Nondestructive Evaluation of Bulk Stresses in Aluminum and Copper

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NONDESTRUCTIVE EVALUATION OF BULK STRESSES IN ALUMINUM AND COPPER

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Houston, Texas 77004

ABSTRACT

The effect of applied stress on the temperature dependence of the longitudinal ultrasonic velocity has been investigated in commercial aluminum and copper. Velocities of 10 MHz longitudinal waves as a function of temperature were measured on ten specimens of these metals while they were subjected to external compressive stresses. In all measurements, the velocity increased linearly as the temperature was lowered in the temperature range between 280 and 200 K. Furthermore, the slope of this linear relationship was found to decrease linearly as the amount of applied compressive stress was increased within the elastic limit of the specimen under investigation. The maximum decrease in the temperature dependence of aluminum and copper were respectively 23% which occurred at a stress of 96 MPa, and 6% which occurred at 100 MPa. The linear relationship of the temperature dependence of the ultrasonic velocity and the applied stress was then used to determine the change as a function of distance of the tangential component of the stresses developed when an aluminum rod was shrunk fit into a slightly smaller hole drilled in an aluminum disc. Excellent agreement was obtained between the computed stress distribution, and that measured using the temperature dependence method.

INTRODUCTION

Only in the case of surface stresses in components made of crystalline materials, can nondestructive evaluation of stresses be performed by x-ray diffraction method. Although considerably improved in the last ten years, this method still suffers from serious problems which severely restrict its applications. Ultrasonic methods appear to hold the best promise in measurements of bulk stresses in both crystalline and non-crystalline materials. All these methods are believed to utilize the anharmonic properties in solids; however, the exact mechanism in each is not yet established.

These anharmonic properties can be described in terms of changes in the elastic constants or velocities of ultrasonic waves when stresses are applied to the solid. Calculations have shown that these velocity changes are linear functions of applied stresses, and combinations of second- and third-order elastic constants. In the application of these calculations to determine unknown stresses, both the velocity in the absence of stress as well as third-order elastic constants have to be known independently. In addition, the measured velocity strongly depends on microstructural features which makes it necessary to develop a calibration between velocity and stress in order to be used in the determination of unknown stresses. Development of preferred orientations (texture) during deformation or fatigue, severely modify the third-order elastic constants. These problems can be solved when the differences between velocities of shear waves polarized perpendicular and parallel to stress direction are used. Due to these differences, a shift in phase will occur, and the out-of-plane components will interfere and cause a change in intensity. This method, however, does not have at present enough sensitivity, and requires an accurate determination of the shear velocity in the absence of stress.

Basically, the temperature dependences of the elastic constants of a solid are due to the anharmonic nature of the crystal lattice, and are directly related to the coefficients of higher-order terms in the strain energy function. A measure of the temperature dependence of the ultrasonic velocity can, therefore, be used to evaluate bulk stresses. Experiments undertaken on pure aluminum and copper plastically deformed in compression showed that the ultrasonic velocity, in the vicinity of room temperature, changed linearly with temperature, and the slope of the linear relationship changed considerably as the amount of prestrain was varied. In aluminum, the relative changes of the temperature dependences of both longitudinal and shear velocities increased by as much as 23% at a prestrain of approximately 13%.

In this paper, the effects of compressional elastic stresses on the temperature dependence of the longitudinal ultrasonic velocity have been studied in commercial aluminum and copper. The results obtained on these two metals show that the relative change in the temperature dependence is a linear function of the elastic stress applied. The linear relationship for aluminum was used to determine the stress distributions generated by an aluminum rod which was shrunk fit into a smaller hole drilled into an aluminum disc. The agreement between stresses measured by the temperature dependence method and those calculated was very good.

