shown in Table 1. Except for two gauges in experiment 81-4-10, all of the gauges had resistivities between 40-45 $\mu\Omega$-cm. This consistency for Yb is considered to be very good.

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*These were purchased from Research Chemicals, Phoenix, Arizona.

†The difficulty in accurately measuring the gauge thickness is a large source of error in resistivity measurements.

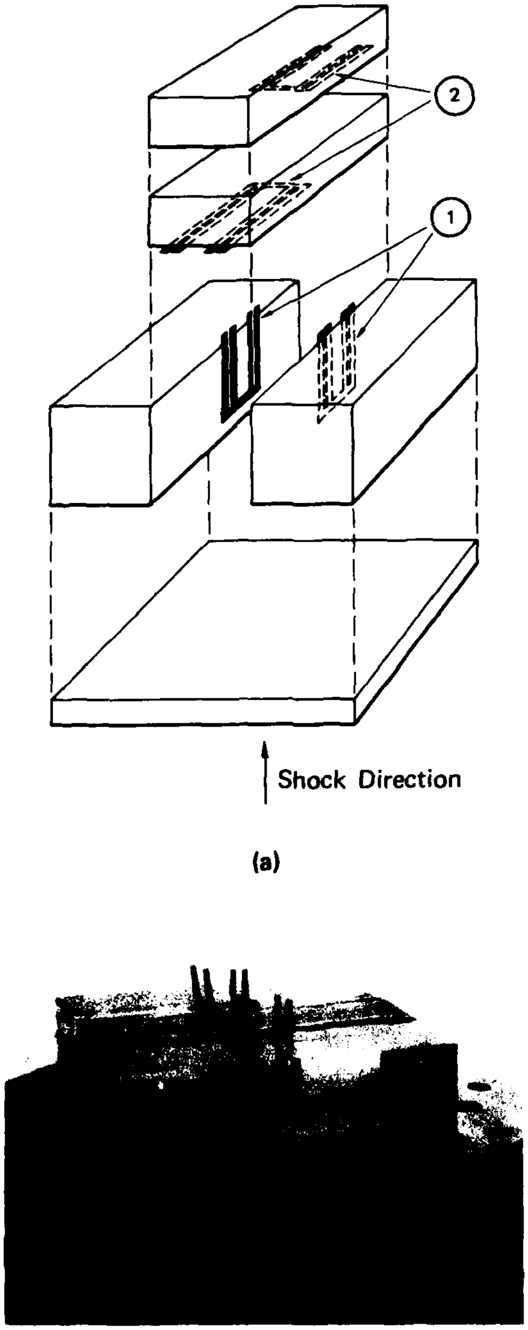

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FIGURE 1 EXPERIMENTAL ASSEMBLY FOR STRESS MANAGEMENT

(a) Schematic view of unassembled blocks showing the four gauges.
(b) Assembled target.

Table 1

GAUGE MEASUREMENTS BEFORE SHOCK LOADING

Experiment No.*	Foil No.*	Resistance Before Assembly (mΩ)	Resistance After Assembly (mΩ)	Resistivity (μΩ-cm)
81-4-10	6			
Gauge 1		No measurements made before lead attachment	74.63	44.49
Gauge 2			56.73	33.82
Gauge 3			75.60	45 [illegible]7
Gauge 4			95.61	5[illegible]
81-4-09	5			
Gauge 1		70.91	71.44	4[illegible]
Gauge 2		71.35	70.71	4[illegible]
Gauge 3		69.50	69.95	4[illegible]
Gauge 4		73.50	74.34	4[illegible]
81-4-07	3			
Gauge 1		71.43	76.77	42.59
Gauge 2		75.70	86.55	45.13
Gauge 3		73.28	72.34	43.69
Gauge 4		71.95	78.63	42.90
81-4-05	1			
Gauge 1		79.06	77.45	47.13
Gauge 2		65.93	66.52	39.31
Gauge 3		72.98	73.05	41.52
Gauge 4		71.85	70.92	42.84
81-4-08	4			
Gauge 1		71.82	71.41	42.82
Gauge 2		75.10	74.50	44.77
Gauge 3		74.31	73.90	44.30
Gauge 4		72.40	72.72	43.16
81-4-06	2			
Gauge 1		74.25	73.34	44.27
Gauge 2		74.02	77.31	44.13
Gauge 3		76.76	76.53	45.75
Gauge 4		69.80	71.53	39.71

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*All the gauges for an experiment come from a single foil.

