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This work performed at Sandia National Laboratories is supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

Experiments and Analysis of Lateral Piezoresistance Gauges

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The response of lateral piezoresistance gauges to shock wave uniaxial strain loading has been examined in a combined experimental and calculational effort. Plate impact experiments provided lateral gauge data which were analyzed using quasi-static and dynamic inclusion analyses. Experimental data showed that the response of the lateral gauge output depended upon the matrix material and gauge emplacement method. The calculations indicated that these differences were due to complex gauge-matrix interactions. These interactions were influenced by the stress and strain distributions in and around the gauge, plasticity effects, properties of the gauge and matrix materials, and emplacement conditions.

INTRODUCTION

The work presented in this paper is part of a comprehensive effort [1-5] to understand and characterize the response of piezoresistance foil gauges under shock compression, uniaxial strain loads. This particular work examines the response of lateral piezoresistance gauges under such loads. A lateral gauge has the major surface of the foil parallel to the direction of wave propagation.

This work has been motivated by the need to be able to specify the lateral stress in shocked materials. However, for uniaxial strain experiments, two major issues make the interpretation of lateral gauge data difficult. The first is that the lateral stress in a material cannot be determined solely from the conservation equations for wave propagation in uniaxial strain [2]. Thus, a lateral stress measurement cannot be validated. Second, the lateral stress in the gauge is not, in general, uniquely related to the lateral stress in the material [3] (or matrix). Rather, the foil gauge must be considered as an inclusion in the matrix, requiring solution of the resulting boundary value problem in order to properly resolve the stress fields in and around the gauge.

In this work experiments and analyses were used to gain an understanding of lateral gauge response. A series of plate impact experiments were performed in which targets of fused silica or aluminum oxide (alumina), containing lateral gauges of manganin or ytterbium piezoresistance foil were subjected to shock wave loading. Quasi-static and dynamic analyses were performed to interpret the resistance change data in terms of gauge-matrix interaction. These analyses were used to examine and understand differences in lateral gauge

data obtained in the experiments.

EXPERIMENTAL TECHNIQUE

The experiments used designs similar to previous work reported by Gupta and coworkers [1-5]. The gauges were stamped from manganin or ytterbium foil and embedded in carefully machined grooves in the matrix. These grooves closely matched the shape and depth of the gauge. Thus, as closely as possible, the gauge was fully embedded and in contact with the matrix.

The matrix consisted of 5.7 cm diameter disks of fused silica or alumina. Many of these disks were cut in half to permit insertion of lateral gauges. A typical configuration is shown in Figure 1.

Both the gauge and matrix materials had been well characterized to permit accurate analysis of the gauge response. The ytterbium and manganin foils were char-

Figure 1. Typical experimental configuration.

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acterized using methods described by Chen, et al. [9]. The fused silica and alumina had been characterized by Connor [10] and Gupta [11], respectively using compression-shear methods.

A set of 19 experiments were performed, 17 in fused silica and 2 in alumina. These data were supplemented with data from a previous set of experiments of manganin gauges in alumina performed by Gupta and Gupta [5]. These data spanned a stress range of 5 - 90 kbar, matrix longitudinal stress.

Figure 2 shows the steady state resistance change values for ytterbium lateral gauges in both fused silica and alumina matrices. Similarly, Figure 3 shows the

Figure 2. Ytterbium lateral gauge data, quasi-static and dynamic calculation results.

steady state resistance change values for manganin lateral gauges in both matrices. Additionally, both figures compare the experimental data with quasi-static and dynamic inclusion analyses.

For both ytterbium and manganin lateral gauges, the steady state resistance change clearly reveals a dependence upon matrix material. The data in fused silica matrices is higher than in alumina matrices. The difference is also indicated in both the quasi-static and dynamic inclusion analyses. This trend indicates that the resistance change and lateral stress cannot be expressed as a unique relationship.

Additional experiments, plotted in Figure 2, were performed with ytterbium gauges in ungrooved matrices (the two data points denoted by squares). This configuration produced steady state resistance change values which differed from the data for gauges in grooved matrices at the same stress. These results indicate that the gauge response is sensitive to the emplacement method.

Figure 3. Manganin lateral gauge data, quasi-static and dynamic calculation

Experiments at the highest matrix lateral stresses in fused silica produced highly time dependent lateral gauge response with no steady state value. These observations are discussed in [6] and [8].

To further illustrate the differences in lateral gauge response, Figure 4 shows the records of three ytterbium lateral gauge outputs: one each in a grooved fused silica matrix, ungrooved fused silica matrix, and grooved alumina matrix. The ytterbium gauges were identical in geometry and from the same batch of foil. All three gauges were subjected to matrix lateral stresses of 3.0 kbar. However, each record indicates unique gauge response. In particular, the steady state resistance change values are different in each case.

