DYNAMIC PIEZORESISTIVITY OF MANGANIN TRANSDUCERS

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ABSTRACT

Manganin, an alloy of copper, manganese and nickel, has been used as a dynamic piezoresistive transducer for shock wave profile measurement in the range from 22 to 410 kbar. Thirty-six gun-accelerated flyer plate impact experiments were performed to dynamically calibrate wires of 1 mil diameter that were electrically insulated with thin dielectric sheets and cemented between target plates. A static calibration gave a linear, reversible, pressure derivative of $2.5 \pm 0.1 \Omega/\Omega$/Mbar to 90 kbar. The dynamic calibration is linear within $\pm 5\%$ to 200 kbar with a pressure derivative of $2.7 \pm 0.1 \Omega/\Omega$/Mbar. At stresses higher than 200 kbar, the dynamic response becomes slightly nonlinear and the data were fit with the polynomial expression:

$$
\sigma = 0.3896(\Delta R/R) - 0.2348(\Delta R/R)^2 + 0.5825(\Delta R/R)^3 - 0.3360(\Delta R/R)^4,
$$

with a standard deviation of $\pm 4.4$ kbar where the stress $\sigma$ is in megabar. A linear hysteresis was observed with a pressure derivative of $2.6 \pm 0.1 \Omega/\Omega$/Mbar during unloading from a peak stress in the range from zero to 247 kbar.

INTRODUCTION

The linear piezoresistive property of Manganin alloy has made it a favorite electrical transducer for static high pressure measurement for the past seventy years. Its dynamic response to shock-induced stresses was first investigated by Fuller and Price in the early 1960's and later by Keough and Wong and by Barsis et al. Various alloy compositions were used and comparisons were made between the alloy in wire and foil form in a great variety of insulator configurations. A fair amount of scatter exists in the data, and it was recognized that the dynamic calibration may be nonlinear, and that the gauge displays hysteresis. This article contains the results of 36 experiments to measure the dynamic response of in-situ gauges in the stress range from 22 to 410 kbar, and the results of 7 experiments to measure hysteresis from zero to 247 kbar.

The alloy was used in wire form and cemented with thin dielectric sheets between metal or ceramic discs. Shock waves were driven into the assemblies by the flat impact of gun-accelerated flyer plates.

The in-situ Manganin gauge causes a disturbance, in the propagation of stress waves, proportional to its thickness and the relative shock impedances of gauge and target. In most of our work, the impedances of the targets were three to six times that of the gauge. The resulting stress and rarefaction wave reflections at the gauge boundaries cause a loss of the higher frequency components of the transmitted wave in the target and produce, by interactions with waves from free surfaces and other interfaces, a variety of effects including internal spall and the opening and closing of voids at surfaces of no strength.
The one-dimensional hydrodynamic finite difference computer calculation described by Wilkins\textsuperscript{4} was used to interpret the gauge response. Included in the problem statement are the equations of state (EOS) and constitutive relations of flyer, gauge, and target materials listed in Appendix A. These were obtained by reference to the literature and by experiments with the gauge to obtain its own EOS.

The dynamic resistance change of the gauge was monitored by cathode ray tube oscilloscopes. It was observed that the signal failed to return to baseline upon unloading from a peak stress to zero stress. An experiment was designed in which the stress was reduced in steps by multiple wave reflections in the flyer plate. The resulting record displayed hysteresis when compared to a machine calculation of the wave profile. The calculation was verified in a comparison experiment in which the particle velocity was measured using the electromagnetic technique of Zaitsev\textsuperscript{5}.

**EXPERIMENTAL TECHNIQUE**

The Manganin wire that was used in these experiments was drawn by the California Fine Wire Company\textsuperscript{6} to 1-mil diam, from 10-mil diam precision grade stock obtained from the Wilbur B. Driver Company. After the final draw the wire was stress-relieved at 485°C in a hydrogen atmosphere. The composition, determined by wet chemistry, was 12.95 wt\% Mn, 4.28 wt\% Ni, and the balance, Cu and impurities. The impurities quoted by the supplier are: 0.32% Fe and 0.01% Si, which are introduced during drawing. The lattice symmetry is face-centered cubic with a constant of 3.66 Å. Specific resistivity of the wire is 48.1 ± 0.4 μΩcm.

