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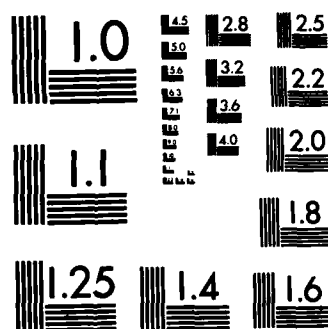
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20. ABSTRACT Continued

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MEASUREMENT OF RESIDUAL STRESS USING THE TEMPERATURE DEPENDENCE OF ULTRASONIC VELOCITY

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Abstract

The temperature dependences of ultrasonic velocities are due to the anharmonic nature of the crystal lattice, and therefore can be used for stress measurements. Experiments performed on 6061-T6 aluminum show that, in the vicinity of room temperature, the ultrasonic longitudinal velocity decreases linearly with temperature, and the slope of the linear relationship varies considerably when the specimen is subjected to stress. For compressive stress applied perpendicular to wave propagation, the temperature dependence of the velocity is found to decrease linearly by as much as 20% at a stress of 80 MPa. The results also indicate that the relative changes in the temperature dependence of velocity as a function of stress are equal to those previously obtained on other aluminum alloys. This shows the insensitivity of the temperature dependence method to texture and alloy composition. The method thus offers a promising possibility for the nondestructive measurement of residual stress.

1. Introduction

There is a general agreement that ultrasonic methods appear to hold the best promise in the non-destructive measurements of bulk stresses in both crystalline and non-crystalline materials.^{1,2} Calculations have shown that changes in ultrasonic velocities are linear functions of applied stress and unknown stresses can be determined when both the velocity in the absence of stress as well as third-order elastic constants are known independently. The measured velocity, however, strongly depends on microstructural features which makes it necessary to develop a calibration between velocity and stress for each material in order to be used in the determination of unknown stresses. In addition, development of preferred orientations (texture) during deformation or fatigue, severely modify the third-order elastic constants to be used for the calibration. These problems can be solved when the differences between velocities of shear waves polarized perpendicular and parallel to stress directions are used. Due to these differences, a shift in phase will occur, and the out-of-phase 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.^{3,4} A measure of the temperature dependence of the ultrasonic velocity can, therefore, be used to evaluate bulk stresses. Experiments undertaken on aluminum and copper^{5,6} elastically 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 applied stress was varied. In aluminum, the relative changes of the temperature dependence of longitudinal velocity decreased linearly by as much as 23% at a stress of approximately 96 MPa. The results obtained on different types of aluminum alloys also indicate that the relative changes in the temperature dependence due to applied stress are insensitive to composition and texture, and the data obtained on these alloys can be represented by a single relationship.⁷

All the above studies have been performed when the stress is applied in a direction perpendicular to that of the ultrasonic wave propagation. In practice, the magnitude as well as the direction of applied or residual stress are not known. In order to apply the temperature dependence of ultrasonic velocity and stress should be available for stress applied parallel as well as perpendicular to wave propagation.

In this paper the effects of applied compressive stress on the absolute as well as the temperature dependence of the ultrasonic longitudinal velocity have been investigated. The experiments were performed with the stress applied in a direction parallel to and perpendicular to the ultrasonic wave propagation.

2. Experimental Procedure

The specimens used in the present study were made from one inch diameter bar stock of commercial 6061-T6 aluminum in the form shown in Fig. 1. All specimens were made identically except the overall length L was varied. The specimens were machined with a 2.54 cm diameter cap on each end which allowed the same specimen to be used for

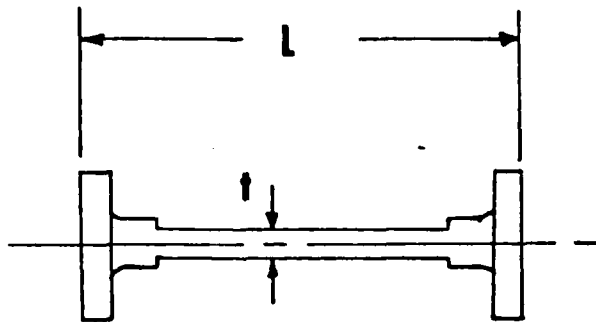


Fig. 1 Specimen used for ultrasonic velocity measurements.

