NONDESTRUCTIVE EVALUATION OF RESIDUAL STRESS IN LOW-CARBON STEEL

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FINAL REPORT
GRANT NAG-1-388

KAMEL SALAMA
MECHANICAL ENGINEERING DEPARTMENT
UNIVERSITY OF HOUSTON

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Nondestructive Determination of Mechanical Properties. Proc. of Review of Progress in Quantitative Nondestructive Evaluation, July 1984.

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BACKGROUND

Residual stresses are those contained in a body which has no external traction or other sources of stress, such as thermal gradients or body forces. When the body is externally loaded, these stresses are called internal stresses, and, accordingly, residual stresses may be considered as a special case for vanishing external loads. Residual stresses result from non-uniform plastic deformation which includes cold working, forming, forging, heat treatment, etc. Their presence in manufactured components plays an important role in determining the behavior of the component when it is subjected to service loads and environment. It has also been shown that the residual stress distribution directly affects the growth rate and frequency of formation of stress induced cracks in steels.

Only in the case of surface stresses in components made of crystalline materials can nondestructive evaluation of stresses be performed by the 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.

Calculations have shown that ultrasonic velocity and changes are linear functions of applied stress 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 prefered orientations (texture) during deformation or fatigue, also severely modify the third-order elastic constants. These problems can be solved when the differences between velocities of shear waves polarized perpendicular to and parallel to stress direction 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.

The temperature dependences of the elastic constant of a solid are due to the anharmonic nature of the crystal lattice, and their measurements can therefore be used to evaluate bulk stresses. Experiments performed earlier on aluminum[1,2], copper[3] and steel[4,5] have demonstrated that the temperature dependence of ultrasonic velocity is strongly affected by the presence of applied as well as residual stresses in the solid. The results of these experiments also indicate that the temperature dependence is insensitive to alloy composition and other metallurgical variables[1]. No studies, however, were made to investigate the effect of anisotropy caused by preferred orientations on the temperature dependence.

OBJECTIVES

It is therefore the goal of this research program to investigate the effects of preferred orientations on the temperature dependence of ultrasonic velocity in low-carbon steels. The main objective of the study is to establish the degree of sensitivity or actually the degree of insensitivity of the temperature dependence method to variations in preferred orientations. The program also aims at measurements of the absolute values as well as the stress dependences of the ultrasonic velocities in the same specimens where the temperature dependences are to be measured. Three tasks comprise the present program:

1. Velocity vs. temperature in 508 low-carbon steel specimens cut at angles of 0, 30, 60 and 90 degrees from the rolling direction. Ultrasonic velocity measurements are to be made using a Pulsed Phase Locked Loop[6] which is capable of measuring velocity changes of better than 1 ppm. The measurements are to be performed in the temperature range of 50 ^{o}C below or above room temperature. The results of these measurements are to establish the degree of sensitivity of the temperature dependence of ultrasonic velocity.

2. Velocity vs. stress in the same specimens to be used in the temperature dependence measurements. The experiments are to be performed when the specimens are subjected to an uniaxial stress perpendicular to the direction of wave propagation. The applied stress is to be in the elastic range up to 200 MPa. These results provide quantitative determination for the changes of the acoustoelastic constant with variations in preferred orientations.

3. Stress-strain relationships in the same specimens in order to characterize their mechanical behavior. These relationships yield the mechanical properties, yield stress, ultimate strength and strain-to-fracture of this material.

RESULTS AND DISCUSSIONS

Task 1 of this project has been accomplished and the results are shown in the following. A typical example for the change in ultrasonic velocity with temperature in A508 steel is shown in Fig. 1. These measurements are obtained using the Pulse Phase Locked Loop (P^2L^2) which is described in details in reference 6. The temperture dependence is computed using the relationship

$$\frac{\partial V}{\partial T} = V \cdot \frac{\Delta F/F}{\Delta T} \qquad (1)$$

where $\frac{\Delta F/F}{\Delta T}$ is the slope of the straight line representing the data shown in Fig. 1, and V is the velocity. The results of the temperature dependence of ultrasonic longitudinal velocity measured on four specimens of A508 steel, cut at different angles are summarized in Table I, and indicate that the temperature dependence in the specimens remains unchanged as a function of orientation within ±2%. This accuracy is equal to that estimated for measuring the temperature dependence in these specimens. These results are also confirmed by the results shown in Table II where the temperature dependence of ultrasonic shear velocity is measured in 6061-T6 aluminum when the polarization is parallel to and perpendicular to the length of the specimen. In these measurements, the propagation direction is always kept along the thickness of the specimen. Again, the data of Table II indicates that the temperature dependence remain unchanged and no anisotropy effect could be detected in this aluminum using shear waves.