Gauges were made of bare Manganin wires by electroplating 10 cm bands of copper onto both ends. The bare portion in the middle was approximately 1 cm long, with a resistance between 7 and 10 Ω. The copper leads had handbook-value specific resistivity, and comprised less than 2% of the total gauge resistance. The plated ends of the wires were flattened in a hydraulic press to about 1 mil thick; the Manganin portion remained circular. This method of gauge construction minimizes the capacitance-to-metal shot parts and, because of the low resistance, eliminates the negative-going precursor signal often observed with higher-resistance photo-etched foil gauges.

The plated wires were assembled as a two-terminal transducer between sheets of mica\textsuperscript{7} or sheets of Kapton\textsuperscript{8} using epoxy\textsuperscript{9} resin as an adhesive. The dielectric sheets were from 1 to 3 mil thick, and the total gauge thickness ranged from 3 to 7 mil. Kapton is the preferred insulator at stresses less than 0.2 Mbar because the electrical signals are less noisy than with mica. Mica is preferred at stresses greater than 0.2 Mbar because it is stiffer than Kapton and the gauges last longer before electrical shorting to metallic shot parts. In nearly all the measurements with mica-insulated gauges in metals, the elastic precursors, if present, were obscured in the initial electrical noise thought to be caused by the compression of the laminar mica.

The gauges were cemented with epoxy between discs of metal or ceramic and placed in an evacuated chamber before the muzzle of a gun. In
the case of metals shocked beyond 0.2 Mbar, it was found useful to machine cylindrical surfaces of radius 12.7 cm on the mating target parts at the gauge location to delay lead failure for several microseconds after the signal. This is shown in Fig. 1. Shocks in the targets were generated by the flat impact of flyer plates of the same material. Our procedures in gun technique for accelerating the flyer plates closely follow those described by Thunborg. 10

In all experiments the release rarefaction originated at the rear surface of the flyer. At the lower impact velocities the flyer was supported only at the rim; the release was to zero stress, and thus useful as a measure of gauge hysteresis. At the higher velocities the flyers were supported by carbon foam ($p_v = 0.4$ gm/cm), polymethylmethacrylate (PMMA), or epoxy resin.

A simplified circuit diagram is shown in Fig. 2. A charged capacitor voltage source supplies a square pulse through the closure of switches, $S_1$ and $S_2$, to the resistive isolation networks, and thence to a bridge consisting of the gauge, a balance resistor, and the amplifiers contained in a differential preamplifier oscilloscope. Calibration is accomplished by comparison to a record made by substituting several standard resistors at the gauge location.

**RESULTS**

The dynamic calibration data are listed in Table I. In addition, a quasihydrostatic measurement of the wire gave a pressure derivative of $2.5 \pm 0.1 \Omega/\Omega$ Mbar, which compares with 2.43 $\Omega/\Omega$ Mbar reported by Barsis.3 The data in the pressure range up to 100 kbar is plotted in Fig. 3 to illustrate the scatter and the relation to the static determination. A least squares linear fit to the data up to 200 kbar gave a pressure derivative of $2.7 \pm 0.1 \Omega/\Omega$ Mbar. At stresses higher than 200 kbar there is a gradual decrease in the pressure derivative until the region near 400 kbar is approached, where the derivative increases again. All the data were fit with a least squares fourth-order polynomial:

$$
\sigma = 0.3886 (\Delta R/R) - 0.2348 (\Delta R/R)^2 + 0.5625 (\Delta R/R)^3
$$

$$
- 0.3360 (\Delta R/R)^4 \pm 0.0044 \text{ Mbar standard deviation.}
$$

A pair of experiments was conducted to observe points along the release path in PMMA from a maximum stress of 31 kbar. The first of these employed an electromagnetic detector of particle velocity according to the technique described by Zaitsev5 and by Al'tshuler.11 The second contained Manganin gauges and shows the characteristic hysteresis behavior. The geometry for these experiments is described for Shot 3226 in Table II, and Fig. 4 is a distance vs time plot that illustrates the multiple wave reflections in the flyer plate that produce the stepped release in the PMMA. Figures 5 and 6 show the experimental results and the computer calculations. The purpose of the particle velocity measurement was to verify the calculation along the release using the EOS and constitutive relations for PMMA that are found in Appendix A. The empirical observation was made that the hysteresis of Manganin is linear with the decrease in stress, and
that the release path can be fit with an equation of the form:

