THE USE OF ACOUSTIC SIGNAL ATTENUATION IN THE EXAMINATION OF RESIDUAL STRAINS: PART B - THE USE OF EXPERIMENTALLY DERIVED ACOUSTIC STRAIN CORRELATIONS IN THE EVALUATION OF RESIDUAL STRAINS AND STRESSES

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INTRODUCTION

In a previous conference we presented a comparison of several different acoustic techniques to estimate residual stresses in complex situations.[1] Of the several methods, the use of the attenuation of broad band pulses appeared to be better than the usual method of inferring strain from changes in the propagation velocity. The measurement of strain through changes in the velocity is effected through the equations

$$\Delta V/V = f(\varepsilon_{ij}) \tag{1}$$

$$\Delta t/t = \Delta d/d - \Delta V/V \tag{2}$$

where ε_{ij} = strain tensor, t = time for the wave to traverse the specimen, d = specimen thickness, V = wave velocity.

The usual method consists of measuring the change in the traverse time t, and in the thickness d, and determining the value of $\Delta V/V$ from Eq. (2). This value of $\Delta V/V$ is then used in Eq. (1) to determine the strain components. Because of the appearance of the strain components ε_{ij} in Eq. (1), the method is practical only for those specimen cases of plane strain or plane stress for which Eq. (1) simplifies to

$$\Delta V/V = C(\sigma_x + \sigma_y) \tag{3}$$

For many situations the specimen thickness cannot be measured, but only estimated. Unfortunately, the term $\Delta d/d$ is often 2 to 4 times larger than the term $\Delta V/V$. Consequently the determination of $\Delta V/V$, and thus ε_{ij}, may be substantially in error.

The attenuation method is based upon the equation

$$\Delta A/A = -\beta\Delta d - d\Delta\beta \qquad\qquad (4)$$

or

$$\Delta\beta = \frac{\Delta A}{d\ A} - \frac{\beta\Delta d}{d} \qquad\qquad (5)$$

and $\Delta\beta$ is only linearly related to the estimate of d. The thickness can be estimated by

$$d = tV \qquad\qquad (6)$$

and since $\Delta V/V$ rarely changes by more than 1%, and since β is itself relatively small, we can approximate $\Delta\beta$ with reasonable accuracy.

The basic concepts of the approach are listed in Table 1. Several items deserve elaboration.

1. The microstructural effects which create the acoustic changes are present in the original state as well as in the stressed state. Thus, the test procedure must utilize a reference material. Under some conditions in which the processing causes a significant spatial variation of the base material, the need for the reference signal may introduce some complications regardless of the acoustic test method used.

2. Because the changes in velocity due to plastic deformation are small,[2] it is more likely that attenuation or scattering will produce a better discrimination than velocity techniques.

3. The unique relationship between the plastic strain and the attenuation is: (a) affected by the specific material and/ or the material processing; (b) is different for different states, e.g., uniaxial, biaxial, etc.; (c) is history dependent. However, it is possible that the small changes which occur during the history may not show up, only the integrated overall effects.

Since the relationship between the state of strain and the attenuation is highly nonlinear and history dependent, it is unlikely that it can be inverted to determine the strain when given the spatial attenuation distribution.

Table 1 - Basic Concepts.

1. Residual stresses are the result of plastic deformations.

2. Plastic deformations induce permanent microstructural
    changes:
    (a) void growth
    (b) intergranular damage
    (c) internal breaking.

3. Microstructural changes can be detected by acoustic
    signal attenuation.

4. A unique relationship exists between plastic strain
    and signal attenuation.

5. Residual stresses will modify the attenuation by
    altering the internal impedance.

Table 2 - Computations.

1. Calculate the mechanical history of the material.

2. Estimate the signal attenuation:
    (a) empirical correlation.
    (b) scattering theory based upon internal damage models.