EXPERIMENTAL

Five aluminum and five copper specimens were used in this investigation. The specimens were machined in the form of rods of 0.95 cm in diameter and 1.29 cm in length, to be suitable for ultrasonic measurements. Three of the aluminum specimens were of the type 2024-0, which were annealed for four hours at 400°C in a vacuum of 10^{-6} torr. The other two specimens were made of Aluminum 6063-T4, and were used as received. The copper specimens were all of the type CDA 110, where two of them were annealed in the same way the aluminum specimens were.
and the other three were used as received. The system used to apply external stresses on the specimens is shown in Fig. (1). It consists of a split collar of inner diameter and height closely equal to those of the specimens used. The collar was made of brass in order to minimize the effect of differences in thermal expansion during the temperature dependence measurements. In addition, high viscosity oil (46,500 cs.) was put between the screws and the collar, which proved to be effective in keeping the stress applied uniform and constant during measurements. The stress was applied by tightening the screws of the collar, and simultaneously measuring the change in the diameter of the specimen. This change was measured by a shadow-graph capable of measuring changes in diameter with an accuracy of ±5%. Values of applied stress were computed from the product of strain and the other three were used as received.

The ultrasonic velocity was measured using the pulse-echo-overlap method which has been fully described elsewhere. Figure 2 displays the experimental system used in this investigation. A pulse of approximately, 1 μsec duration of variable pulse-repetition rate is generated by the ultrasonic generator and impressed on a transducer of a fundamental frequency of 10 MHz which is acoustically bound to the specimen. The reflected rf echoes are received by the same transducer, amplified and displayed on the screen of an oscilloscope. Two of the displayed echoes are then chosen and exactly overlapped by critically adjusting the time base of the oscilloscope, and the division factor on the decade divider. This frequency, accurately determined by the electronic counter, is employed to compute the ultrasonic velocity using the relation

\[ \text{Velocity} = \frac{c}{T} \]

where \( c \) is the speed of sound in the specimen, \( T \) is the length of the specimen, \( x \)-cut transducer is used for the generation of the longitudinal waves. A continuous flow cryostat in conjunction with a temperature control arrangement is used to maintain the temperature of the specimen at any desired value between 300 and 200 K. The system is capable of measuring changes in the ultrasonic velocity to an accuracy of better than 1 part in \( 10^5 \), and the temperature of the specimen to within ±0.1°C.

**RESULTS**

The velocity of longitudinal ultrasonic waves was measured as a function of temperature on five aluminum specimens denoted A, B, C, D and E. The measurements were undertaken while the specimens were subjected to various amounts of compressional stresses applied in a plane perpendicular to the direction of propagation of the ultrasonic waves. Typical examples of the results obtained on specimen E are shown in Fig. 3, where the longitudinal velocity \( V_L \) is plotted vs. temperature \( T \) at the stresses 0, 27.6, 46.2 and 75.8 MPa. From these data, one can see that the longitudinal velocity increases linearly with the lowering of temperature and the slope of this linear relationship \( dV_L/dT \) decreases as the applied stress \( \sigma \) is increased. The absolute value of the velocity, however, is increased with the increase of the applied stress, indicating that the specimen becomes stiffer when it is subjected to compressional stresses. The least mean square method was used to determine the slope of the straight line \( (dV_L/dT) \) which best fit the experimental data representing \( V \) vs. \( T \). The accuracy in determining \( dV_L/dT \) by this method was estimated to be ±2%.

Table I lists the results obtained on the five aluminum specimens investigated in this work. The table includes the values of the temperature dependence of the longitudinal velocity, measured at stresses ranging between zero and the yield stress of the specimen. Because the values of \( dV_L/dT \) at zero stress were found to vary among specimens investigated, the relative change in the temperature dependence, \( \Delta \), due to the application of stress was calculated, and its values are listed in column 4 of table I.

**TABLE I.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Applied Stress (MPa)</th>
<th>(-dV_L/dT)</th>
<th>(dV_L/dT)_{o})</th>
<th>(\Delta%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (2024-0)</td>
<td>0.0</td>
<td>0.923</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B (2024-0)</td>
<td>21.4</td>
<td>0.878</td>
<td>0.0</td>
<td>4.9</td>
</tr>
<tr>
<td>C (2024-0)</td>
<td>37.2</td>
<td>0.856</td>
<td>0.0</td>
<td>10.6</td>
</tr>
<tr>
<td>D (6063-T4)</td>
<td>0.0</td>
<td>1.007</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>E (6063-T4)</td>
<td>44.1</td>
<td>0.908</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Pure, Annealed</td>
<td>94.5</td>
<td>0.866</td>
<td>22.1</td>
<td></td>
</tr>
</tbody>
</table>