In our first 3 experiments, we attempted to bond the PMMA blocks using a solvent for PMMA. In retrospect, this was not a good idea. The solvent bonding method works well only if the PMMA pieces are machined perfectly. Although we obtained data from our first 3 experiments, the wave profiles were of poor quality and showed the problems in specimen assembly. In our subsequent experiments, we used Hysol 815 (an epoxy well suited for PMMA assembly for shock experiments[4]) for bonding, and good results were obtained. In the future, we plan to use Hysol exclusively in sample assembly.

C. Quasi-Static Experiments

Previous quasi-static experiments have been done with a gauge package being hydrostatically compressed in a fluid. In our work, we used a different method: the gauges were encapsulated in a PMMA matrix, similar to the dynamic experiments. A schematic view of the experimental assembly is shown in Figure 2. Gauges along two perpendicular orientations (analagous to the dynamic experiments) were encapsulated in a PMMA cylinder; PMMA sections were bonded using Hysol. Resistivity measurements were made of the gauges before they were shipped to Terra-Tek[*] for testing.

In addition to a preliminary test to ensure proper functioning of all components, 4 tests were performed.[†]

(i)	Hydrostatic Loading:	$\sigma_1 = \sigma_2 = \sigma_3$ at the PMMA boundary; peak pressure of 3 kbar.
(ii)	Uniaxial Strain:	$\varepsilon_1 \neq 0$, $\varepsilon_2 = \varepsilon_3 = 0$; peak compressive stress of 2 kbar.
(iii)	Uniaxial Strain:	$\varepsilon_1 \neq 0$, $\varepsilon_2 = \varepsilon_3 = 0$; peak compressive stress of 4 kbar.
(iv)	Uniaxial Strain:	Sample loaded to 2 kbar, unloaded and reloaded to 4 kbar.

---

[*] The triaxial tests were done at Terra-Tek under a SRI subcontract and SRI specifications.

[†] The conventions we have chosen are such that x_1 is along the cylindrical axis and x_2, x_3 represent two perpendicular radial directions.