\[ \sigma = \sigma_1 - (0.38 \pm 0.01) \frac{R_1 - R}{R_0} \]

where \( \sigma \) is the released stress, \( \sigma_1 \) is maximum stress, \( R_1 \) is the resistance at \( \sigma_1 \), \( R_0 \) is the initial resistance. This equation was used to calculate release stresses in six other experiments in the range up to 247 kbar with a maximum error of 6.7\%. The data appear in Table II.

**DISCUSSION**

The accuracy of the results reported here is limited by uncertainties in flyer velocities (which were measured to within 1\%), and in equations-of-state and constitutive relations for materials that were shocked to stresses above their Hugoniot elastic limits. In addition, "identical" gauges in the same experiment often exhibit variations of several percent in \( \Delta R/R_0 \). Therefore, stresses calculated from the gauge performance listed here are only considered accurate to within 15\%.

At present, there is no generally recognized explanation for the piezoresistive behavior of Manganin which would allow one to quantitatively or qualitatively predict the observed increase in resistance with increasing stress, or to predict the magnitude of the hysteresis. Rosenberg\(^1\) pointed out that the piezoresistance coefficient of Manganin was decreased by prior cold work. Similarly, Keough\(^2\) suggested that shear deformation causes lattice defect generation and accounts for the greater observed resistivity change of wires compared to foils in the same one-dimensional shock environment. If lattice defects cause the hysteresis, then suitable prior cold working treatment may make possible Manganin gauges with wide range linear response without hysteresis.
APPENDIX A

Equations of State and Constitutive Relations of Materials Used to Calibrate Manganin Gauges

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>Initial density</td>
<td>gm/cm$^3$</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Longitudinal sound speed</td>
<td>cm/μsec</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
<td>Mbar</td>
</tr>
<tr>
<td>$U_p$</td>
<td>Particle velocity</td>
<td>cm/μsec</td>
</tr>
<tr>
<td>$V_0 = \frac{1}{\rho_0}$</td>
<td>Initial specific volume</td>
<td>cm$^3$/gm</td>
</tr>
<tr>
<td>$V$</td>
<td>Specific volume</td>
<td>cm$^3$/gm</td>
</tr>
<tr>
<td>$\mu = \frac{V_0}{V} - 1$</td>
<td>Compression</td>
<td>dimensionless</td>
</tr>
<tr>
<td>HEL</td>
<td>Hugoniot elastic limit</td>
<td>kbar</td>
</tr>
<tr>
<td>$Y_0$</td>
<td>Yield strength</td>
<td>kbar</td>
</tr>
<tr>
<td>G</td>
<td>Shear modulus</td>
<td>kbar</td>
</tr>
<tr>
<td>E</td>
<td>Energy/initial volume</td>
<td>Mbar - cm$^2$/cm$^0$</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>Mbar</td>
</tr>
</tbody>
</table>

1. Alumina, Diamonite, P-3142-1, Diamonite Products Co., Shreve, Ohio. Used in its elastic range only.
   \[ \rho_0 = 3.72 \quad C_L = 0.99 \quad \text{HEL} = 88 \pm 5 \text{ kbar} \]
   \[ \sigma = 1.902 \mu + 0.1521 \mu^2 \]

2. Aluminum alloy 2024-T4$^{14,15}$
   \[ \rho_0 = 2.785 \quad Y_0 = 2.8 \text{ kbar} \quad G = 287 \]
   \[ P = 0.73 \mu + 1.72 \mu^2 + 0.4 \mu^3 \]

3. Aluminum alloy 6061-T6$^{15,16}$
   \[ \rho_0 = 2.70 \quad Y_0 = 3 \text{ kbar} \quad G = 248 \text{ kbar} \]
   \[ P = 0.73 \mu + 1.72 \mu^2 + 0.4 \mu^3 \]