3. Compare the predicted and measured signal attenuation
    patterns.

4. Agreement implies the correctness of the computations.

5. Lack of agreement requires re-computation with
    different parameters.

THE METHOD

     A proposed method for extracting this information is given in
Table 2. In the sense that incremental plastic calculations contain
the history of the specimen, the method should be suitable. The
most critical feature of Table 2 is the technique used to estimate
the signal attenuation. Method (a), based upon theory, requires a
knowledge of the type of damage sustained by the specimen and the
computation of the attenuation or scattering associated with this
damage. Inasmuch as different stress fields may involve substan-
tially different damage mechanisms, the resulting attenuation pat-
terns will depend uniquely upon the stress computed in step 1.
Method (b), the empirical correlation, requires that the correlation
be obtained from test specimens which experience a history which is

equivalent to that of the object being examined. This equivalence
may take the form of a point-by-point equal history, or may simply
be one in which the final microstructural changes are the same. In
either case, it is obvious that some inexactness will be introduced
into the analysis since, by definition, the current internal state
of the material is not known.

Once the predicted attenuation pattern is known, it is to be
compared with the measured pattern. Even if the patterns agree,
the uncertainty described above suggests that agreement in defining
the strain state can only be obtained within a range of input vari-
ables and not for a single choice of conditions. Consequently the
method of Table 2 must be coupled with a rather complete uncertainty
and sensitivity analysis to permit a realistic assessment. If the
agreement is unsatisfactory, the process must be repeated, starting
from step 1, with new parameters. Since it will not be clear, at
this point, whether it is the computation of the plastic deformations
or the attenuation model which is in error, these recomputations are
likely to be extensive in scope. With regard to step 1, there is
considerable national effort in the development of numerical tech-
niques for predicting plastic deformation and the accuracy of the
several methods is well characterized. Thus the uncertainty will
probably be in defining the initial state of the material or in the
evaluation of the loads during the specimen's history, the latter
being one of the features that the analysis is expected to define.
At the same time we expect that the uncertainty in the attenuation
calculation will be reduced through experience. Repeated experi-
ments, with their natural codification, should lead to a library of
typical attenuation patterns to be associated with specific stress
states. Thus the investigator should be able to choose the damage
model or the empirical correlation based upon a history of similar
experiments.

CURRENT RESULTS

In an effort to develop empirical correlations and an under-
standing of the internal microstructural damage models needed in
step 2, Table 2, a series of experiments has been conducted. We
had hoped to have used the correlations to perform numerical simu-
lations and at this time to demonstrate the usefulness of the method.
Unfortunately, the accuracy of the results obtained to date has not
been sufficient to define the correlations, and we have been able
to demonstrate only that the attenuation effect exists and to infer
its usefulness.

The tests consisted of sampling the attenuation along the axis
of a standard tensile specimen, Fig. 1, over a distance of 1 inch,
centered approximately over the neck region. The attenuation was
measured for zero, 1000, and 2000 pound loads. The specimen was
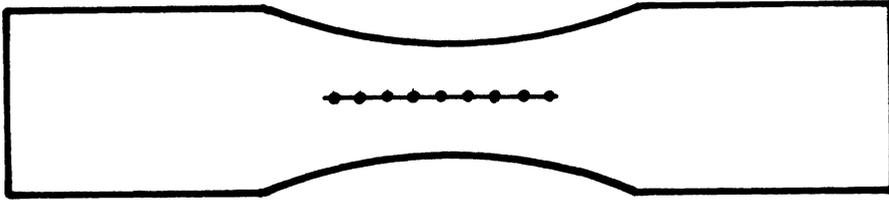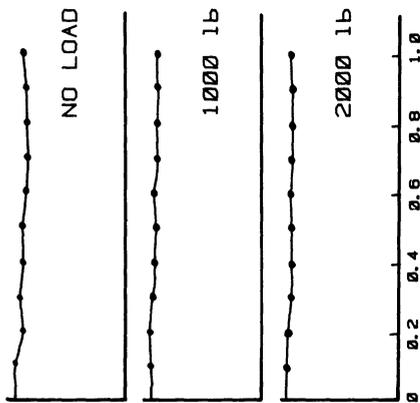then plastically deformed (using a load of 4000 pounds) to a true

Fig. 1. Sampling Points.

strain of approximately 16% in the necked region and then unloaded. The surfaces were then machined to remove the texture and the warpage that had developed during the plastic deformation. The specimen was again loaded and the attenuation measured for zero, 1500 and 2000 pound loads.