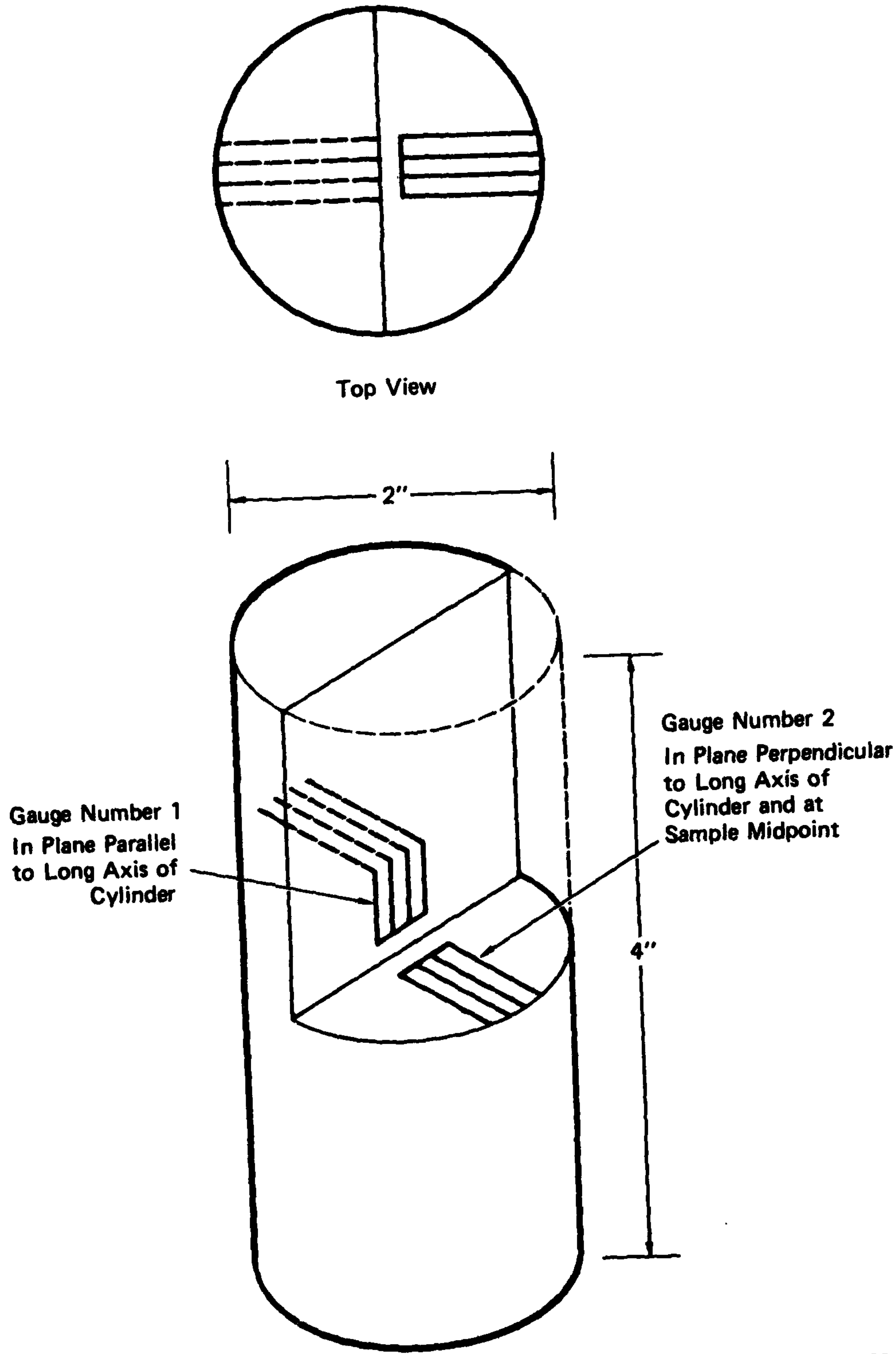

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FIGURE 2 SCHEMATIC VIEW OF SAMPLE FOR STATIC MEASUREMENTS

All nonzero stresses and strains were measured using the usual methods.[7] In addition, temperature in the proximity of the sample was measured using a nickel gauge.* The temperature measurements were used to correct for resistance changes due to temperature variations during the tests (this correction was on the order of 1-2 percent).

The combination of the hydrostatic and uniaxial strain experiments can provide a determination of the piezoresistive coefficients and an assessment of the plastic yielding effects. The reloading data is important in assessing the effect of plastic deformation on subsequent loading. Further discussion of these experiments is presented in the next section.

---

*Suggested by D. D. Keough.

III RESULTS AND ANALYSIS

A. Dynamic Experiments

Results of the 6 dynamic experiments are summarized in Table 2. The longitudinal stress and strain were obtained from a knowledge of the particle velocity (one half the projectile velocity) using the results of Barker and Hollenbach.[4] These values, along with the resistance change values, correspond to the flat portion of the stress wave. (Gauges denoted as (1) had longer rise times.) The resistance change data as a function of the matrix strain is plotted in Figure 3. Except for one of the gauge 2 measurements, the data lie on a smooth nonlinear curve. At very low matrix strains, the two sets of curves appear to cross over. Although more data are needed in the 0 to 0.02 strain region, the two low strain data points support our theoretical predictions based on an elastic-plastic inclusion analysis.[1]

The gauge 1 results can also be used as calibration data for lateral stress measurements. This is possible because we have an independent knowledge of the PMMA stresses. Other workers have assumed the validity of the lateral stress gauge without appropriate justification.

In the future, we plan to repeat two of these experiments (corresponding to matrix strains of 6 and 8 percent) to obtain better quality data and confirm these results.