The variations of the temperature dependence of ultrasonic shear velocity in A508 steel as a function of applied stresses are shown in Table III. These measurements are made with the propagation direction perpendicular to the direction in which the stress is applied and the polarization direction either parallel to or perpendicular to the stress direction. The quantity Δ in the table represents the relative percentage of the change in the temperature dependence with respect to that obtained when no stress is applied. Again the results show that the temperature dependence values at zero stress are equal (within experimental error) regardless whether the polarization direction is to parallel or perpendicular to the direction in which the stress is applied.

The results in Table III are also plotted in Figs. 2 and 3, and show the variations of the relative changes in the temperature dependence of ultrasonic shear velocity as a function of applied stresses. Figure 2 shows the effects of applied tensile and compressive stresses when the polarization is parallel to the direction in which the stress is applied, while Fig. 3 shows the same effects when the polarization direction is perpendicular to that of stress. In both cases, the propagation direction is along the thickness of the specimen and perpendicular to the direction of stress. Figures 2 and 3 also show that the lines of best fit for the experimental data do not pass through the origin and intercept the Δ-axis at equal values of about 0.9%. This intercept could be due to misalignment in the load application system where bending stresses could be introduced. These results, however, confirm the results obtained using longitudinal waves, and the two sets of data represent the complete set of calibration curves for this type of steel.

The results and discussions concerning Tasks 2 and 3 are described in the paper included in Appendix I. This paper was published in the Proceedings of the 1984 Review of Process in Quantitative Nondestructive Evaluation[7], and deals with the study performed to establish a relationship between the acoustoelastic constant and mechanical properties. The study was made on five alumium alloys, where three of these represent the work-hardenable group and the other two are heat treatable. In the first group the strength of the alloy is increased by strain or work hardening, while the strength in the second group is developed when a second phase is precipitated out of the solid solution phase.

The results obtained in this paper, show that there is a strong relationship between the acoustoelastic constant and the percentage of solid solution phase in aluminum alloys. Furthermore, the results show that this relationship is sensitive to the mechanisms which control the mechanical properties in these alloys. In addition, the paper establishes a linear relationship between the acoustoelastic constants and the yield strength and hardness. The relationship depends on whether the alloy is strain-hardened or precipitation-hardened. In the strain-hardened alloys, the acoustoelastic constants increase as the amount of solid-solution phase is decreased, while the behavior is opposite in the precipitation-hardened alloys. These relationships indicate the possibility of determining some mechanical properties using nondestructive methods.

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6. Heyman, J. S. "Pulsed Phase Locked Loop Strain Monitor," NASA Patent Disclosure, LAR 12772-1 (1980).

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TABLE I

Variation of Temperature Coefficient of Ultrasonic Longitudinal Velocity as a Function of Orientation in Steel

Specimen Orientation	Specimen	$\frac{\partial V}{\partial T}$	Specimen	$\frac{\partial V}{\partial T}$	Ave. $\frac{\partial V}{\partial T}$
90°	A1	-0.650	A2	-0.674	-0.662
30°	B1	-0.670	B2	-0.643	-0.6565
60°	C1	-0.683	C2	-0.695	-0.689
0°	D1	-0.645	D2	-0.632	-0.6385
Ave. $\frac{\partial V}{\partial T}$		-0.662		-0.661	-0.6615

