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Towards a final analysis of lateral gauge response

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Abstract. The non-invasive measurement of in-material states of stress and strain within loaded targets is a paradigm that has yet to be fully achieved. However great advances have been made using manganin sensors to achieve this goal. The gauge element for measuring the lateral stress component was redesigned from a grid configuration to a T shaped wire or foil and further the flow around the gauge was investigated by several workers numerically and experimentally and shown to be stable and tracking changes in state faithfully. Finally a staged refinement of the analysis used to deconvolve the change in resistance back to stress has given a device now fit for use as a fiducial over the range of stresses up to the weak shock limit where homogeneous and hydrodynamic behaviour ensue. This work brings together latest refinements in gauge use with comparisons with other techniques. One of these concerns the tracking of elastic-plastic transitions in target materials due to the rapid gauge response. In particular we show broad agreement with the analysis of material strength using the deconvolution due to Asay and Lipkin and attempt to reconcile the two techniques here.

1. INTRODUCTION

A transducer should approximate a point sensor, responding accurately and reproducibly to an applied stress or strain whilst being insensitive to variations in other properties. Piezoresistance describes the change of the electrical resistivity of a material with applied external stresses. Bridgman used manganin (an alloy of 84% copper, 12% manganese, and 4% nickel) which fits the requirements outlined above and has been used successfully to 10 GPa [1]. The relative change in resistivity may be expressed as a piezoresistive coefficient multiplied by the stress. Since a crystal generally has anisotropic piezoresistive properties, and the stress is generally expressed in terms of its components in various defined directions, the full formulation is necessarily of tensor form.

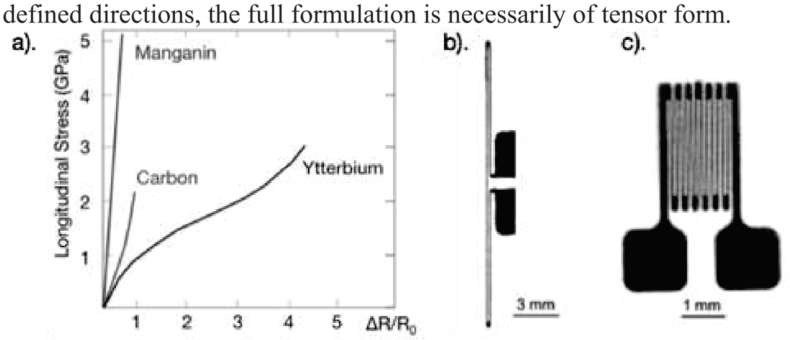

FIGURE 1. a). Manganin, ytterbium and carbon resistance change as function of pressure. b). MicroMeasurements manganin gauges J2M-SS-580SF-025. (c). MicroMeasurements C-951213-C.

Manganin is the alloy of choice for constructing sensors placed to measure stresses in ranges up to 150 GPa (to the weak shock limit of materials). Other materials have also been studied as possible candidates, including carbon and ytterbium. Several caveats should be noted in using these. The first is that the change of resistance with temperature, found negligible for manganin, is not so in their case although they are more sensitive. Secondly their purity and defect distributions are difficult to control. Finally the expense and variability of sensors using these materials reduce their suitability for experiment. Typically metals can be drawn as thin wires or sputtered onto substrates (typically fibre epoxy) to act as foil sensors. The response of piezoresistive gauges results in a change of resistance that is a function of the pressure in the gauge, *P,* and this may be different for various geometries and orientations. Further the material properties will determine this pressure and this is reflected in the yield strength of the gauge Y_G. For this reason it is crucial to understand how P depends on Y_G for various orientations and gauge geometries, as

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well as to quantify Y_G as a function of P for a given gauge material. The resistance of the section of metal fabricated into a gauge element alters with pressure in proportion to changes in the cross-sectional area and length of some piece of the active element (Fig. 1 b, c).