stress applied in compression as well as in tension. The two caps at the ends were made flat and parallel to within ± 0.002 cm in order to avoid diffraction effects in the ultrasonic beam during propagation. These caps were also connected to the center portion of the specimen by a 0.06 cm radius in order to minimize stress concentrations. After experiments of the stress applied parallel to the axis of specimen were completed, two parallel surfaces of thickness, t , were milled in the center of the specimen to allow measurements for stress applied perpendicular to wave propagation direction. In this case the ultrasonic waves were propagated in the center portion of the specimen where the stress is expected to be uniform.

The application of external stress was carried out with a model 1125 floor type Instron machine

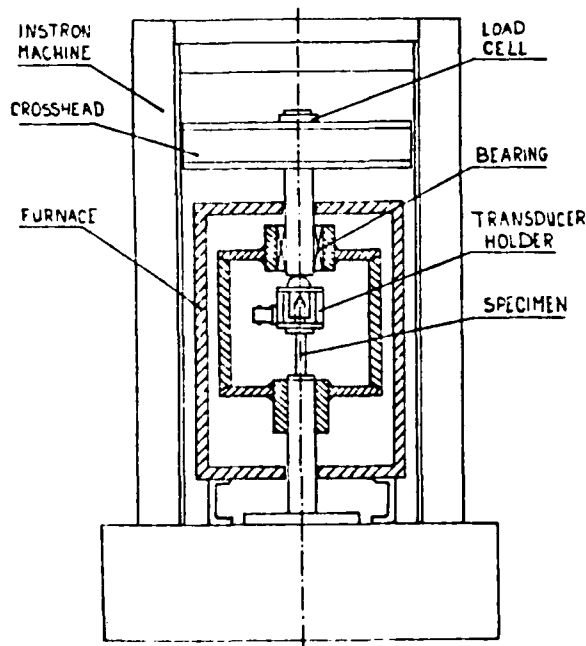


Fig. 2 Loading system used for the application of compressive stress in a direction parallel to the ultrasonic propagation.

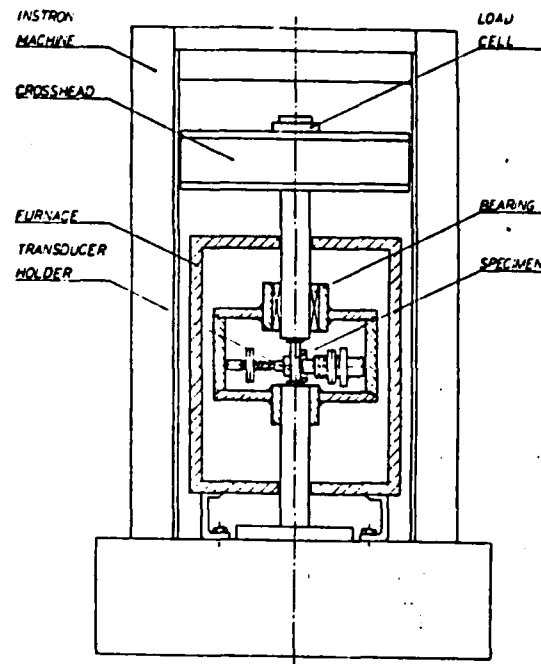


Fig. 3. Loading system used for the application of compressive stress in a direction perpendicular to the ultrasonic propagation.

The application of external stress was carried out with a model 1125 floor type Instron machine of 20,000 kg maximum load capacity. Two different types of loading arrangements are used in the present work. Figures 2 and 3 show the systems used for applying the compressive stresses. To help ensure the uniformity of stress in the specimens, special effort was made in designing these systems to minimize effects of misalignment between the axis of the specimen and the loading axis. A linear ball bearing served as the first alignment between the upper and lower loading axes and a hemispheric steel ball served as the second alignment between the specimen and the loading axis. The shafts used in the compression tests were made of surface hardened steel rod ($R_c = 40$) to resist possible wearing from the bearing during loading.

