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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A127699	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle)  Nondestructive Stress Measurements in Aluminum		5. TYPE OF REPORT & PERIOD COVERED Interim, Feb-May, 1983
7. AUTHOR(s) K. Salama, G. C. Barber and N. Chandrasekaran Department of Mechanical Engineering, University of Houston, Texas 77004		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering University of Houston Houston, Texas 77004		8. CONTRACT OR GRANT NUMBER(s) N00014-82-K-0496
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, VA 22217		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DD-1473
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ONR Resident Representative Room 582 Federal Building Austin, Texas 78701		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 8
		15. SECURITY CLASS. (of this report) Non-classified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  Unlimited		
18. SUPPLEMENTARY NOTES  Presented at 14th Symposium on NDE, held in San Antonio, 1982 April 1983		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)  Residual Stress - Ultrasonics - Temperature Dependence of Ultrasonic Velocity Aluminum		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  The effects of applied stress on the temperature dependence of 10 MHz ultra- sonic longitudinal velocity have been studied in aluminum 6061-T6. Velocities of longitudinal ultrasonic waves were measured as a function of temperature in several specimens using a pulse-echo overlap system. Experiments were performed with the stress applied in a direction parallel to and perpendicular to the ultrasonic propagation direction. In all temperature dependence measurements, the ultrasonic velocity is found to decrease linearly with temperature, and the		

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## 14 th Symposium on Nondestructive Evaluation

### NONDESTRUCTIVE STRESS MEASUREMENTS IN ALUMINUM

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#### Abstract

The effects of applied elastic stress on the temperature dependence of 10 MHz ultrasonic longitudinal velocity have been studied in aluminum 6061-T6. Velocities of longitudinal ultrasonic waves were measured as a function of temperature in several specimens using a pulse-echo-overlap system. Experiments were performed with the stress applied in a direction parallel to and perpendicular to the ultrasonic propagation direction. In all temperature dependence measurements, the ultrasonic velocity is found to decrease linearly with temperature, and the slope of the line of best fit of ultrasonic velocity versus temperature is found to vary considerably when the specimens are subjected to stress. The results obtained when the stress is applied in a direction parallel to the ultrasonic propagation show that the temperature dependence of ultrasonic velocity increases linearly with either applied tensile or compressive stress. In the case of stress applied perpendicular to the ultrasonic propagation, the results indicate that the temperature dependence decreases linearly with either applied tensile or compressive stress. Calibration curves relating the relative change in the temperature dependence of ultrasonic velocity to applied stress are constructed. Using these calibration curves, the sensitivity in determining unknown applied stresses in aluminum is estimated to be  $\pm 10$  MPa.

#### 1. INTRODUCTION

Materials in machine components are always in a state of stress. This stress can be applied stress due to external loading, residual stress within the material without any external loading, or a combination of applied and residual<sup>1</sup>. Applied stresses can be calculated using formulae from mechanics of materials or can be found experimentally using strain measuring devices attached to the machine. Residual stresses, however, can seldom be calculated because there is usually no data on which stress calculations are based. There are presently several methods of experimentally finding residual stresses by destructive means, such as hole drilling and ring coring<sup>2</sup>. To measure residual stresses in a body non-destructively, however, several approaches based on three major methods have been proposed. These methods are x-ray diffraction, electromagnetics, and ultrasonics. None of these methods measures stress directly. X-ray diffraction measures lattice strain, electromagnetic methods measure magnetic properties, and ultrasonic methods measure ultrasonic

velocity. All of these methods have limitations which prevent any of them from being used in all stress measurement applications. For the non-destructive evaluation of bulk residual stresses in crystalline and non-crystalline materials, the methods using ultrasonic techniques seem to hold the best promise.