These values of \( \Delta \) are calculated from the relationship

\[ \Delta = \frac{(dV_L/dT) - (dV_L/dT)_{o}}{(dV_L/dT)_{o}} \]  

(1)

The variations in the temperature dependence measured on these specimens at zero stress are believed to be due to the differences in residual stresses in these specimens, even after annealing. Also included in this table, is the value of \( (dV_L/dT)_{o} \) obtained on annealed pure aluminum\(^1\) (99.99%) which is smaller than any of the temperature dependence measured on these commercial specimens at zero stress.

The results in table I indicate that the temperature dependence of longitudinal velocity decreases as the amount of compressional stress is increased. The relative changes in the temperature dependence, obtained on all five specimens investigated, are plotted in Fig. 4, as a function of stress applied. The plot shows that all data points lie on a straight line which passes through the origin. This indicates that, regard-
less of the type of aluminum used, the relative change in the measured temperature dependence is a linear function of the applied stress. The slope of this linear relationship is $2.4 \times 10^{-3}$ per MPa, which yields a maximum change of 23% at a stress of 96 MPa.

Table II contains the results of the temperature dependence of ultrasonic longitudinal velocity obtained on five copper specimens designated A, B, C, D, and E when they were subjected to compressional stress applied in a plane perpendicular to the direction of wave propagation. Two of these five specimens were in the annealed state; before any velocity measurements were undertaken, while the other three were as received. Also included in this table is the value of $(dV/\partial T)_0$, measured on pure annealed copper. In this case, $(dV/\partial T)_0$ is approximately equal to those obtained on commercial annealed specimens, but considerably lower than the temperature dependence determined on the as received specimens.

**TABLE II**

Effect of applied compressive stress on the temperature dependence of ultrasonic longitudinal velocity in copper. Stress is applied in a plane perpendicular to the waves propagation direction.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Applied Stress (MPa)</th>
<th>$-dV/\partial T$ (m/S/K)</th>
<th>$\Delta$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (annealed)</td>
<td>0.0</td>
<td>0.487</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>23.4</td>
<td>0.484</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>205.4</td>
<td>0.463</td>
<td>4.9</td>
</tr>
<tr>
<td>B (annealed)</td>
<td>0.0</td>
<td>0.486</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>117.2</td>
<td>0.468</td>
<td>3.6</td>
</tr>
<tr>
<td>C (CDA 110)</td>
<td>0.0</td>
<td>0.557</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>100.7</td>
<td>0.541</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>179.9</td>
<td>0.523</td>
<td>6.1</td>
</tr>
<tr>
<td>D (CDA 110)</td>
<td>0.0</td>
<td>0.509</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>59.3</td>
<td>0.502</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>131.0</td>
<td>0.496</td>
<td>2.5</td>
</tr>
<tr>
<td>E (CDA 110)</td>
<td>0.0</td>
<td>0.497</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>124.1</td>
<td>0.485</td>
<td>2.9</td>
</tr>
<tr>
<td>Pure, Annealed</td>
<td>0.0</td>
<td>0.495</td>
<td></td>
</tr>
</tbody>
</table>

The stresses generated in the disc due to the presence of the rod can be represented by an axial component $\sigma_a$, a radial component $\sigma_r$, and a tangential component $\sigma_t$, which are related by the relationship $\sigma_a = \nu(\sigma_r + \sigma_t)$, where $\nu$ is the Poisson's ratio. Three independent measurements are then required to determine the values of these components: the temperature dependence of the longitudinal and the two shear velocities of the ultrasonic waves propagating along the thickness of the disc. The two shear dependencies of the velocity were found to increase instead of further decreasing. This occurred in both aluminum and copper specimens, where the increase in $(dV/\partial T)$ is increased as long as the stress applied on the specimen was beyond the elastic limits. These results are consistent with those obtained by Salama and Ippolito in their study on the effect of plastic deformation on the temperature dependence of the ultrasonic velocity.