B. Quasi-Static Experiments

Before describing the results of the resistivity measurements, we briefly discuss the stress and strain measurements in these tests. The data from the hydrostatic pressure measurements showed that the strain measurements were not correct because the three principal strain components were not equal. This difficulty exists only for the strain measurements and not the stress measurements. For the hydrostatic measurements, the error in strain measurements does not pose a severe problem because we

Table 2

SUMMARY OF THE DYNAMIC DATA[a]

Experiment No.	Projectile Velocity (mm/μs)	PMMA Matrix[b]		Resistance Change		$(\Delta R/R_o)_1/(\Delta R/R_o)_2$
		Longitudinal Stress (kbar)	Longitudinal Strain	$(\Delta R/R_o)_1$	$(\Delta R/R_o)_2$	
81-4-10	0.105	1.8	0.0177	0.085	0.08	1.06
81-4-09	0.228	4.0	0.0366	0.190	0.225	0.84
81-4-05	0.373	6.75	0.0584	0.3	0.42	0.71
81-4-07[c]	0.373	6.75	0.0584	0.33	0.55,0.49	——
81-4-08	0.539	10.0	0.0863	0.56	0.75	0.75[d]
81-4-06	0.635	11.9	0.101	0.66	1.0	0.66

[a] All of the gauges were contained in a PMMA matrix; PMMA impactors were used in all of the experiments.

[b] These values have been obtained using the data of Barker and Hollenbach.[4]

[c] The results of this experiment are questionable because of apparent problems in experimental assembly.

[d] The reason for this high value is apparent from Figure 3.

can obtain these values from the literature. We were, however, concerned about whether the strain measurements in the uniaxial strain data were correct.* The uniaxial strain results (in the present work) were carefully checked against the earlier mechanical measurements of Stephens, et. al.[3] and good agreement was found between both the σ_1 vs ε_1 and $(\sigma_{mm}/3)$ vs ε_1 curves for the two studies. We therefore concluded that all of the present data (except strains in the hydrostatic test) are valid.

In Figure 4, the resistance change is plotted as a function of pressure. Although the gage 1 data are slightly higher than the gauge 2 data, the differences are well below experimental error. We have chosen to fit both sets of data using a single curve. The same value of $\Delta R/R_0$ for the two gauges was gratifying, for it showed that no asymmetrical response was induced by the experimental assembly and procedure. Because all three principal components of the stress are equal, the two gauges should appear symmetric. This is indeed the case. The curvature of our data is opposite to the hydrostatic results cited in Ref. 2. The cause of this difference is not as yet known.

In Figure 5, we have shown the results from the uniaxial strain experiment for a peak compressive stress (σ_1) of 4 kbar (the 2 kbar results are not shown, but they showed good agreement with data in Figure 5). Gauge 1 data are higher than gauge 2 data with both sets of data showing distinct changes in slopes. The two sets of data appear to approach each other at the higher compressive stresses.†

In Figure 6, we have shown the results of the reloading experiment. The data shown were obtained by reloading a sample that had been initially loaded to 2 kbar and unloaded. The first cycle showed results similar to previous tests and confirmed that our results are reproducible. Comparison

---

*If the lateral strain measurements are not zero as measured, then all of the data are incorrect.

†The matrix strains corresponding to 1, 2, 3, and 4 kbar stresses are 1.02, 3.50, 4.90, and 6.08 percent, respectively.