The temperature dependences of the elastic constants of a solid are due to the anharmonic nature of the crystal lattice.<sup>3,4</sup> A measure of the temperature dependence of the ultrasonic velocity can, therefore, be used to evaluate bulk stresses. Experiments undertaken on aluminum and copper<sup>5,6</sup> 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<sup>7</sup>, as

$$\Delta = \frac{(dv/dT)_\sigma - (dv/dT)_0}{(dv/dT)_0} = K\sigma \quad (1)$$

where  $(dv/dT)$  is the temperature dependence at zero applied stress,  $(dv/dT)_\sigma$  is the temperature dependence at an applied stress  $\sigma$ , and  $K$  is a constant equal to  $2.3 \times 10^{-3}$  per MPa. In addition, the effects of tensile elastic stresses on the temperature dependence of longitudinal velocity were studied using the aluminum alloys 2024-0, 3003-T251, and 2024-T351 by Salama and Wang (5). The results from these experiments were found to satisfy Eq. (1) with the constant  $K$  equal to  $-1.89 \times 10^{-3}$  per MPa. All the above studies have been performed when the stress was applied in a direction perpendicular to that of the ultrasonic wave propagation.

In the present investigation, experiments were performed to study the effects of both compressive and tensile elastic stresses on the temperature dependence of longitudinal ultrasonic velocity in three specimens of the aluminum alloy 6061-T6. 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 identical 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 stress applied in compression as well as in tension. The two caps at the ends were made flat and parallel to within  $\pm 0.002$  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 of 20,000 Kg maximum load capacity. Four different types of loading arrangements

are used in the present investigation. These arrangements are described in detail elsewhere<sup>5,6</sup>. To help ensure the uniformity of stress in specimens, special effort was made in designing these stress application systems to minimize any effects of misalignment between the axis of the specimen and the loading axis. For tensile testing, this was achieved by using two universal joints between specimen and connections to load cell and to the loading frame. For compressive testing, a two-stepped alignment system was used. A linear ball bearing served as the first alignment between the upper and lower loading axes and the hemispheric steel ball served as the second alignment between the specimen and the loading axis.

The ultrasonic velocity was measured using the pulse-echo-overlap method which has been fully described elsewhere<sup>8</sup>. X-cut transducers are used for the generation of the longitudinal waves, which were used in all measurements. The transducer is placed on the specimen by means of special holders which are designed to clamp to the specimen as shown in Fig. 2 for the parallel configuration and Fig. 3 for the perpendicular configuration. The spring-supported plunger serves as the inner conductor of the coaxial cable which carries the 10 MHz electrical signals to and from the transducer which is bonded to the specimen. These signals are transmitted from the plunger by a piece of teflon-coated wire to a BNC receptacle which is mounted directly to the transducer holder. The spring is used to produce a pressure-coupled transducer which is required to insure uniformity of the thin layer bond. A small clamping force of 30 to 50 Newtons was used in the present work.

A temperature control system is designed to enclose the specimen gripping assemblies to ensure stabilized temperature for the entire specimen during the time required for velocity measurements. All experiments were performed between approximately 310°K and 370°K where the coupling condition between the transducer and the specimen was found to be satisfactory. A test furnace was used for heating. This furnace provides a uniform temperature performance by making use of a recirculating blower and plenum system. The furnace is equipped with a temperature controller which is capable of providing precision temperature control. Before taking velocity measurements, the furnace is set at a desired maximum temperature. After this desired temperature is reached, the furnace is turned off and the cooling rate of the specimen is controlled to achieve a constant cooling rate. The temperature of the specimen is measured by a copper-constantan thermocouple attached directly to the specimen. The thermocouple along with a potentiometer provides the measurement of the specimen temperature to an accuracy  $\pm 0.1^\circ\text{K}$ .