TABLE II

TEMPERATURE COEFFICIENT OF ULTRASONIC SHEAR VELOCITY IN 6061-T6 ALUMINUM AT ZERO APPLIED STRESS

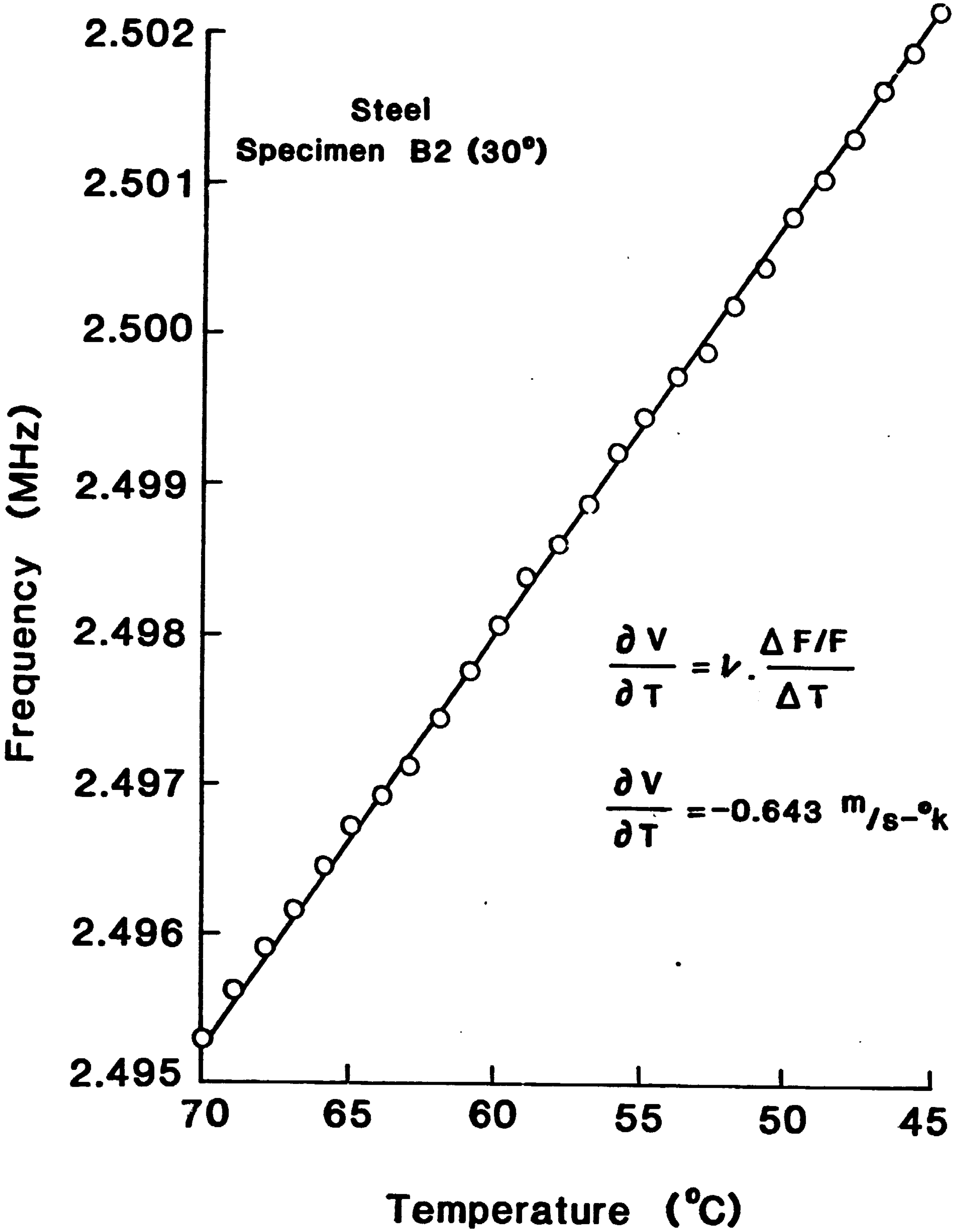
Polarization Parallel to Length $(\partial V/\partial T)_{//}$ m/s.k	Polarization Perpendicular to Length $(\partial V/\partial T)_{\perp}$ m/s.k
-0.841	-0.856
-0.850	-0.849
-0.851	-0.852

TABLE III

Variations of (dV/dT) of Ultrasonic Shear Velocity with Uniaxial Stress Applied Perpendicular to Propagation Direction in Steel.