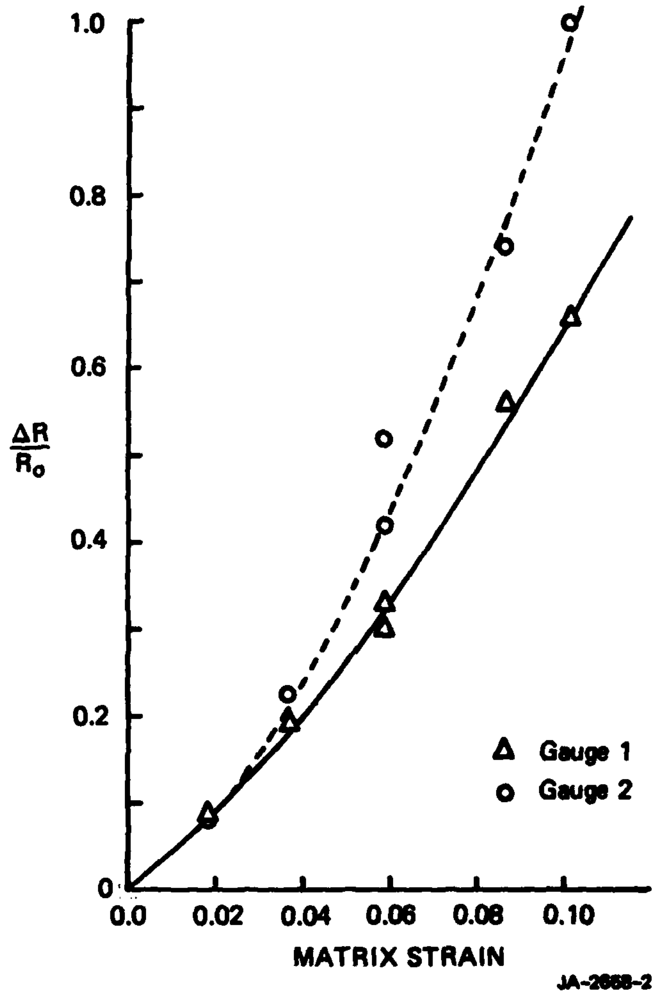

FIGURE 3 GAUGE RESISTANCE CHANGE AS A FUNCTION OF LONGITUDINAL STRAIN IN THE DYNAMIC EXPERIMENTS

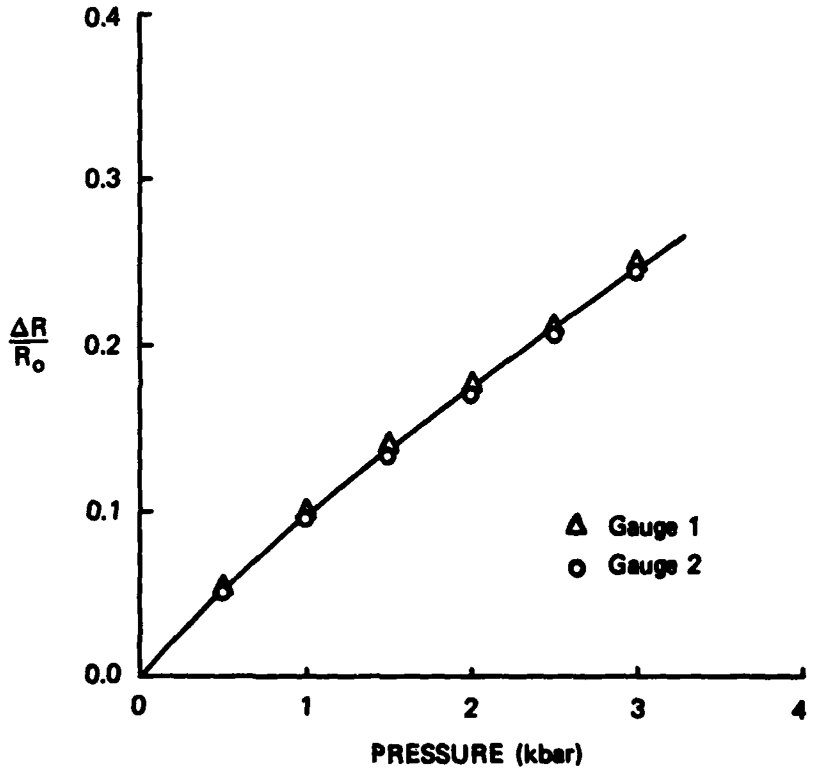

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FIGURE 4 RESISTANCE CHANGE AS A FUNCTION OF PRESSURE IN STATIC EXPERIMENTS
(Hydrostatic Loading)