4. Uranium$^{17}$
   \[ \rho_0 = 19.045 \quad Y_0 = 12 \text{ kbar} \quad G = 844 \text{ kbar} \]
   \[ P = \frac{1.171 \mu (1 - 0.21 \mu - 0.295 \mu^2)}{(1 - 0.53 \mu)^2} + (2.42 + 0.59 \mu) E \]

5. Sapphire, single crystal Z-cut Al$_2$O$_3$. Used in its elastic range only.
   \[ \rho_0 = 3.965 \quad C_L = 1.119 \quad \text{HEL} > 120 \text{ kbar} \]
   \[ \sigma = \rho_0 (1.119 + 1 \cdot U_p) U_p \]
6. Copper, OFHC$^{19}$
\[ \rho_0 = 8.03 \quad Y_0 = 1.2 \text{ kbar} \quad G = 477 \text{ kbar} \]
\[ P = 1.19 \mu + 4.435 \mu^2 \]

7. Magnesium alloy AZ31B$^{20}$
\[ \rho_0 = 1.735 \quad Y_0 = 1.7 \text{ kbar} \quad G = 165 \text{ kbar} \]
\[ P = 0.37 \mu + 0.54 \mu^2 + 0.186 \mu^3 \]

8. PMMA, Polymethylmethacrylate$^{18}$
\[ \rho_0 = 1.185 \quad Y_0 = 1.5 \exp \left( - \frac{E \times 10^{-16}}{0.0058 - E} \right) \text{ kbar} \quad G = 23.2 \text{ kbar} \]
\[ P = \frac{0.0583 \mu (1 + 0.575 \mu)}{1 - 1.088 \mu + 1.124 \frac{\mu^2}{\mu + 1}}^2 + 0.85 E \]

9. Silica, Dynasil 1000$^{18}$ Used in the nonlinear elastic range only.
\[ \rho_0 = 2.201 \]
\[ \sigma = 0.7745 \mu - 4.404 \mu^2 + 30.15 \mu^3 - 70.37 \mu^4 + 0.0752 E \]

10. Alumina, AD-85$^{13}$ Used in its elastic range only.
\[ \rho_0 = 3.435 \quad Y_0 = 38 \text{ kbar} \quad G = 830 \text{ kbar} \]
\[ \sigma = 1.54 \mu \]

11. Gauge, Mica, clear muscovite$^{21-23}$
\[ \rho_0 = 2.67 \quad Y_0 = 0 \quad G = 0 \]
\[ \sigma = 0.427 \mu + 0.72 \mu^2 + 1.5 \mu^3 + 1.13 E \]

Kapton and/or Epoxy$^{15}$
\[ \rho_0 = \frac{1.19 t + 1.44 t_k}{t} \quad Y_0 = 0 \quad G = 0 \]
\[ t = \text{total thickness of gauge} \]
\[ t_k = \text{thickness of epoxy} \]
\[ t_k = \text{thickness of Kapton} \]
\[ \sigma = 0.0884 \mu + 0.101 \mu^2 + 0.226 \mu^3 + 1.13 E \]

30/70 Mix of Mica and Epoxy$^{21-23}$
\[ \rho_0 = 2.0 \quad Y_0 = 0 \quad G = 0 \]
\[ P = 0.162 \mu + 0.234 \mu^2 + 0.745 \mu^3 + 1.2 E \]

ACKNOWLEDGMENTS

It is a pleasure to thank A. B. Copeland, who performed many of the experiments, V. W. Morasch, who made most of the gauges, and A. E. Abey, who made the static measurements.
REFERENCES

This work was performed under the auspices of the United States Atomic Energy Commission.

6. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.
8. Trade name: Polyimide Film, E. E. DuPont de Nemours & Co.
9. 828 Epon, Shell Oil Company.
with a Diamonite target. In each other shot, target and flyer were of the same material.

Material equations of state are found in Appendix A. Wide range of target, flyer and target-gauge systems were used in this study.