The ultrasonic velocity was measured using the pulse-echo overlap method which has been fully described elsewhere.⁸ Figure 4 displays the experimental system used in this investigation. A pulse of approximately 1- μ sec 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 frequency of the cw oscillator. This frequency f , accurately determined by the electronic counter, is employed

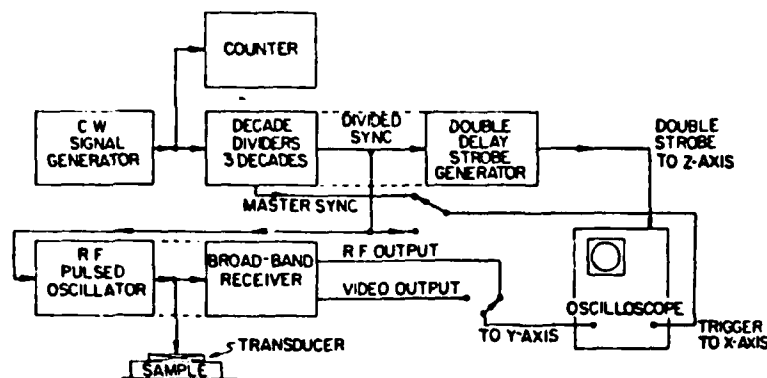


Fig. 4: Pulse-echo Overlap System.

to compute the ultrasonic velocity using the relation $V = 2lf$, where l is the length of the specimen. X-cut transducers are used for the generation of the longitudinal waves, which were used in all measurements.

The temperature control system is designed to enclose the specimen and its gripping assemblies in order to ensure stabilized temperature for the whole specimen during the time required for velocity measurements. These measurements were performed between 300 K and 370 K where the coupling condition between the transducer and the specimen was found to be satisfactory. At all temperatures, the actual temperature of the specimen was measured by a copper-constantan thermocouple attached directly to the specimen. The thermocouple along with a potentiometer provided a measurement of the temperature with an accuracy of ± 0.01 K.

3. Results

Temperature Dependence of Ultrasonic Velocity:

The effects of applied stress on the temperature dependence of ultrasonic longitudinal velocity were investigated on three specimens 1, 2 and 3 of 6061-T6 aluminum. Specimens 1 and 2 were used when the stress was applied parallel to wave propagation, while specimens 2 and 3 were used when the stress was applied perpendicular to the direction in which ultrasonic waves were propagated. Typical examples of the results obtained on specimen 1 showing the variations of ultrasonic velocity with temperature at the compressive stresses 0 and -19.8 MPa applied parallel to the propagation direction are shown in Fig. 5. From this figure it can be seen that, in the temperature range from 310-370 K, the ultrasonic velocity decreases linearly with temperature and the slope of the linear relationship varies when the stress is applied. A computer program was used to process the velocity-temperature data to determine the temperature dependence of ultrasonic velocity (dV/dT).

Table 1 lists the results of (dV/dT) obtained on the three specimens investigated when the stress was applied parallel to (specimens 1 and 2) as well as perpendicular to (specimens 2 and 3) the direction of wave propagation. Also included in this table are the offset uncertainties which measure the degree of linearity of the relationship between velocity and temperature. From these results one can see that the temperature dependence of ultrasonic velocity in aluminum increases or decreases according to whether the stress is applied parallel to or perpendicular to the direction in which the ultrasonic waves are propagated. The results also show that the changes in the temperature dependence are larger when the stress is perpendicular to wave propagation than when the stress is applied parallel to propagation direction.

Because the values of (dV/dT) at zero applied stress were found to vary among the specimens investigated, the relative change in the temperature dependence, Δ , due to the application of stress was calculated and its values are listed in column 6 of Table (1). The variations in the temperature dependence of the three specimens tested at zero stress are believed to be due to differences in the residual stress in these specimens. The values of Δ were calculated using the relationship,

$$\Delta = \frac{(dV/dT)_0 - (dV/dT)}{(dV/dT)} \quad (1)$$

where (dV/dT) is the temperature dependence at zero applied stress.