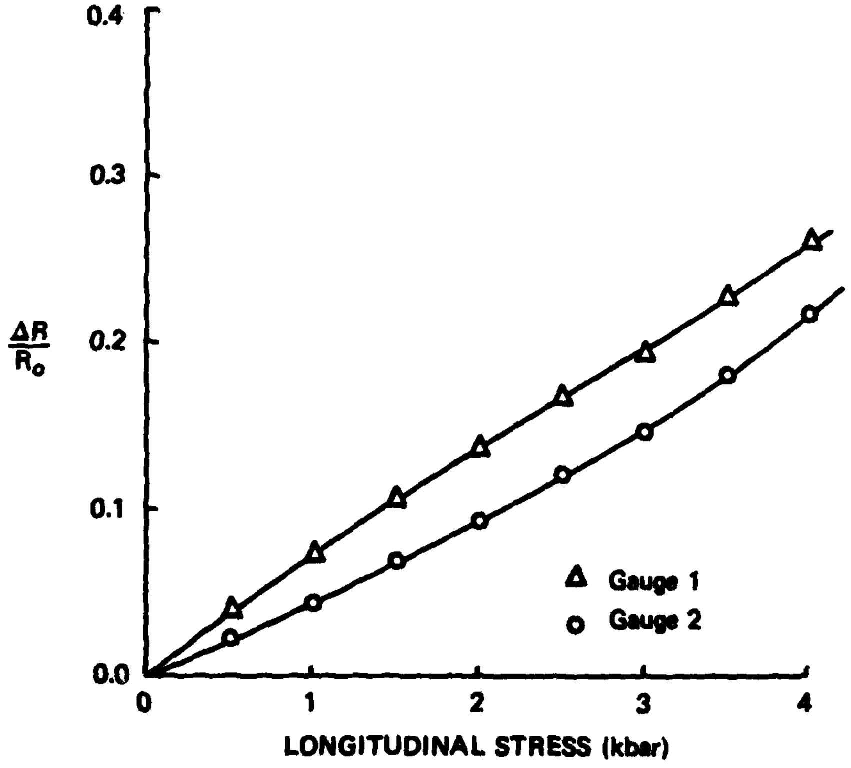

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FIGURE 6 RESISTANCE CHANGE AS A FUNCTION OF LONGITUDINAL STRESS IN STATIC EXPERIMENTS

(Uniaxial Strain with Recycling of Load)

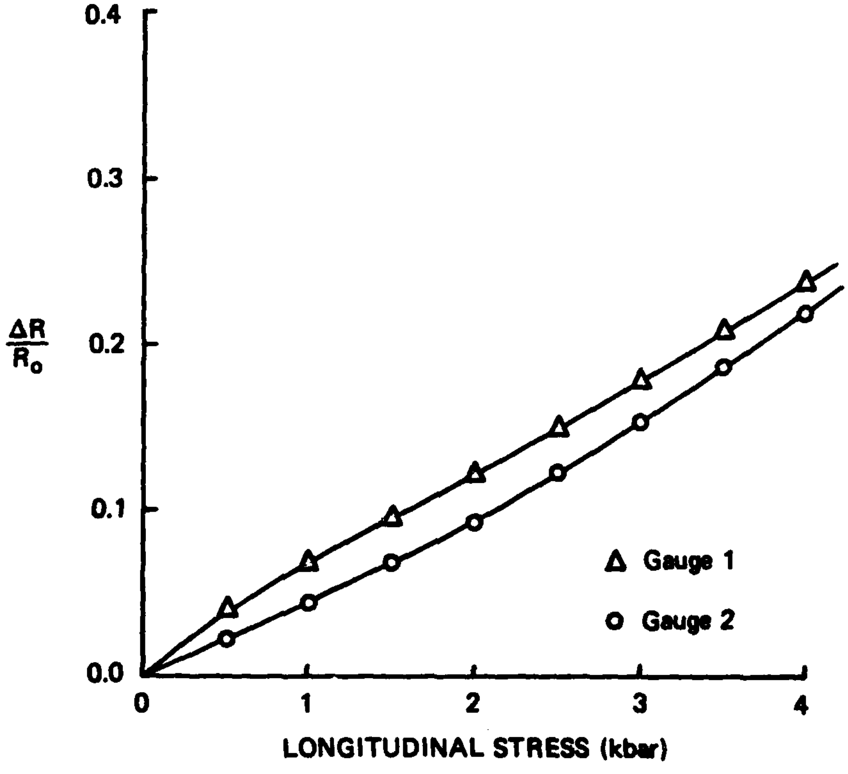

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FIGURE 5 RESISTANCE CHANGE AS A FUNCTION OF LONGITUDINAL STRESS IN STATIC EXPERIMENTS
(Uniaxial Strain)