2. ANALYSIS OF GAUGE RESPONSE

Any sensor may be regarded as an intrusion or defect at some scale within the target material it samples. The dimension of the sensor thus defines a mesoscale structure embedded inside the material of interest. This must equilibrate with the local stress field and this defines a response time for the sensor of order three times its thickness divided by the mean speed of the wave in the package. Recent work has considered the effects of hardening (which effects yield strength) on the deconvolution of the alloy response in the flow to quantify Y_G as a function of P.

Firstly consider two geometrical forms for the sensors; a single wire or a grid of elements closely aligned to one another. Locally a wire experiences a hydrostatic stress and strain state around the element. This results in the strain states around a wire and a grid gauge being different although the same stress is applied to both. The strength of the gauge material Y_G will be significant for its response at this scale and the grid and wire geometries will cause the metal element to follow different shock states in one- and two-dimensional compression. This means that the pressures P in the wire and grid gauges and the dynamic confined elastic limits will be different when compared with a common stress within them since

$$P_{\mathrm{Grid}} = \square_{x} \square \frac{2}{3} Y_{G} \text{ and } P_{\mathrm{Wire}} = \square_{x} \square \frac{Y_{G}}{3}. \tag{1}$$

Further, since annealing will reduce the value of Y_G, the measured resistance change should be higher at a given stress than that of an as-received gauge and the orientation of a grid gauge will affect the output recorded from it, particularly if it is placed in a plane perpendicular to that of shock front [3, 4]. To define orientation it is conventional to talk in the following terms. A grid gauge will be in the longitudinal orientation (responding to σ_x) when it is emplaced perpendicular to the flow direction in the target and in the lateral configuration (responding to σ_y) when placed parallel to this direction. This leads to several differences between gauge types such as different calibration curves for longitudinal and lateral stress states and hysteresis observed with sensors in a lateral geometry dealt with here [3, 4, 5].

The resistance changes of wires or grids will be close to the same when the pressure or stress becomes large compared with the yield stress of the gauge. However it is important to consider the latter if the gauges are to be used in low stress regimes and to understand the observed calibration curves. The sensor alloy manganin was found to have a yield stress of 0.75 GPa for the commercial grid gauges discussed here. However, all metals display some plasticity under shock and dislocation generation and storage in this alloy causes shock hardening to occur. Thus the yield stress will generally be a function of the stress level to which it is shocked. The effect of gauge strength on its piezoresistive behavior was first demonstrated by Barsis *et al.* who analyzed the different responses of manganin wires and foils [6]. Mounting the sensor in the direction of the flow defines a stress tensor around the elements which may be used to describe the stress transmitted to the gauge through its thickness. This stress state results in a hydrostatic pressure component $P_{Grid}=\sigma_y+Y_g/3$ in the gauge. Within its elastic range, the piezoresistive response of the lateral gauge, is not unique since it depends on the impedance of the embedding specimen. However this is not the case for lateral stresses higher than about 1.0 GPa, where the lateral gauge is plastically deformed and its piezoresistive response depends uniquely on the pressure inside the gauge. Recently a new analysis for lateral stress based upon experimental data has examined resistive hysteresis upon stress unloading to deduce gauge strength [7]. This work has provided a unique relation between lateral stress and resistance change that holds for stresses *above* 1.0 GPa, where the gauge is deforming plastically; σ_y (GPa) = -2.19 $(\Delta R/R_0)^2$ + 38.58 $(\Delta R/R_0)$ - 0.4 where $\Delta R/R_0$ is the relative resistance change of the gauge [7].

The direct measurement of lateral stresses with piezoresistive gauges as now been used across a range of materials to deliver a better understanding of strength development within materials under load. The response of the gauges to various loading conditions in both longitudinal and lateral configurations has been analysed and understood and as demonstrated here agrees with methods employed that use entirely independent techniques.

3. DISCUSSION

The gauge has proved itself a means of tracking evolution of strength within a range of materials. Performance in an engineering application, for instance its resistance to penetration during impact, is reflected in the strength it

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displays when loaded with different impulses and there is always a need to better understand the wealth of data that has been collected on all materials in order to map their dynamic strengths. It is possible to monitor directly the longitudinal (σ_x) and lateral (σ_y) stresses, and (in isotropic materials) assign the difference between the two to the compressive strengths that exist behind the shock front at high pressures. Measurement of histories for the two components of the stress field, σ_x and σ_y, within an isotropic material loaded under one-dimensional strain allows a direct measurement of the shear stress, τ, as a function of time since $2\tau = \sigma_x - \sigma_y$.