The relative changes in the temperature dependence of ultrasonic velocity as a function of applied stress, obtained on the three specimens investigated are plotted in Fig. 6. The plots show that the data points obtained on specimens 1 and 2 when the stress was applied parallel to wave propagation, lie on a straight line which passes

Table (1) - Variations of the temperature dependence of longitudinal ultrasonic velocity with applied compressive stress in aluminum 6061-T6.

Specimen Number	Specimen Length cm	Applied Stress (MPa)	dV/dT (m/s·K)	Offset Uncertainty (m/s)	Δ%
STRESS // PROPAGATION					
1	3.897	0	-0.969	.166	0.0
		-19.8	-0.982	.234	1.5
		-39.7	-0.996	.252	3.0
		-59.6	-1.016	.233	5.0
		-79.5	-1.032	.342	6.7
2	6.985	0	-1.009	.226	0.0
		-9.9	-0.975	.272	1.0
		-19.8	-0.984	.230	2.0
		-39.7	-0.998	.289	3.4
		-59.6	-1.022	.174	5.8
STRESS ⊥ PROPAGATION					
2	t = 0.624	0.0	-1.007	.358	0.0
	L = 6.985	-16.6	-0.966	.326	-3.9
		-33.1	-0.933	.358	-7.1
		-66.2	-0.863	.197	-14.1
3	t = 0.624	0.0	-0.890	.332	0.0
	L = 7.638	-22.1	-0.845	.234	-5.3
		-44.1	-0.779	.313	-12.6
		-66.1	-0.736	.211	-17.5

through the origin with a slope equal to -8.63×10^{-4} per MPa and a correlation coefficient equal to -0.992. The figure also shows that the results obtained when the stress was perpendicular to wave propagation (specimens 2 and 3), also lie on a straight line which passes through the origin, but with a slope equal to 24.4×10^{-4} per MPa and a correlation coefficient of 0.982.

perpendicular to wave propagation. The slope of the straight line representing the velocity and stress when the ultrasonic waves are propagating parallel to stress is -0.210 m/s·MPa with a correlation coefficient equal to -0.998. The slope, however, is equal to 0.0832 m/s·MPa with a correlation coefficient equal to 0.993 when the stress is applied perpendicular to wave propagation.

Stress Dependence of Ultrasonic Velocity:

The effects of applied stress on the velocity of longitudinal ultrasonic waves propagating parallel to and perpendicular to stress has been measured on specimens 1 and 3 respectively. The measurements were performed at room temperature with applied stress ranging from 0 to -59.6 MPa for specimen 1 and from 0 to -44.1 MPa for specimen 3. The results of these measurements are given in Table 2, which also lists the values of the relative change in the velocity $\Delta V/V$. Plots of these values as a function of applied stress for the two specimens are shown in Fig. 7. From this figure, one can see that $\Delta V/V$ increases or decreases linearly with stress according to whether the stress is applied parallel to or

Table (2) - Variations of longitudinal ultrasonic velocity with stress in specimens 1 and 3 of 6061-T6 aluminum at room temperature.

Stress // Prop (Specimen 1)			Stress $\perp$ Prop (Specimen 3)		
Stress (MPa)	Velocity (m/s)	$\Delta V/V$	Stress (MPa)	Velocity (m/s)	$(\Delta V/V)10^4$
0.0	6118.6	0.00	0.0	6191.2	0.00
-9.9	6119.7	1.83	-5.5	6191.1	0.18
-19.9	6121.8	5.28	-11.0	6190.6	-1.03
-29.8	6123.7	8.40	-16.5	6190.2	-1.70
-39.7	6125.7	11.6	-22.1	6189.5	-2.78
-49.7	6128.1	15.5	-27.6	6188.9	-3.76
-59.6	6130.7	19.7	-33.1	6188.2	-4.86
			-38.8	6187.5	-6.06
			-44.1	6186.9	-7.01

Stress Dependence $dV/d\sigma = -0.210 \text{ m/s}\cdot\text{MPa}$
Correlation Coefficient = -0.998