of Figures 5 and 6 show that data from gauge 2 are quite close for the two experiments. For gauge 1 the data are in good agreement up to 1 kbar (the region where the slope changes) and beyond that $\Delta R/R_0$ remains higher during recycling than during first loading. These observations are analyzed below.

C. Analysis

In Figure 7, we reproduce the theoretical calculations[*] of the gauge resistance change as a function of matrix strain from our previous work.[1] The calculations are not quantitatively applicable for our present work because we are using a different batch of ytterbium and hence the numerical constants will be different. However, the results in Figure 7 provide a good framework for discussing the present results. Also, the present data will point out the improvements that need to be incorporated in the theory.

A comparison of Figures 3 and 7 shows that the intersection predicted by the theoretical calculations is observed in the experiments. More data below 2 percent strain are needed to unequivocally confirm the theoretical predictions. Above the intersection point, the theory and experiment show gauge 2 data to be higher. Comparisons of Figures 3 and 7 clearly shows the need to include nonlinear piezoresistive coefficients in the theory to model the nonlinear increase seen in the resistance change values. With the available data, we should be able to obtain a reasonable estimate of the piezoresistive coefficients.

Although the results in Figure 7 are not based on the static response of PMMA, they can be used to qualitatively examine the uniaxial strain data. Comparing Figures 5 and 7, we see that three features are noteworthy:[*]

---

[*] The PMMA properties used in obtaining the results in Figure 7 correspond to the shock response, and not the quasi-static response, of PMMA.

[†] Although different quantities are plotted along the x-axis in Figures 5 and 7, we can make a comparison because of the one to one correspondence between matrix strain and longitudinal stress.