The data plotted in Figs. 4 and 5 suggest that the temperature dependence of the ultrasonic velocity measured at an applied compressional stress $\sigma$, can be represented by

$$\frac{(dV/\partial T) - (dV/\partial T)_0}{(dV/\partial T)_0} = -K\sigma$$

where $(dV/\partial T)_0$ is the temperature dependence at zero stress, and $K$ is a constant equal to $2.4 \times 10^{-3}$ or $0.25 \times 10^{-3}$ per MPa for aluminum or copper respectively. Equation 2 relates the relative difference of the temperature dependence of the velocity with and without stress as a function of the applied stress.

The use of equ. 2 in the determination of unknown stresses in a specimen, requires the knowledge of the temperature dependence of the ultrasonic velocity at zero stress in the material from which the specimen was made. Theoretical calculations of $(dV/\partial T)_0$ are not available at present. This means that values of this parameter should be either determined independently by a separate experiment, or estimated from other appropriate results. Measurements of $(dV/\partial T)$ at zero stress, made on different types of specimens (Tables I and II) have shown that this quantity differs considerably with heat treatment, and to a lesser extent from one specimen to the other. These differences are mainly due to the variations of residual stresses in specimens, even when they are given the same heat treatment. This, of course, limits the use of equ. 2 in the determination of the absolute values of unknown stresses. However, as will be shown in the next section, a reasonable estimate of the stress at any location on the specimen, will make it possible to determine bulk stresses at other locations on that specimen using equ. 2.
velocities will be measured with the polarization vector parallel to and perpendicular to the radial line connecting the center of the rod and the tip of the circumference of the disc. These measurements will evaluate the resultant of the stress components acting in a cylinder of cross-sectional area equal to that of the transducer used in the measurements (0.08 cm²), and of length equal to the thickness of the disc (0.79 cm). The used in the measurements (0.08 cm²), and of length equal to the thickness of the disc (0.79 cm). The used in the measurements (0.08 cm²), and of length equal to the thickness of the disc (0.79 cm). The used in the measurements (0.08 cm²), and of length equal to the thickness of the disc (0.79 cm).

As the distance, the sum of the tangential and the compressive radial components of stress was calculated as a function of the radial distance, and plotted in Fig. 6. From this plot, one can see that the tangential component in this disc is compressive near the rod, equal to zero at approximately 0.4 cm, and becomes tensile at larger distances. Between 0.4 cm and the circumference of the disc, this component has a maximum at 0.6 cm of approximately 95 MPa, which decreases to 1.4 MPa at the circumference. The values of the tangential stress component at the locations where ultrasonic measurements were undertaken, are listed in Table IV.

Table IV

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Applied Stress (MPa)</th>
<th>Applied Stress (calculated in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>0.831</td>
<td>34.0</td>
</tr>
<tr>
<td>0.70</td>
<td>0.756</td>
<td>74.4</td>
</tr>
<tr>
<td>0.95</td>
<td>0.849</td>
<td>22.8</td>
</tr>
<tr>
<td>1.60</td>
<td>0.899</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Also included in this table, are the values of the temperature dependence of the shear velocity measured when the polarization vector was perpendicular to the radial direction. At 1.6 cm (close to the circumference of the disc), (dVs/dT)l is -0.899 m/s.K and the value of the tangential component is 1.4 MPa. Assuming this value of temperature dependence corresponds to the stress calculated at this point, values of the tangential component at other three locations were calculated using equ. 2, and the measured values of the temperature dependence. These values are included in column 4 of Table IV. The agreement between these values of the tangential component, and those calculated using Savin's equations is very good considering the approximations made in calculating these stresses.

Unfortunately, no comparison could be made between radial stresses determined from the temperature dependence measurements and those calculated from elasticity theory, which are difficult to compute for an eccentric hole in a disc. Nevertheless, the values of (dVs/dT) listed in Table III, indicate that the distribution of the radial stress component along the axis OX will be similar to that of the tangential component. At the circumference, σr will be equal to zero, increases to a maximum compressive value at R = 0.7 cm, and then drops sharply to zero at R = 0.4 cm. As a function of distance, the sum of the tensile tangential and the compressive radial components (σt + σr) should be constant, as indicated from the small variations found in the measurements of (dVs/dT) listed in Table III. Values of this quantity determine the axial component of the stress σz which is equal to v(σt + σr). The sum of the tangential and the radial stress components are expected to be small, as the values of (dVs/dT) listed in Table III are very close to those measured on specimens D and E of Table I at zero stresses.