## 3. RESULTS

The velocity of longitudinal ultrasonic waves propagating perpendicular to the applied stress

was measured as a function of temperature in specimens 1 and 2. Typical examples of the ultrasonic velocity obtained on specimen 2 at the applied tensile 0.0 MPa and 66.8 MPa are shown in Fig. 4. This figure shows that, in the temperature range from 310°K to 370°K, ultrasonic velocity decreases linearly with temperature. A computer program was used to determine the temperature dependence of ultrasonic velocity,  $dV/dT$ .

for the experimental results are given in Table (2). Also listed in Table (1) are the relative changes in the temperature dependence, due to application of stress. These relative percentage changes of the temperature dependence are plotted as a function of applied stress in Fig. (5). From this figure, it can be seen that the data points for tensile stress lie on a straight line which passes through the origin. This line has a slope of  $-1.18 \times 10^{-3}/\text{MPa}$  and a correlation coefficient equal to  $-0.972$ . The data

Table (1) - Variations of the temperature dependence of longitudinal ultrasonic velocity with applied tensile and compressive stress in 6061-T6 aluminum. The stress is applied perpendicular to the direction of ultrasonic propagation.

Specimen Number	Specimen Dimensions cm (inch)	Applied Stress (MPa)	$dV/dT$ (m/s·K)	Offset Uncertainty (m/s)	$\Delta\%$
1	t = 0.624 (0.2455) L = 6.985 (2.750)	66.2	-.9177	.158	-8.04
		44.1	-.9518	.198	-4.62
		22.1	-.9530	.304	-4.50
		0.0	-1.0070	.358	0.00
		-16.6	-.9657	.326	-3.88
		-33.1	-.9333	.358	-7.11
2	t = 0.495 (0.195) L = 6.351 (2.5005)	66.8	-.9396	.224	-8.44
		46.7	-.9685	.234	-5.62
		26.7	-.9973	.195	-2.81
		0.0	-1.0230	.192	0.00

Table (2) - Values of slope, Y-intercept, and correlation coefficient in the lines of best fit of  $dV/dT$  versus applied stress in aluminum 6061-T6. The stress is applied perpendicular to the direction of ultrasonic propagation.

Specimen Number	Specimen Dimensions cm (inch)	Applied Stress	Slope (m/s·K MPa)	Correlation Coefficient	Y-Intercept (m/s·K)
1	t = 0.624 (0.2455) L = 6.985 (2.750)	Tensile	$1.22 \times 10^{-3}$	.941	-0.9979
2	t = 0.495 (0.195) L = 6.351 (2.5005)	Tensile	$1.26 \times 10^{-3}$	.995	-1.0262
1	t = 0.624 (0.2455) L = 6.985 (2.750)	Compressive	$-2.15 \times 10^{-3}$	-.999	-1.0047

Table (1) lists the values of the temperature dependence of longitudinal velocity and the offset uncertainty in specimens 1 and 2 when they were subjected to applied stresses ranging from -66.2 MPa to 66.8 MPa. This table shows that the magnitude of the temperature dependence of ultrasonic velocity decreases linearly with applied compressive or tensile stress with the maximum value for the temperature dependence of ultrasonic velocity occurring at 0.0 MPa. The values of the slope, the intercept, and the correlation coefficient of the lines of best fit

points for compressive stress also lie on a straight line which passes through the origin and has a slope of  $2.44 \times 10^{-3}/\text{MPa}$  and a correlation coefficient equal to 0.982.

The velocity of longitudinal ultrasonic waves propagating parallel to applied stress was measured as a function of temperature on the two aluminum specimens 2 and 3. Table (3) lists the results obtained on these two aluminum 6061-T6 specimens investigated in the parallel configuration. Included in this table

are the values of the temperature dependence of longitudinal ultrasonic velocity determined at applied compressive and tensile stresses ranging between -79.5 MPa and 59.6 MPa. Also listed in table (3) are the offset uncertainties which measure the linearity of the relationship between velocity and temperature. The results of Table (3) are plotted in Fig. (6) which illustrates the effect of applied compressive and

temperature dependence of ultrasonic velocity increases linearly with either applied compressive or tensile stress, with the minimum value of the temperature dependence occurring at 0.0 MPa. The values of the slope, the intercept, and the correlation coefficient for the lines of best fit for the experimental results shown in Fig. (6) are given in Table (4). From Tables (2) and (4), it can be seen that the slopes of

Table (3) - Variations of the temperature dependence of longitudinal ultrasonic velocity with applied tensile and compressive stress in aluminum 6061-T6. Stress is applied parallel to the direction of ultrasonic propagation.