Figures 2 and 3 illustrate the attenuation profiles obtained for the original specimen when elastically loaded and it is apparent that there is no spatial variation. Figure 4 shows the attenuation pattern measured for the deformed specimen. First we note that under no load condition, while there is some effect, it is impossible to determine which portion of the test specimen experiences the plastic deformation. Apparently the internal microstructural damage consisted of intergranular cracking and small void formation. The voids are permanent and cause the attenuation observed for the no load case. However, the cracks appeared to have closed upon unloading and to have had no effect in attenuating the signal. When the deformed specimen was loaded these cracks opened up, increasing the scattering and giving rise to the patterns shown in the bottom two profiles of Fig. 4. For these profiles the location of the neck is clearly evident. When the load was increased, the pattern did not change measurably. This is in agreement with our model, as once a crack opens, any further opening should not affect the attenuation unless the load is so large that the shape of the voids and the cracks is markedly distorted.
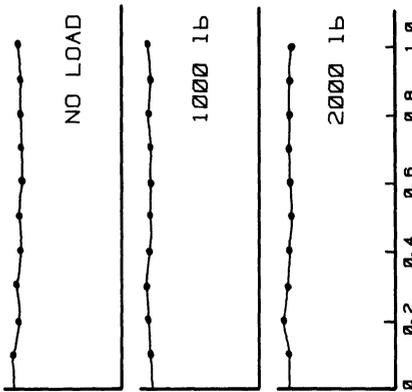
CONCLUSIONS

The results shown in Fig. 4 suggest that the effect of permanent, plastically induced damage is not likely to be accurately evaluated in the absence of an applied stress. However, when a stress is applied, or when residual stresses exist, the areas which suffered internal damage due to the plastic strains can be determined easily and accurately. What the method does not appear to do is to give a response which is linear with the stress. Thus the method appears to be suited best to defining the extent and the location of the plastic strains. For situations in which the stresses are determined by plastic deformations (e.g., residual stresses), and not by other mechanisms, the stresses should be well defined. The
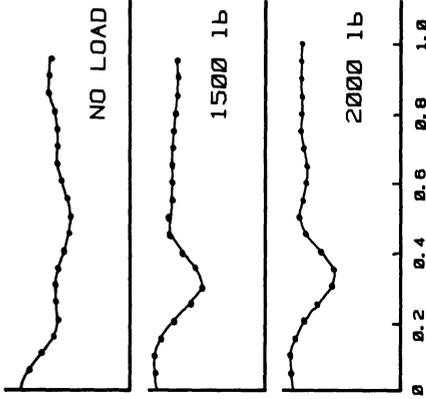
DEFORMED SPECIMEN

Fig. 4.   Attenuation
patterns for
plastically
deformed (16%
strain) alumi-
num 6061-T6.

UNDEFORMED SPECIMEN

Fig. 3.   Attenuation
patterns for
undeformed alum-
inum 6061-T6.

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Fig. 2.   Attenuating
patterns for
undeformed alum-
inum 6061-T6.

method appears to be most appropriate to thermally induced strains, welding stresses and problems of gross internal damage.

ACKNOWLEDGEMENT

REFERENCES

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2. G.S. Kino and J.H. Shaw, "Acoustic Techniques for Measuring Stress Regions in Materials," EPRI Report NP-1043, April 1979.