TABLE III

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Radial Temperature dependence of ultrasonic velocity (m/S.K)</th>
<th>(dV/dT)</th>
<th>(dV/dT)</th>
<th>(dV/dT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>1.123</td>
<td>0.821</td>
<td>0.831</td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>0.821</td>
<td>0.770</td>
<td>0.756</td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td>1.088</td>
<td>0.868</td>
<td>0.849</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td>1.113</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>1.107</td>
<td>0.914</td>
<td>0.899</td>
<td></td>
</tr>
</tbody>
</table>

The data listed in Table III, also show that the values of the temperature dependences of the two shear velocities obtained at the same distance, are equal to within ±1%. This indicates that the stress components measured by these two temperature dependences at the same distance from the center of the rod should be equal. As a function of distance, however, the values of either of the shear temperature dependences change considerably. Close to the edge of the disc, where the radial or the tangential stress component is small, the temperature dependence is the largest, and equal to about -0.9 m/S.K. This value decreases as the distance from the center of the rod is decreased, and reaches a minimum around 0.7 cm. As the distance from the rod is further decreased, the value of (dVs/dT) is increased again.

The stress distribution in the disc shown in Fig. 6, may be approximated by that generated in a circular plate of 2.3 cm in diameter, with an eccentric hole of 0.5 cm in diameter and at distance 0.6 cm from the center of the plate. The hole is subjected to inside radial pressure. Savin calculated the distribution of the tangential stress component in this case, and his calculations are shown in the Appendix. Using the dimensions shown in Fig. 6, along with a shear modulus μ = 0.26 x 10⁵ MPa and a Poisson's ratio ν = 0.346, the tangential component of the stress was calculated as a function of the radial distance, and plotted in Fig. 6. From this plot, one can see that the tangential component in this disc is compressive near the rod, equal to zero at approximately 0.4 cm, and becomes tensile at larger distances. Between 0.4 cm and the circumference of the disc, this component has a maximum at 0.6 cm of approximately 95 MPa, which decreases to 1.4 MPa at the circumference. The values of the tangential stress component at the locations where ultrasonic measurements were undertaken, are listed in Table IV.
ACKNOWLEDGMENT

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REFERENCES


APPENDIX

Cylinder stressed by a constant pressure $P$.

In a cylinder of cross-section defined by two eccentric circles of radii $R_1$ and $R_2$ (Fig. 7), Savin$^{5}$ has shown that the tangential stress component along the contour of the outside circle can be given by

$$\sigma_t = 2P \frac{R_1^2 [R_2^2/(R_2^2 - 2d \cos \theta)]^2 - (R_1^2 - d^2)^2}{(R_1^2 + R_2^2)[R_2^2 - (R_1 + d)^2][R_2^2 - (R_1 - d)^2]}$$

In the case of stressed generated by a rod shrunk fit into the inside circle, the pressure $P$ may be calculated from

$$P = \frac{R_2^2}{2} \frac{\mu R_1 (1 + \nu)}{\epsilon}$$

where $\mu$ is the shear modulus $\nu$ is the Poisson's ratio, and $\epsilon$ is the difference between the diameters of the rod and the inside circle.

13AASS HOLDER

Fig. 7.

Fig. 1. Holder used to apply compressive stress to specimen.
Fig. 2. Pulse-echo overlap system for measuring ultrasonic velocity.

Fig. 3. Effect of applied compressive stress on the temperature dependence of ultrasonic longitudinal velocity in aluminum. Stress is applied in a plane perpendicular to the direction of propagation of the ultrasonic waves.

Fig. 4. Percentage of the relative change in the temperature dependence of ultrasonic longitudinal velocity as a function of applied stress in aluminum.

Fig. 5. Percentage of the relative change in the temperature dependence of ultrasonic longitudinal velocity as a function of applied stress in copper.

Fig. 6. Aluminum disc used for the determination of unknown stresses generated by shrink fit method.