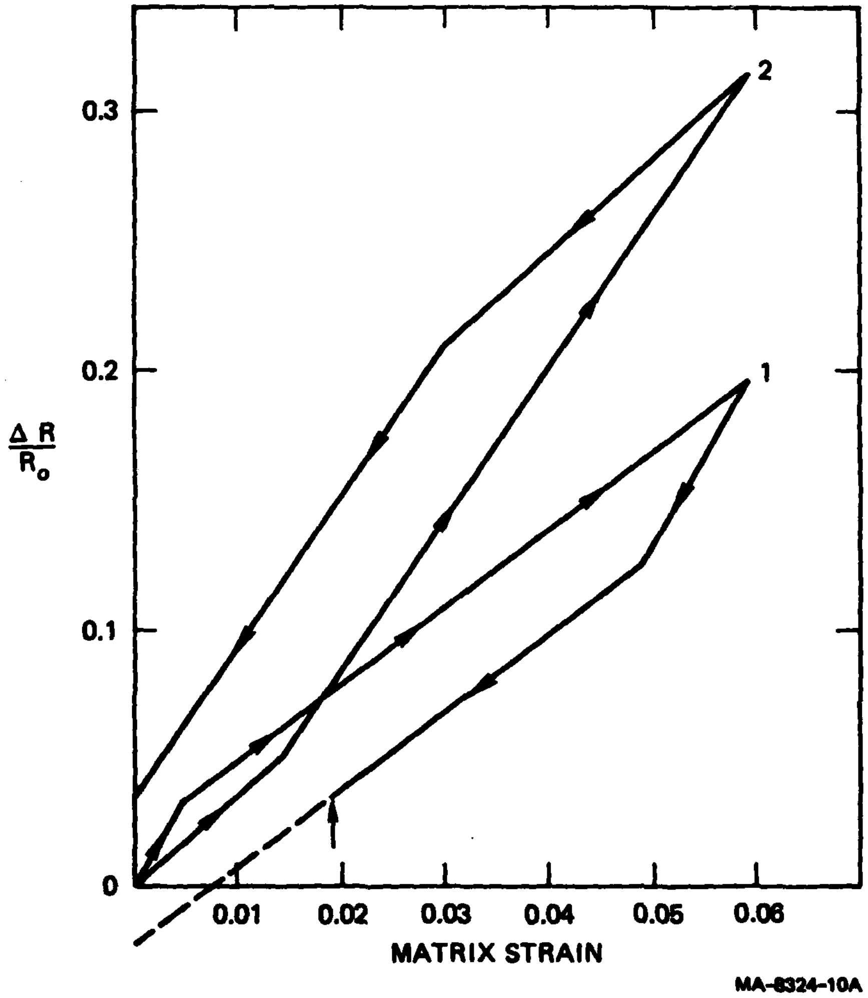

FIGURE 7 CALCULATED RESISTANCE CHANGE OF Yb GAUGE (MODELED AS ELASTIC-PLASTIC INCLUSIONS) VERSUS MATRIX STRAIN

The response shown in this figure is for gauges with major surface normal to shock propagation direction 2 and major surface parallel to shock propagation direction 1.

(a) gauge 1 data are initially higher than the gauge 2 data in agreement with the theory; (b) the change in the slope for the two gauges due to plastic yielding in Figure 7 is observed in Figure 5 (although it is considerably more rounded than Figure 7); and (c) unlike the theoretical prediction, the experimental curves do not intersect at least up to a stress of 4 kbar (strain of 6.08 percent); however, they appear to be approaching an intersection. Initially, this last feature was both surprising and disturbing. We have recently redone the calculation in Figure 7 using an approximate set of PMMA mechanical properties at low strain rates. The results were very encouraging: the intersection point shifted from 1.8 percent strain to 6 percent strain. Although this result is preliminary and we will repeat this calculation, it does show that the differences in the static and dynamic results are due to difference in matrix properties. This preliminary calculation shows the importance of the matrix-inclusion interaction and the ability of the analysis to account for it. We plan to refine our calculations using the most accurate set of PMMA mechanical properties and ytterbium piezoresistive constants applicable to our work.

The importance of the plastic response of the inclusion (gauge) can also be seen by examining Figures 5 through 7. Comparing Figures 5 and 6, we find that the gauge 2 response is not appreciably altered by reloading. Gauge 1 response is nearly unchanged to 1 kbar; beyond 1 kbar the resistance change during reloading differs. This result supports the incorporation of plasticity in the theoretical calculations and indicates that for gauge 1 the onset of inelastic deformation occurs at 1 kbar matrix longitudinal stress. Why the resistance change for gauge 1 beyond 1 kbar during reloading is higher, in comparison to the results in Figure 5, is not understood at the present time.

Further analyses of these results are currently in progress and will be reported upon completion.

IV CONCLUDING REMARKS

The present experimental results show the general validity of the theoretical analysis used in calculating gauge response. The difference between the two gauge orientations for static and dynamic loading cannot be understood without a proper understanding of the elastic-plastic inclusion analysis. However, these data also indicate several areas where the theory needs refinement: the nonlinear piezoresistive coefficients need to be included in the theory to model the experimental data, work-hardening needs to be included in the gauge mechanical behavior, and the analysis during reloading needs to be carefully worked out.

In the experimental work, we need to obtain dynamic data below 2 kbar and repeat one or two experiments above 6 kbar. Future dynamic experiments should be designed to provide unloading data.

The static experiments are very valuable because of the ability to load along different strain paths. The use of a matrix similar to the dynamic experiments is necessary to correlate the two types of data. An important future task is to determine if the two types of experiments can be reconciled using a single set of material properties for ytterbium. Present applications implicitly assume this result.

The measurements reported here represent an important start in understanding the piezoresistance response of gauges subjected to mechanical deformation. We need this understanding if gauge data in complicated situations are to be inverted with accuracy and confidence.

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