**Table I. Manganin maximum stress calibration.**

<table>
<thead>
<tr>
<th>Flyer</th>
<th>Target</th>
<th>Stress, Gauge</th>
<th>Initial gauge resistance</th>
<th>Gauge resistance at maximum stress</th>
<th>Calculated unload stress at gauge data</th>
<th>Unloading stress from shot parameters</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>shot No.</td>
<td>Materials (Ref.) Thickness (cm)</td>
<td>Materials (Ref.) Thickness (cm)</td>
<td>Velocity mm/sec</td>
<td>σ₀ kbar</td>
<td>R₀ ohm</td>
</tr>
<tr>
<td>3226</td>
<td>Al₂O₃</td>
<td>31, 975 &amp; 757</td>
<td>Al₂O₃ &amp; PMMA</td>
<td>0.217</td>
<td>21.3</td>
<td>21.2</td>
<td>0.5</td>
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<tr>
<td>3224</td>
<td>PMMA &amp; SiO₂</td>
<td>0.502</td>
<td>11.27</td>
<td>12.21</td>
<td>11.75</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>3200</td>
<td>Al₂ &amp; PMMA &amp; Al₂</td>
<td>0.809</td>
<td>65</td>
<td>7.57</td>
<td>8.56</td>
<td>8.23</td>
<td>27</td>
</tr>
<tr>
<td>3201</td>
<td>Al₂</td>
<td>0.811</td>
<td>66</td>
<td>7.40</td>
<td>8.66</td>
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</tr>
<tr>
<td>3236</td>
<td>Cu &amp; Al₂</td>
<td>0.317</td>
<td>78.5</td>
<td>9.856</td>
<td>12.93</td>
<td>11.74</td>
<td>67.3</td>
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<tr>
<td>3155</td>
<td>Al₂</td>
<td>1.247</td>
<td>107</td>
<td>9.58</td>
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<td>11.55</td>
<td>77.4</td>
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<tr>
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<td>Zelus &amp; Al₂</td>
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<td>247</td>
<td>7.64</td>
<td>12.51</td>
<td>10.02</td>
<td>23</td>
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</table>

Material equations of state are listed in Appendix A.

Gauges were of 1 mil wire insulated with 1 mil kapton in shots 3226, 3224, 3200, 3201, 3236; 1 mil mica was used in shots 3155 and 3200. Gauges were placed between the first two plates of the target.

---

**Table II. Manganin dynamic hysteresis.**

<table>
<thead>
<tr>
<th>Flyer</th>
<th>Target</th>
<th>Geometry</th>
<th>Stress, Gauge</th>
<th>Initial gauge resistance</th>
<th>Gauge resistance at maximum stress</th>
<th>Calculated unload stress at gauge data</th>
<th>Unloading stress from shot parameters</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.317</td>
<td>31</td>
<td>9.75</td>
<td>10.65</td>
<td>10.49</td>
<td>21.3</td>
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<tr>
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<td>PMMA &amp; SiO₂</td>
<td>0.502</td>
<td>30</td>
<td>11.27</td>
<td>12.21</td>
<td>11.78</td>
<td>15</td>
<td>14</td>
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<tr>
<td>3200</td>
<td>Al₂ &amp; PMMA &amp; Al₂</td>
<td>0.809</td>
<td>65</td>
<td>7.57</td>
<td>8.56</td>
<td>8.23</td>
<td>27</td>
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<td>2</td>
<td>0</td>
</tr>
<tr>
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<td>78.5</td>
<td>9.856</td>
<td>12.93</td>
<td>11.74</td>
<td>67.3</td>
<td>66</td>
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<tr>
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<td>Al₂</td>
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<td>107</td>
<td>9.58</td>
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<td>7.64</td>
<td>12.51</td>
<td>10.02</td>
<td>23</td>
<td>120</td>
</tr>
</tbody>
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FIGURE CAPTIONS

Fig. 1 Gun-accelerated flyer impact geometry.

Fig. 2 Manganin gauge circuit.

Fig. 3 Static and dynamic calibration of 1 mil Manganin wire.

Fig. 4 Shot 3226 X-T diagram illustrating the wave reflections in the flyer that cause the stepped release at the gauge location. The target is made thick enough so that a rarefaction from its free surface arrives at the gauge much later in time.

Fig. 5 Shot 3227 stepped release. Particle velocity, dotted line; machine calculation, solid line.

Fig. 6 Shot 3226 stepped release. Manganin hysteresis, dotted line; machine calculation, solid line.
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