Applied Load (Kg)	$-(dV/dT)_{//}$ (m/s.k)	Δ %	$-(dV/dT)_{\perp}$ (m/s.k)	Δ %
		TENSION		
0	0.418	0.0	0.436	0.0
500	0.435	+4.1	0.422	-3.2
750	0.440	+5.2	0.418	-4.1
1000	0.454	+8.6	0.412	-5.5
1250	0.454	+8.6	0.410	-6.0
1500	0.460	+10.0	0.408	-6.5
		COMPRESSION		
0	0.452	0.0	0.442	0.0
300			0.447	+1.1
500	0.442	-2.2		
600			0.458	+3.6
750	0.438	-3.1		
800			0.461	+4.3
1000	0.424	-6.2		
1250	0.419	-7.3	0.480	+8.5
1400	0.416	-8.0		
1500			0.492	+11.3

Figure 1


Steel
Specimen B2 (30°)
2.502
2.501
2.500
2.499
2.498
2.497
2.496
2.495
Frequency (MHz)
70
65
60
55
50
45
Temperature (°C)
$\frac{\partial V}{\partial T} = \nu \cdot \frac{\Delta F/F}{\Delta T}$
$\frac{\partial V}{\partial T} = -0.643\ m/s\text{-}°k$

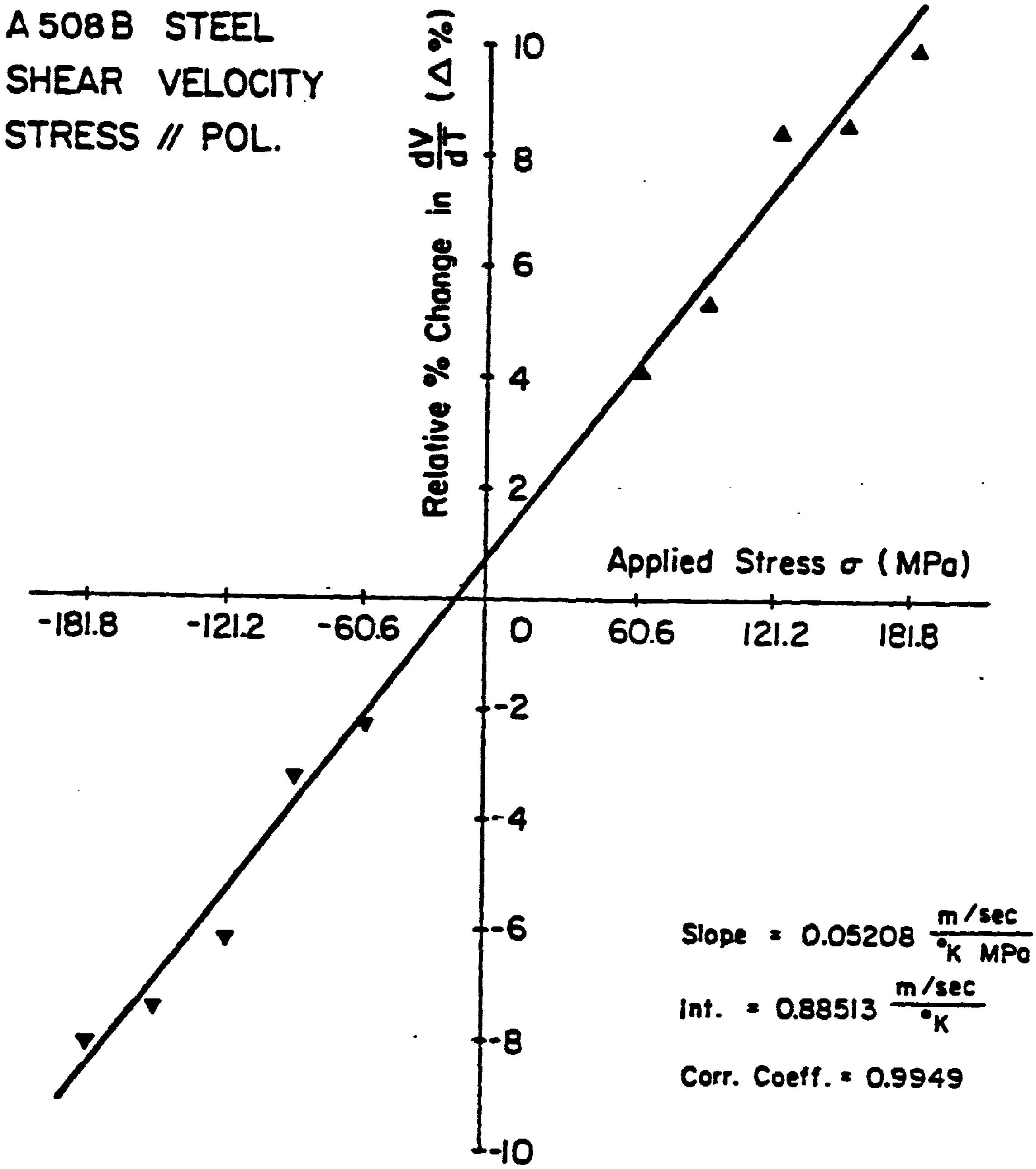


Fig. (2) Relative percentage change in the temperature dependence of ultrasonic shear velocity as a function of applied tensile or compressive stress in A 508 B steel. The stress is applied in a direction perpendicular to the direction of ultrasonic propagation and parallel to the direction of polarization.