Stress Dependence $dV/d\sigma = 0.0832 \text{ m/s}\cdot\text{MPa}$
Correlation Coefficient = 0.993

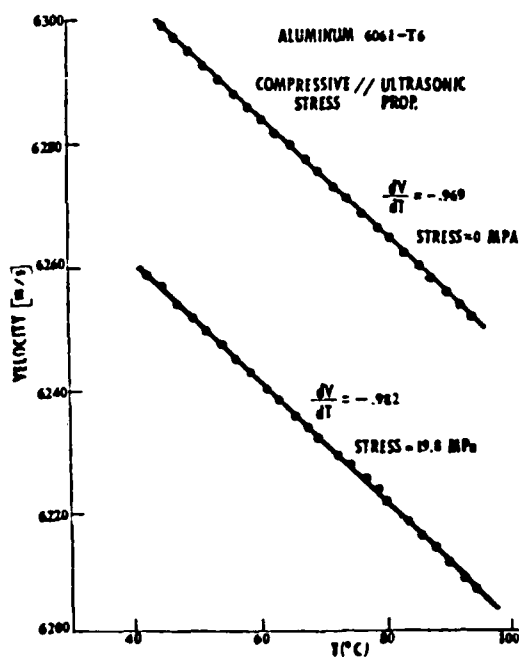


Fig. 5 Effect of applied compressive stress on the temperature dependence of ultrasonic longitudinal velocity in the aluminum alloy 6061-T6. The stress is applied in a direction parallel to the ultrasonic propagation.

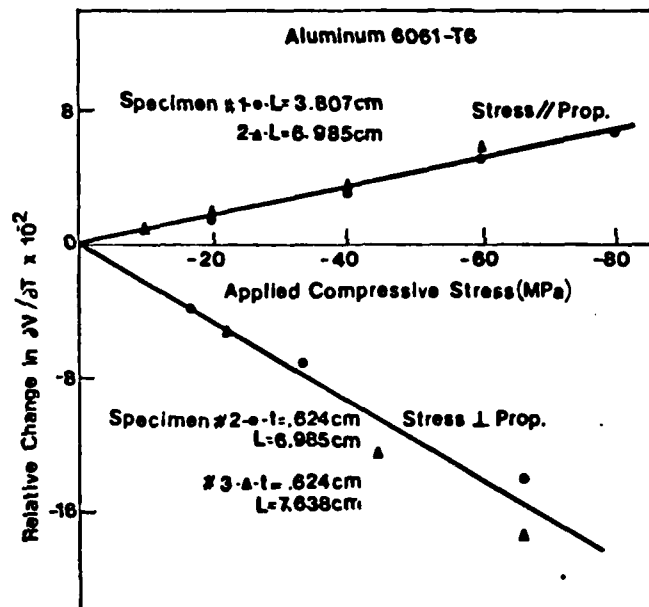


Fig. 6 Effect of applied compressive stress on the relative change in the temperature dependence of longitudinal ultrasonic velocity in 6061-T6 aluminum. Stress was applied parallel to and perpendicular to wave propagation.

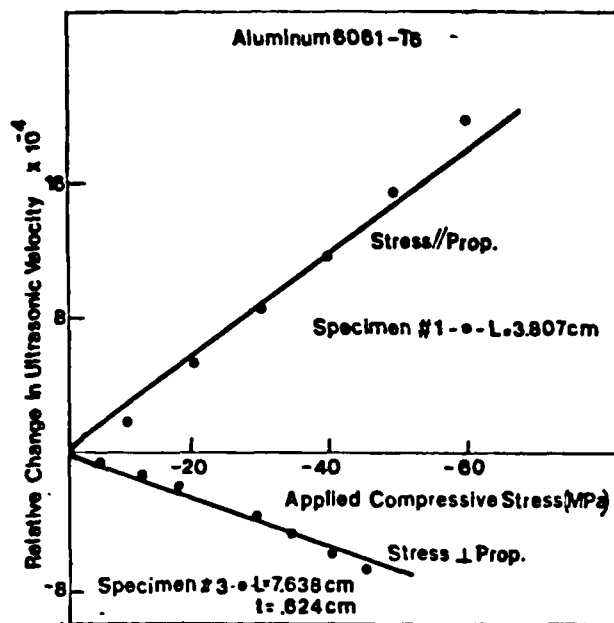


Fig. 7 Relative change in ultrasonic velocity as a function of applied compressive stress in 6061-T6 aluminum. Stress was applied parallel to and perpendicular to ultrasonic wave propagation.