The measurement of shear strength has been attempted using other techniques. These include using the measured stress- and shock velocity versus particle velocity data to construct Hugoniot and hydrodynamic curves (corrected for temperature) to determine their offset and then calculate inferred strength or by employing the pressure-shear technique to directly map the deviatoric behavior possible on thin samples of target material. Another method is to load the material and then allow release from states induced by single and double shocks (the self-consistent technique developed by Asay and Lipkin) to determine the stress offset of the Hugoniot and isentrope [8].

Recent comparisons have suggested that the stress gauge appears to over-estimate dynamic strength compared with these other techniques. Thus a reanalysis has been conducted and in this section lateral strength data on a range of materials will be presented calculated using the latest experimentally lateral stress calibrations discussed earlier [7]. Stress sensors must be employed in range of materials and two are illustrated here that span a range of response. The first is soda-lime glass and the second is the polymer polyethylene; materials of very different strength and impedance used in differing stress ranges in the examples shown here.

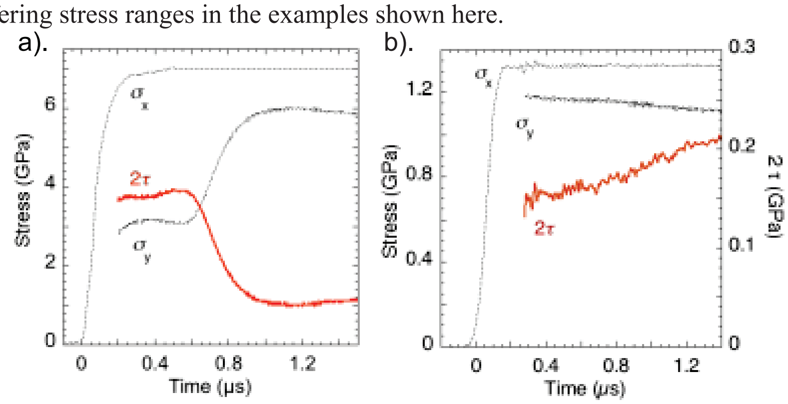

FIGURE 2. a). Soda lime glass; b). Polyethylene; showing stress histories from piezoresistive sensors mounted 4 mm from an impact face. The stress histories show development of strength behind the shock front.

Fig. 2 shows the development of the stress field within soda lime glass (SL) and the polymer polyethylene (PE) compressed by impact in the weak shock regime. In each case sensors were embedded in the flow, a distance from the impact face to observe the development of the stress field behind the shock front. Fig. 2 a). shows the shock response at an intermediate stress in the response of this glass. The longitudinal stress jumps to *ca.* 7 GPa and ramps upward at this gauge location. The lateral stress rises to *ca.* 3 GPa for 0.5 µs but then jumps again to 6 GPa thereafter coincident with the arrive of the fracture front. The shear stress follows a trajectory starting at just below 4 GPa and then after 0.5 µs drops to *ca.* 1 GPa. A failure front arrives after *ca.* 0.5 µs and drops the strength of the glass taking it from intact to comminuted material with only a quarter of the strength at this stage [9]. This value is lower than the failed strength we have previously assumed for the comminuted glass. Fig. 2 b) shows response of the thermoplastic PE. The hydrogenated carbon chains and their stacking give steric hindrance under flow dominates the response of the strain to the strains applied in shock. The longitudinal stress rises rapidly reaching a flat plateau, whilst the lateral stress rises over the loading time. The difference between the two values determines twice the shear stress behind the front that is represented by a solid line. The shear stress in polyethylene rises behind the shock over the microsecond of the impulse applied; a feature found only in these thermoplastics under load [10]. In both cases the lateral stress (and by inference then the strength) is not displayed for the first 200 ns of the histories. This is since there is a time for the foil to equilibrate within its gauge package to the stress field around it. However this time is much faster in PE and SL since the gauge packages is matched to the material under test.