Specimen Number	Specimen Length cm (inch)	Applied Stress (MPa)	dV/dT (m/s·K)	Offset Uncertainty (m/s)	Δ%
2	6.351 (1.5005)	39.7	-1.0529	.423	1.37
		29.8	-1.0484	.185	.93
		19.8	-1.0469	.163	.79
		9.9	-1.0417	.248	.29
		0	-1.0146	.243	0
		-19.8	-1.0231	.236	.88
		-49.7	-1.0355	.266	2.10
		-59.6	-1.0427	.351	2.81
3	3.807 (1.499)	59.6	-1.0071	.466	3.14
		49.7	-.9960	.318	2.01
		29.8	-.9944	.530	1.84
		9.9	-.9798	.326	.35
		0	-.9692	.166	0
		-19.8	-.9820	.234	1.53
		-39.7	-.9961	.252	2.99
		-59.6	-1.0158	.233	5.02
-79.5	-1.0317	.342	6.69		

Table (4) - Values of slope, intercept, and correlation coefficient taken from lines of best fit of dV/dT versus applied stress in aluminum 6061-T6. The stress is applied parallel to the direction of ultrasonic propagation.

Specimen Number	Specimen Length cm (inch)	Applied Stress	Slope (m/s·K MPa)	Correlation Coefficient	Y-Intercept (m/s·K)
1	6.351 (2.5005)	Tensile	$-3.53 \times 10^{-4}$	-.961	-1.0387
3	3.807 (1.499)	Tensile	$-4.82 \times 10^{-4}$	-.948	-.9764
1	6.351 (2.5005)	Compressive	$4.56 \times 10^{-4}$	.996	-1.0142
3	3.807 (1.499)	Compressive	$7.99 \times 10^{-4}$	.997	-.9672

tensile stresses on the temperature dependence of ultrasonic velocity. This figure shows that, within the applied stress range used in these measurements, the magnitude of the

the lines of best fit for the perpendicular configuration are much larger and opposite in sign to those obtained in the parallel configuration.

Figure (6) indicates that the plot of  $dV/dT$  versus stress for a given specimen has an abrupt change in direction where the applied stress equals zero. The intercept for the tensile portion of the graph is also significantly higher than the intercept for the compression portion of the graph. In the case of tensile loading, bending stresses are introduced and likely to exist throughout the entire length of the specimen. This non-uniform loading is expected to affect the absolute magnitude of  $dV/dT$ , but not the relative differences between quantities as indicated by the consistency of the slopes of the lines of best fit of  $dV/dT$  versus stress in these specimens. In the case of compressive loading, the bottom end cap of the specimen is loaded uniformly which gives the compression loading a better probability of uniform stress throughout the ultrasonic path.

Because the values of the intercept of the lines of best fit were found to vary among the 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 6 of Table (3). The values of  $\Delta$  were calculated using the relationship,

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

where  $(dV/dT)$  is the temperature dependence given by the intercept of the line of best fit and  $(dV/dT)_\sigma$  is the temperature dependence at an applied stress,  $\sigma$ . 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 relative changes in the temperature dependence, obtained on all three specimens investigated, are plotted in Fig. 7. The plot for tensile stress shows that the points lie on a straight line which passes through the origin with a slope equal to  $4.39 \times 10^{-4}$  per MPa and a correlation coefficient equal to 0.930. The plots for compressive stress show that the points for specimen 3 lie on a straight line that passes through the origin with a slope equal to  $-8.63 \times 10^{-4}$  per MPa and a correlation coefficient equal to -0.992. The points for specimen 2 for compressive stress also lie on a straight line that passes through the origin with a slope equal to  $-4.56 \times 10^{-4}$  per MPa and a correlation coefficient equal to -0.996. There is no explanation for why the slope of the data obtained on specimen 2 is smaller than that found from the data obtained on specimens 3.