4. DISCUSSION

1. Temperature Dependence of Ultrasonic Velocity

The effects of compressive stresses on the temperature dependence of longitudinal ultrasonic velocity have been studied in the aluminum alloys 2024-0 and 6063-T4 by Salama and Ling⁹. These experiments were performed with the stress applied in a direction perpendicular to the ultrasonic propagation. The results obtained by these authors show that the relative change in the temperature dependence of ultrasonic velocity is a linear function of the applied elastic compressive stress and can be represented by the relationship

$$\Delta = \frac{(dV/dT)_0 - (dV/dT)}{(dV/dT)} = K\sigma \quad (2)$$

where (dV/dT) is the temperature dependence at zero applied stress, $(dV/dT)_0$ is the temperature dependence at an applied stress σ , and K is a constant equal to 2.3×10^{-3} per MPa.

In the present investigation, the experiments were performed to study the effects of compressive

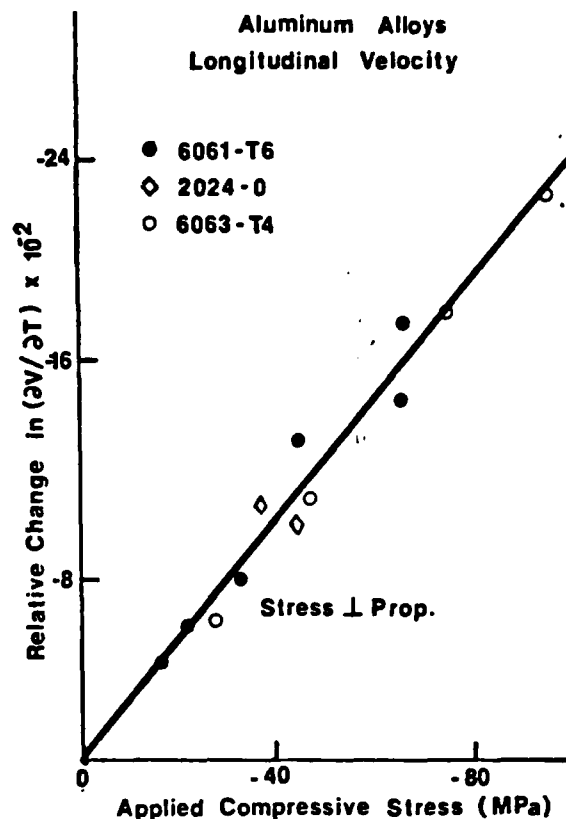


Fig. 8 Relative change in the temperature dependence of ultrasonic velocity as a function of applied stress in three aluminum alloys.

stress on the temperature dependence of longitudinal ultrasonic velocity on three specimens (1,2 and 3) of the aluminum alloy 6061-T6. The relative changes in the temperature dependence of longitudinal ultrasonic velocity as a function of applied stress obtained in this work as well as those published in reference 9 are plotted in Fig. (8). The solid data points in this figure represent the data obtained in this investigation and the hollow data points represent those obtained in this references. From this figure it can be seen that the relative changes in the temperature dependence of these three aluminum alloys as a function of compressive stress can be represented by Eq. (2) with K equal to 2.38×10^{-3} per MPa. This result emphasizes an earlier finding concerning the insensitivity of the temperature dependence of ultrasonic velocity to texture and alloy composition, and makes this method more suitable for the nondestructive evaluation of stress than direct velocity measurements. The latter method has been shown to be strongly influenced by metallurgical variables and requires calibration for each alloy or perhaps for each specimen¹⁰.