QUASI-STATIC INCLUSION ANALYSES

Figure 4. Comparison of ytterbium lateral gauge output at 3 kbar lateral stress.

Quasi-static solutions to the gauge-matrix interaction and electromechanical problems were obtained using methods developed by Gupta [1]. As shown in Figure 2 and Figure 3, these analyses were able to predict measured resistance changes with reasonable accuracy. Furthermore, these calculations demonstrate that the lateral gauge response depends on the matrix and gauge materials and is not a unique measure of matrix lateral stress. However, the limitations of this approach (see [8]) do not allow it to properly analyze the ungrooved gauge case nor the nonequilibrium cases.

DYNAMIC INCLUSION ANALYSES

Dynamic finite element calculations were performed to examine the response of the lateral gauges from impact through equilibration to the steady state resistance change. The EXCALIBUR finite element program [12] was used for the analyses.

The simulations were performed in plane strain. The cross section of the sensing element of the gauge was in the plane of calculation and the flow of current through the gauge was perpendicular to the plane. Simulations of the three experiments shown in Figure 4 are discussed.

For calculations in the grooved fused silica and alumina matrices, the gauge was modeled as an inclusion, completely surrounded by the matrix material. For the calculation of the gauge in the ungrooved fused silica matrix, material in the plane of the gauge foil was modeled as epoxy. Details of the calculational method may be found in [7] and [8].

The most significant finding of the dynamic calculations is that the distribution of stress and strain in the gauge is highly nonuniform. Figure 5 shows the highly nonlinear stress and strain distributions through the width of the gauge for the case of the ytterbium gauge in the grooved fused silica matrix. The zero position is the upstream edge of the piezoresistance foil. Both stress and strains are largest at the upstream edge. Also, the longitudinal and lateral stresses in the gauge are nearly equal. Furthermore, the strains are of similar magnitudes, but opposite sense. The interpretation of these two graphs is that the shock, propagating through the matrix, loads the upstream edge of the foil and induces plastic deformation. This plastic response increases the lateral stress in the gauge. The gauge expands laterally in the upstream region, pressing upon the surrounding matrix.

In the fused silica matrix, a lateral stress of 3 kbar corresponded to a longitudinal stress 23 kbar. Thus, a

Figure 5. Steady state stress (top) and strain (bottom) distributions through gauge width for grooved fused silica.

relatively large longitudinal stress loaded the edge of the gauge while a smaller lateral stress provided limited containment of the expanding foil. As a result, the lateral strain in the upstream region of the gauge indicates expansion.

By comparison, Figure 6 shows the stress distributions for the ytterbium gauge in the alumina matrix. In this case, the matrix longitudinal stress was 9.8 kbar while the matrix lateral stress was 3.0 kbar. The stress and strain distributions are quite different from those of the fused silica case. The stress distribution is more uniform. The effect of the matrix longitudinal stress does not dominate the stress distribution. Furthermore, the lateral stress in the gauge is close to the matrix lateral stress.

The stress distribution in the gauge for the ungrooved fused silica case is shown in Figure 7. The

Figure 6. Steady state stress distribution through gauge width for grooved alumina matrix calculation.

stresses in this case are more uniform than for the grooved case with the most nonuniformity occurring at upstream end of the gauge. Because, the gauge was surrounded by epoxy in the plane of the foil, the loading due to the longitudinal wave was less than for the grooved case. Furthermore, because the gauge material was stiffer than the surrounding epoxy, the gauge experienced larger compression than for the grooved case. The larger lateral compression contributed to the higher resistance change shown in Figure 4.

Figure 7. Steady state stress distribution through gauge width for ungrooved fused silica matrix calculation.

CONCLUSIONS

This combined experimental and calculational effort has been used to gain an understanding of lateral gauge response under dynamic loading. The experimental data show that the response of lateral piezore-

sistance gauges is dependent upon matrix material and emplacement method, not simply the matrix lateral stress. Furthermore, the calculations show that the response is a complex gauge-matrix interaction. The effects of gauge plasticity and longitudinal loading must be considered when examining the interaction. The approach and general understanding of lateral piezoresistance gauges from this work can be the basis for examining gauge response under more complicated loading conditions and more practical gauge designs.

ACKNOWLEDGEMENTS

This work was performed with Dr. Y.M. Gupta of the Shock Dynamics Laboratory, Washington State University. Paul Bellamy and Jerry Thompson provided substantial experimental support. Dr. Y.M. Ito and Y. Muki provided the EXCALIBUR program and invaluable guidance with the dynamic calculations.

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