#### 4. DISCUSSION

In the present investigation, experiments were performed to study the effects of both compressive and tensile elastic stresses on the temperature dependence of longitudinal ultrasonic

velocity measured in a direction perpendicular to that of stress in three specimens 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 references 7 and 9 are plotted in Fig. (8). The solid data points in this figure represent the results obtained in this investigation and the hollow data points represent those obtained in these references. From this figure it can be seen that the relative changes in the temperature dependence of aluminum alloys as a function of compressive stress can be represented by Eq. (1) with  $K$  equal to  $2.38 \times 10^{-3}$  per MPa. The line of best fit of the relative changes in temperature dependence versus tensile stress for aluminum 6061-T6 is seen to vary slightly from the line of best fit of the other aluminum alloys. This variance is believed to be due to the non-uniform stress induced in the specimens in the case of tensile loading. Therefore, the line of best fit for tensile stress for the aluminum alloys 2024-0, 3003-T251, and 2024-T351 is chosen to represent the true line of best fit of aluminum alloys.

In order to use the temperature dependence method to determine unknown applied stresses, a calibration curve was constructed and is shown in Fig. 9. This calibration curve shows the lines of best fit of the relative percentage changes of the temperature dependence versus applied stress found in Fig. (8). The bands drawn around these lines of best fit are for a 95% confidence level for stress. These bands were determined by means of an inverse regression technique which is described in detail in reference 10. From Figure (9) it can be seen that the relative change in temperature dependence decreases when either compressive or tensile stresses are applied to the specimen. No explanation is available at present for this behavior which makes it difficult to differentiate between tensile and compressive stresses when using the temperature dependence method in the non-destructive evaluation of applied stress in aluminum alloys. To use the calibration curve shown in Fig. (9) to determine applied stresses, the temperature dependence of ultrasonic velocity is measured in the specimen at zero applied stress. This measurement should be repeated several times and the average value is taken as the true value. The specimen is then loaded and the temperature dependence is measured perpendicular to the applied stress. Using the values found above, the relative percentage change in the temperature dependence of ultrasonic velocity if calculated using Eq. 1. This value along with Fig. (9) are used to determine the applied stress. If greater accuracy is required, the temperature dependence at the unknown stress should be measured several times and the average value used to determine the applied stress.

The effects of compressive and tensile stress on the temperature dependence of longitudinal ultrasonic velocity were measured on two specimens

(2 and 3) of aluminum 6061-T6. These experiments were performed with the stress applied in a direction parallel to the ultrasonic propagation. These experiments showed that the relative change in the temperature dependence of ultrasonic velocity is a linear function of the applied stress and can be represented by Eq. (1). The values of K found from Fig. (7) are  $4.39 \times 10^{-4}$  per MPa for tensile stresses,  $-4.56 \times 10^{-4}$  per MPa for specimens 2 in compression, and  $-8.63 \times 10^{-4}$  per MPa for specimen 3 in compression.

In order to use the temperature dependence method to determine unknown applied stress, a calibration curve was constructed and is shown in Fig. 10. From this figure it can be seen that the relative change in temperature dependence increases when either compressive or tensile stress is applied to the specimen. This makes it difficult to differentiate between tensile and compressive stress (as was the case in the perpendicular configuration) when using the temperature dependence method in the non-destructive evaluation of applied stress in aluminum 6061-T6.