On the other hand, the effect of stress on the temperature dependence of ultrasonic longitudinal velocity becomes much smaller and opposite in sign

when the stress is applied parallel to the direction in which the waves are propagated. This agrees with the results obtained by Chern and Heyman¹¹ who also observed small changes in the temperature dependence with stress in 2024-T4 aluminum when the stress was applied in the same direction of wave propagation. From Figs. 6 and 7 it is interesting to note that the behavior of the temperature dependence with stress (Fig. 6) is opposite to that of the velocity itself (Fig. 7). The comparison between the effects of stress on the temperature dependence and on the velocity will be discussed below.

2. Stress Dependence of Ultrasonic Velocity

For a longitudinal ultrasonic wave propagating parallel to the direction of applied stress, the change in velocity with stress, $dV/d\sigma$, may be expressed as¹²

$$\frac{dV}{d\sigma} = \frac{-1}{2\rho V(3\lambda + 2\mu)} \left[2\ell + \lambda + \frac{\lambda + \mu}{\mu} (4m + 4\lambda + 10\mu) \right] \quad (3)$$

In Eq. 3 λ and μ are the second order elastic constants, ℓ and m are the third order elastic constants of Murnaghan¹², ρ is density, V is ultrasonic velocity, and σ is applied stress. This equation indicates that for small stresses, $dV/d\sigma$ is a constant. Heyman and Chern¹³ have used the following relationship to measure axial stresses in fasteners

$$\frac{\Delta f}{f} = \left[\frac{1}{V} \frac{dV}{d\sigma} - \frac{1}{E} \right] \Delta\sigma \quad (4)$$

where f is the round-trip frequency of a longitudinal wave propagating in the axial direction of the fastener, V is the ultrasonic velocity, E is Young's modulus and σ is applied stress. For small strains, the term in brackets is constant and Eq. (4) can be written as

$$\frac{\Delta f}{f} = H^{-1} = \Delta\sigma \quad (5)$$

where

$$H^{-1} = \left[\frac{1}{V} \frac{dV}{d\sigma} - \frac{1}{E} \right]^{-1} \quad (6)$$

For aluminum, they found H^{-1} to be a constant equal to -1.86×10^4 MPa.

In the present investigation, the effects of compressive applied stress on ultrasonic longitudinal velocity are shown in Fig. 7. From this figure, it can be seen that for stress applied in a direction parallel to that of ultrasonic propagation, the results give a value of -0.210 m/s·MPa for the stress dependence, $dV/d\sigma$. Substituting the values $V = 6200$ m/s, $E = 70.3$ GPa, and $dV/d\sigma = -0.210$ m/s·MPa into Eq. (6) yields $H^{-1} = -1.96 \times 10^4$ MPa. This value is in excellent agreement with the value of H^{-1} equal to -1.86×10^4 MPa obtained by Heyman and Chern for 2024-T6 aluminum.

For stress applied perpendicular to wave propagation, the change in velocity with stress is given by¹²

$$\frac{dV}{d\sigma} = \frac{-1}{2\rho V(3\lambda + 2\mu)} \left[2\ell - \frac{2\lambda}{\mu} (m + \lambda + 2\mu) \right] \quad (7)$$

Table (3) - Summary of important quantities found in this investigation for aluminum 6061-T6.

Row #	Quantity	Stress $\perp$ Propagation	Stress $\parallel$ Propagation
1)	$\left[\frac{\partial V}{\partial T} \right] ; \sigma = 0$	$-0.985 \frac{\text{m/s}}{\text{K}}$	$-0.985 \frac{\text{m/s}}{\text{K}}$
2)	$\left[\frac{\partial V}{\partial T} \right]_{\sigma} - \left[\frac{\partial V}{\partial T} \right]_{\sigma=0}$	$-23.4 \times 10^4 \frac{\text{m/s}}{\text{K} \cdot \text{MPa}}$	$8.50 \times 10^{-4} \frac{\text{m/s}}{\text{K} \cdot \text{MPa}}$
3)	$\left[\frac{\partial T}{\partial \sigma} \right]_T ; \text{Room Temperature}$	$0.0832 \frac{\text{m/s}}{\text{MPa}}$	$-0.210 \frac{\text{m/s}}{\text{MPa}}$