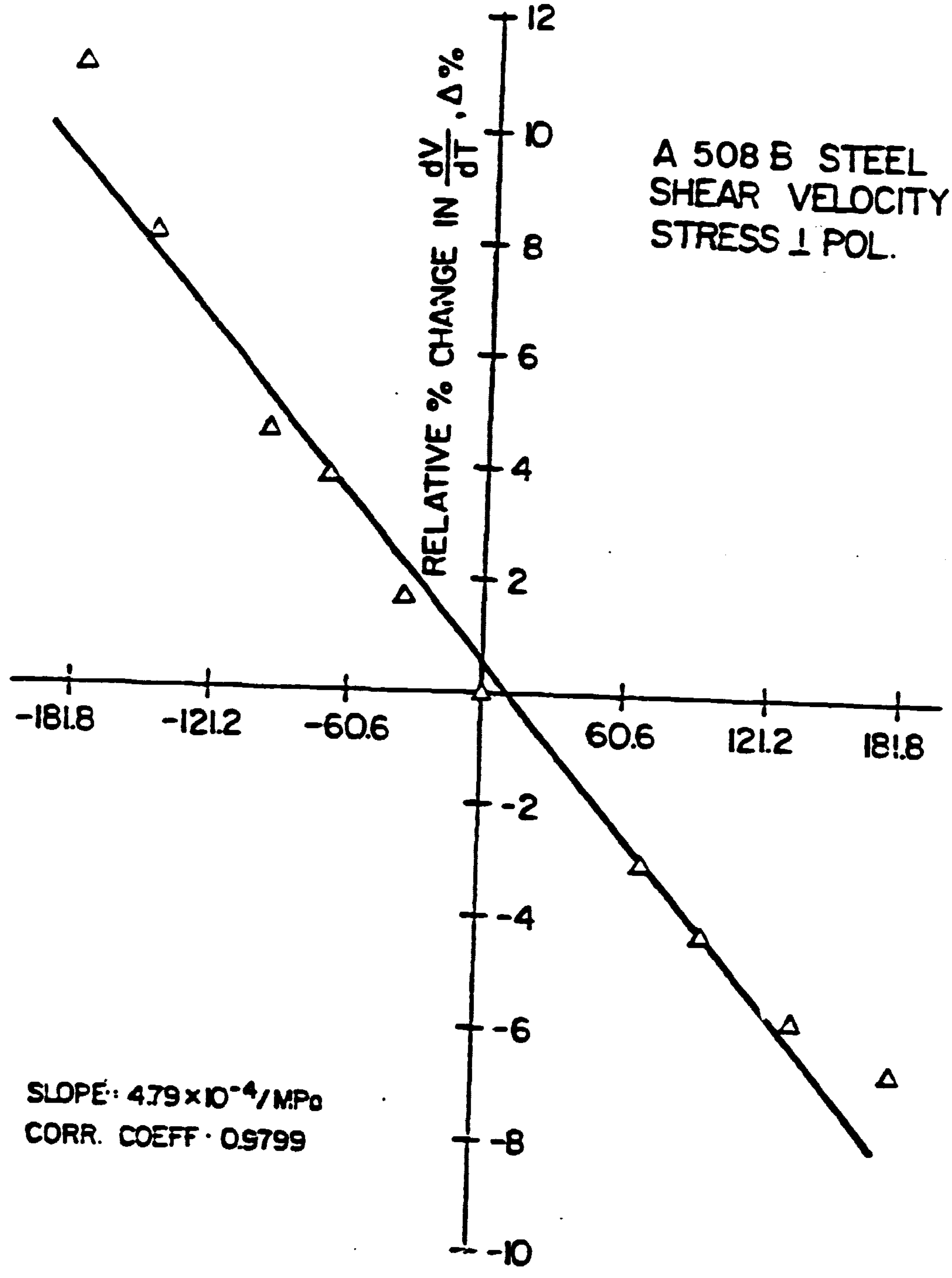


Fig. (3) Relative percentage change in the temperature dependence of ultrasonic shear velocity as a function of applied tensile or compressive stress in A 508 B steel. The stress is applied in a direction perpendicular to the directions of both propagation and polarization.

APPENDIX

NONDESTRUCTIVE DETERMINATION OF MECHANICAL PROPERTIES

Eckhardt Schneider[1], Shyr-Liang Chu and Kamel Salama

Department of Mechanical Engineering
University of Houston
Houston, TX

INTRODUCTION

The propagation velocities of ultrasonic waves are determined by the density and the elastic constants of the material under consideration. The changes of sound velocities with applied or residual stress are caused by changes of the interatomic potential, resulting in changes of the elastic behavior. Based on the nonlinear elasticity theory, Hughes and Kelly (1953) described the stress dependence of the ultrasound velocities in terms of second and third order elastic constants. It is evident from the introduction of the third order elastic constants, that these constants are more sensitive to the changes in the elastic behavior than the second order Young's - and shear moduli.

The purpose of this investigation is to study the sensitivity of the acousto-elastic constant to changes in the microstructure. The knowledge of this constant is extremely important to the evaluation of stress states using ultrasonic techniques. In particular, one acousto-elastic constant was determined in Al-alloys containing different amounts of solid-solution phases and was correlated with the yield strength and the hardness of the material. The second objective is to prove the possibility to determine some mechanical properties of the material under consideration by measurements of the acousto-elastic constants.

EXPERIMENTAL

The experiments were made using Al-alloys of types 1100, 3003, 5052, 6061 and 2024. The chemical compositions of these alloys are listed in Table 1. The first three alloys in this table are non heat treatable alloys; their strength can be increased by strain or work

[1]Institut für zerstörungsfreie Prüfverfahren, Universität Geb. 37, 6600 Saarbrücken, FRG.

Table 1. Chemical composition and temper designations of the test samples

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Others	Al
1100	1.0		0.05-0.20	0.05	——	——	0.10	0.15	99
3003	0.6	0.7	0.05-0.20	1.0-1.5	——	——	0.10	0.15	97-98
5052	0.45		0.10	0.10	2.2-2.8	0.15-0.35	0.10	0.15	96-97
6061	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	96-98
2024	0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	0.10	0.25	0.15	91-93