Ramp wave loading of annealed and cold worked tantalum has been carried out by Asay *et al.* using magnetic induction techniques [11]. Their work is one of the few that allow direct comparison between independent strength measurements. The authors directly measured the shear strength using the self-consistent technique [8]. The results obtained allow direct comparisons to the gauge method discussed here through independent measurements on the same metal (Fig. 3) although the loading rate is different in the two experiments. The strengths are deduced from particle velocity histories measured may be compared with lateral stress measurements made under plate impact

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loading. Histories for shocked tantalum are shown in Fig. 3 a) [11, 12]. In annealed tantalum the stress rises to a precursor peak known as the isentropic elastic limit (IEL) by analogy with the Hugoniot Elastic Limit (HEL). It dips to a minimum in the case of the annealed material and rises again with the arrival of the plastic front. This can be converted into a yield stress *Y* and the behaviour of the precursor with travel distance is shown in Fig. 3 b).

The values of the IEL and minimum recorded values for the strength of the same tantalum were close to those recorded for the shock measurements. Asay found that the average elastic limit for annealed Ta was found to be 3.16 GPa, corresponding to a dynamic yield strength of 1.54 GPa. After yielding, the longitudinal stress relaxed to an asymptotic value of 1.6 GPa, corresponding to a minimum yield stress of 0.78 GPa. The shock histories with the lateral stress calculated using the new calibration show an initial value of 3.5 GPa after gauge equilibration (*ca.* 200 ns) decaying to 1.6 GPa after shear stress relaxation (*ca.* 1 µs). This later value is in accordance with the flow stress calculation at later time made using the self-consistent method.

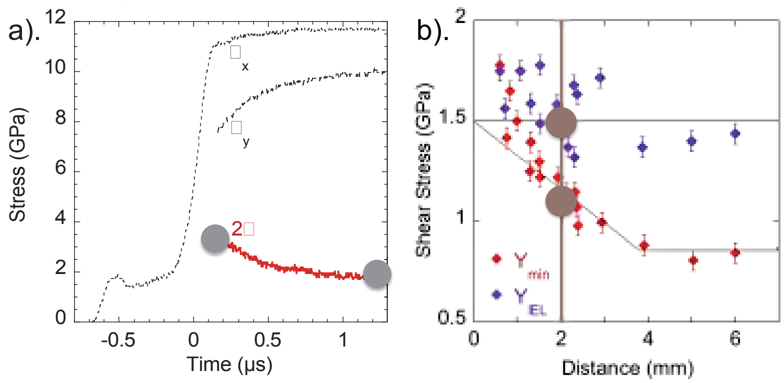

FIGURE 3. Shear strength measurements using ramp and shock loading. a). lateral/longitudinal stress histories for tantalum under plate impact taken at 2 mm [12] and b). development of shear stress as a function of travel distance at 2 mm from [11]. The appended circles on the shock data to the left and the IEL/minimum strength in the ramp to left show equivalent measurement.

4. CONCLUSIONS

Piezoresistive gauges are vital components in the armoury of an experimentalist aiming to understand the complex physics occurring in materials under load. To accurately mount and power such sensors and to understand their response and limitations is a complex technical task that must be understood before interpreting data. The gauge samples a volume element of a size commensurate with it package. This determines it response time which must be understood before conclusions are drawn as to details in response. Yet the benefits of persevering to understand the device are manifold since these techniques are the only means of observing the development of a continuum state *within* a macroscopic volume. Other sensing methods employ surface measurements sensing components of the compression fields that exist within a material at the time it is loaded. Further, deducing state information in this manner risks using steady wave linkages between state variables that may not apply for the loading impulse applied. Nevertheless, calibrations are now accurate to less than a few percent on these sensors and with gauges correctly mounted, a means exists to sample continuum lateral and longitudinal stress and strain states within a shocked flow. Eventually limits are reached on temporal resolution and breakdown of insulation which limits the stress range over which the sensor responds, but in the weak shock regime there is no better means of understanding the evolution of material properties and strength.

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