where all the terms in the equation are as defined above. Since the values of the third order elastic constants l and m of aluminum are both negative and of the same magnitude¹⁴, the value of $(dv/d\sigma)$ represented by eq. (7) should be negative and smaller than that of eq. (3). This agrees with the results shown in Fig. 7 where $(dv/d\sigma)$ in case of stress applied perpendicular to wave propagation is negative and has a smaller value (0.0832 m/s.MPa) than that obtained when the stress is applied parallel to the propagation direction (-0.210 m/s.MPa).

3. Relationship Between Temperature and Stress Dependences

Table (3) lists a summary of the important relationships obtained in this investigation for aluminum 6061-T6. The temperature dependence quantity given in row 1 represents the average value of the temperature dependence of ultrasonic velocity found in this investigation when the applied stress is equal to zero. The quantity in row 2 represents the change in the temperature dependence due to the application of compressive stress, which is calculated from Fig. 6. The values of the stress dependence at room temperature, are shown in row 3.

From Table (3), it can be seen that the product of the change in the temperature dependence due to applied stress (row 2) and the stress dependence at room temperature (row 3) is the same for both the parallel and the perpendicular configurations. The relationship between these two quantities can then be written as,

$$\left[\left(\frac{\partial v}{\partial T} \right)_\sigma - \left(\frac{\partial v}{\partial T} \right) \right] \left[\left(\frac{\partial v}{\partial \sigma} \right) \right] = k_1 \sigma \quad (8)$$

where

$$k_1 = -1.915 \pm 0.035 \{ (m/s)/MPa \}^2 (1/^\circ K).$$

This relationship indicates that the change in the temperature dependence with applied stress is inversely proportional to the dependence of the velocity on stress regardless of the relative direction of the stress with respect to the wave propagation. Equation 8 can thus be used to predict the magnitude as well as the sign of the change in the temperature dependence with stress when the corresponding dependence of velocity is known. This later can be calculated from available relationships similar to those expressed in eqs. 3 and 7.

5. Acknowledgement

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6. References

1. Proceedings of a Workshop on Nondestructive Evaluation of Residual Stress, NT1AC-72-2 (1976).
2. James, M. R. and Buck, O., Critical Reviews in Solid State and Materials Sciences, p. 61 (1980).
3. Huntington, H. B., Solid State Phys. 7, 213 (1958).
4. Garber, J. A. and Granato, A. V., Phys. Rev. 131A, 3990 (1975).
5. Salama, K., Collins, A. L. W. and Wang, J. J., Proceedings DARPA/AF Review of Progress in Quantitative NDE, p. 265 (1980).
6. Salama, K. and Ling, C. K., Proceedings ARPA/AFML Review of Progress in Quantitative NDE, p. 96 (1979).
7. Salama, K., Ling, C. K. and Wang, J. J., Experimental Techniques 5, 14 (1981).
8. Papadakis, E. P., J. Acoust. Soc. Am. 42, 1045 (1967).
9. Salama, K. and Ling, C. K., J. Appl. Phys. 51, 1505 (1980).
10. Kino, G. S., Barnett, D. M., Grayeli, N., Hermann G., Hunter, J. B., Illic, D. B., Johnson, G. C., King, R. B., Scott, M. P., Shyne, J. C. and Steele, C. R., Journal of Nondestructive Evaluation 1, 67 (1980).
11. Chern, E. J., Heyman, J. S. and Cantrell, J. H., Proceedings IEEE Ultrasonic Symposium p. 960 (1981).
12. Hughes, D. S. and Kelly, J. L., Phys. Rev. 92, 1145 (1953).
13. Heyman, J. S. and Chern, E. J., Proceedings ASTM Symposium on Ultrasonic Measurements of Stress, (1981).
14. Smith, R. T., Stern, R. and Stephens, R. W. B., J. Acoust. Soc. Am. 40, 1002 (1966).

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