To demonstrate the use of this calibration curve consider an example where the temperature dependence is measured parallel to an applied compressive stress and the relative percentage change in the temperature dependence calculated to be 3.0%. The accuracy of  $dV/dT$  measurements in these experiments was found to be  $\pm 1.6\%$  using the method of standard error estimation.<sup>11</sup> Thus in this example, the true value of the temperature dependence will be  $3 \pm 1.6\%$ . The applied stress is read from Fig. (10) as -35 MPa with a lower bound of -57 MPa and an upper bound of -13 MPa. This amount of variance is large and would be unacceptable for many applications. This variance, however, can be reduced by measuring the temperature dependence at the applied compressive stress several times. Consider the case where the temperature dependence at an applied compressive stress is measured five times and the average value is used to calculate a relative percentage change of  $(dV/dT)$  of 3.00%. The standard error in this example is  $1.6/5 = 0.7\%$ . The true value of the relative percentage of  $(dV/dT)$  is  $3.00 \pm .7\%$ . The applied stress is read from Fig. 10 as -35 MPa with a lower bound of -24 MPa and an upper bound of -46 MPa. These examples show that the temperature dependence measurement should be repeated several times when the stress is applied in a direction parallel to the ultrasonic propagation. This will produce a stress measurement with an acceptable amount of error for most applications.

##### 5. ACKNOWLEDGEMENT

This work is supported by the Office of Naval Research under Contract N00014-82-0496.

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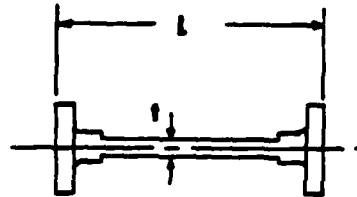


Fig. Specimen used for ultrasonic velocity measurements.

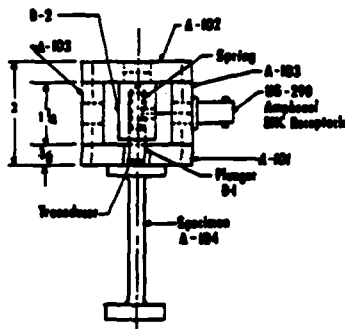


Fig. 2 Transducer holder used for the measurement of ultrasonic velocity when the stress is applied in a direction parallel to ultrasonic propagation.

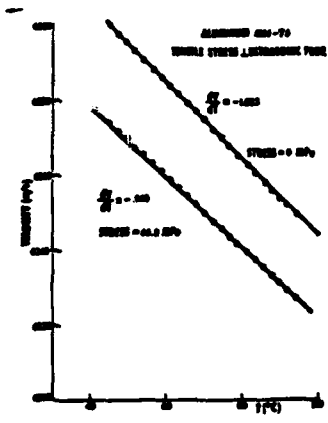


Fig. 4 Effect of applied tensile stress on the temperature dependence of ultrasonic longitudinal velocity in aluminum alloy 6061-T6.

Fig. 5 Effect of applied compressive and tensile stresses on the temperature dependence of ultrasonic longitudinal velocity.

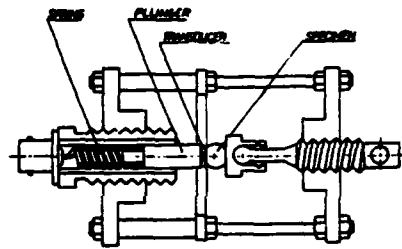


Fig. 3 Transducer holder used for the measurement of ultrasonic velocity when the stress is applied in a direction perpendicular to ultrasonic propagation.

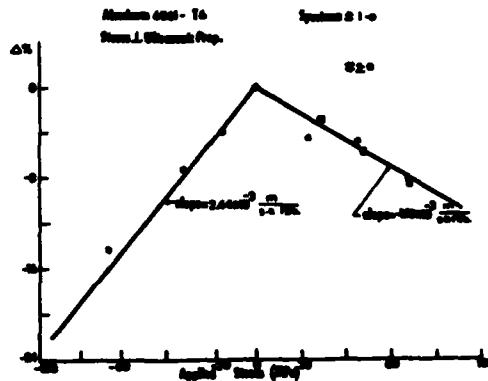
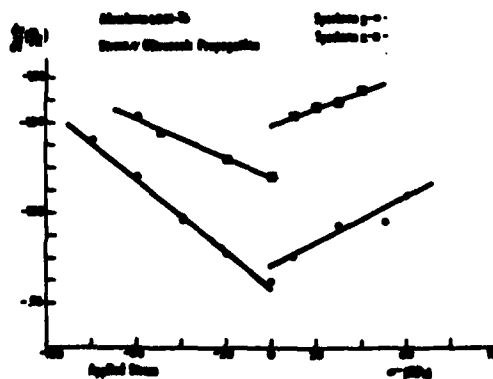


Fig. 5 Relative percentage change in the temperature dependence of ultrasonic longitudinal velocity as a function of applied compressive and tensile stresses in aluminum 6061-T6.



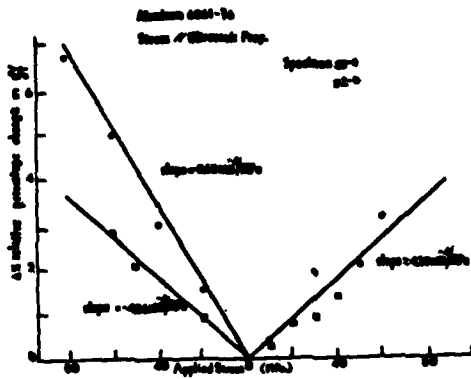


Fig. 7 Relative percentage change in the temperature dependence of ultrasonic longitudinal velocity as a function of applied compressive and tensile stress in aluminum 6061-T6.

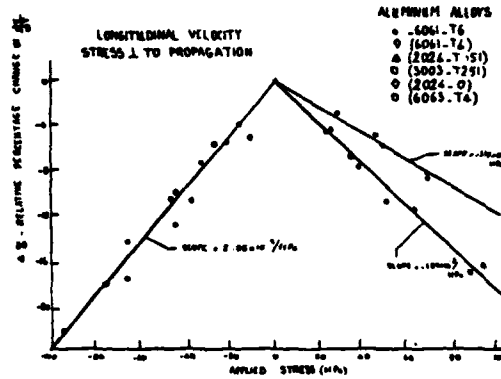


Fig. 8 Relative percentage change in the temperature dependence of longitudinal ultrasonic velocity as a function of applied stress in aluminum alloys. The 'hollow' data points were obtained by Salama, Ling and Wang<sup>7,9</sup>.

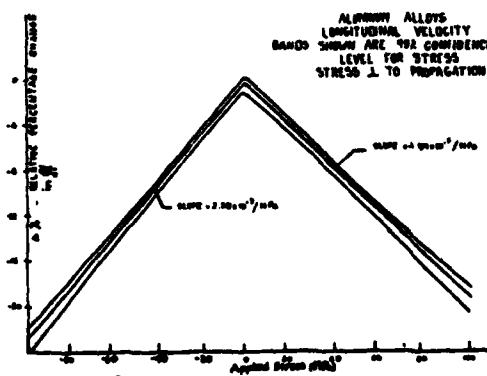


Fig. 9 Calibration curve using the relative change of the temperature dependence of ultrasonic velocity to determine applied stress in aluminum alloys.

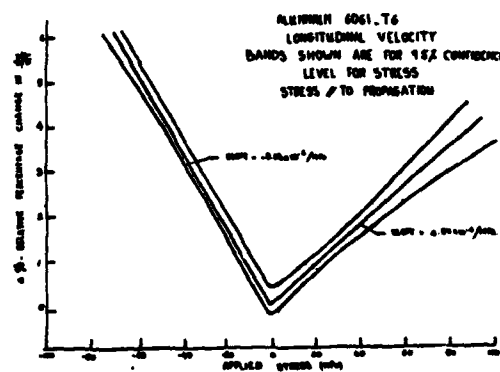


Fig. 10 Calibration curve using the relative change of the temperature dependence of ultrasonic velocity to determine applied stress in aluminum 6061-T6.

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