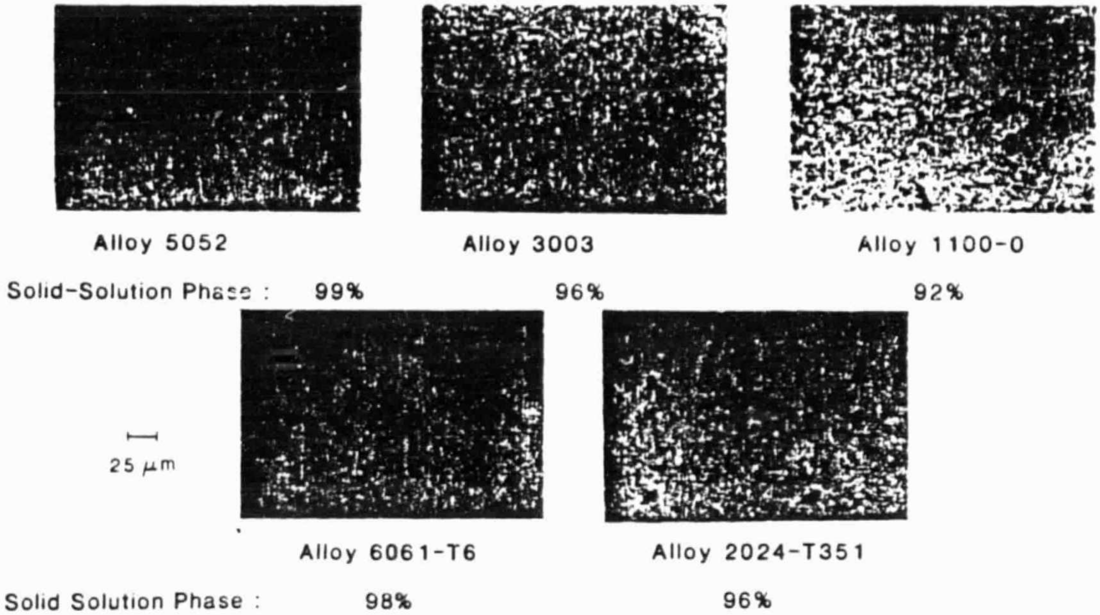
Al-Alloy	Major Elements	Temper Designations
1100-0	Si, Fe	Annealed
3003	Mn	Strain-hardened
5052	Mg	Strain-hardened and stabilized
6061-T6	Si, Mg	Solution heat-treated and then artificially aged
2024-T351	Cu, Mg	Solution heat-treated, cold worked and stress relieved

hardening. The other two alloys 6061 and 2024 are of the heat treatable type. Here the strength of the material is developed when a second phase is precipitated out of the solid-solution phase.

Tensile test samples of each alloy were cut from 6.3 mm thick rolled plates such that the rolling direction is parallel to the specimen axis. In order to evaluate the acousto-elastic constants, the velocity change of a 10 MHz longitudinal wave was measured as a function of the applied tensile stress. The sound propagation direction was perpendicular to the stress. The time-of-flight measurements were performed using the pulse-echo-overlap method. The acousto-elastic constant is determined by dividing the change of stress by the change in normalized longitudinal wave velocity. Experimental details like sample size, transducer holder, tensile test and measuring technique are described elsewhere (Salama and Wang, 1982). The yield strengths were determined from tensile tests. Also the hardness values of the specimens were evaluated using conventional techniques.

In order to evaluate the percentage of solid solution phases in the alloys, samples are cut from the examined tensile test samples and are polished on two surfaces perpendicular and parallel to the sound propagation direction. After etching (0.5 ml HF, 15 ml HCl,

Fig. 1 Micrographs and solid-solution phase percentage of the examined Al-alloys.



2.5 ml HNO_3, remainder H_2O; and cleaning with 5% NaOH), the precipitations appear as dark areas, while the solid-solution phase is white. The areas of the precipitations were measured on both surfaces of each sample and an average value was obtained. Relating the averaged value to the entire area, the percentage of solid-solution phase was evaluated within 0.5% inaccuracy. Fig. 1 displays the micrographs as well as the amounts of solid-solution phase of the examined alloys.

EXPERIMENTAL RESULTS

In order to obtain reproducible values for the acousto-elastic constants of the strain hardened alloys, it was found that the specimens must be deformed by a certain amount of prestrain. In these experiments, the specimens were first strained elastically and then the applied stress was stepwise increased to produce different amounts of prestrain. From the Figure 2, one can see that the slope of the initial stress-strain line is changed by about 20% in the second run and then reached a constant value after 0.25% prestrain. The changes in sound velocity with stress after various amounts of prestrain are plotted in Figure 3, where one can see that the slope of these plots remain unchanged after the 0.25% prestrain.

In similar experiments with the precipitation hardened alloys, it was found that the slopes of the stress-strain lines as well as the acousto-elastic constants are not affected by this small amount of prestrain, as it is shown in Table 2, where the acousto-elastic constants of one strain hardened (5052) and one precipitation hardened (2024) alloy are displayed after various amounts of prestrain.

Fig. 2. Stress-strain diagram for Al-alloy 5052

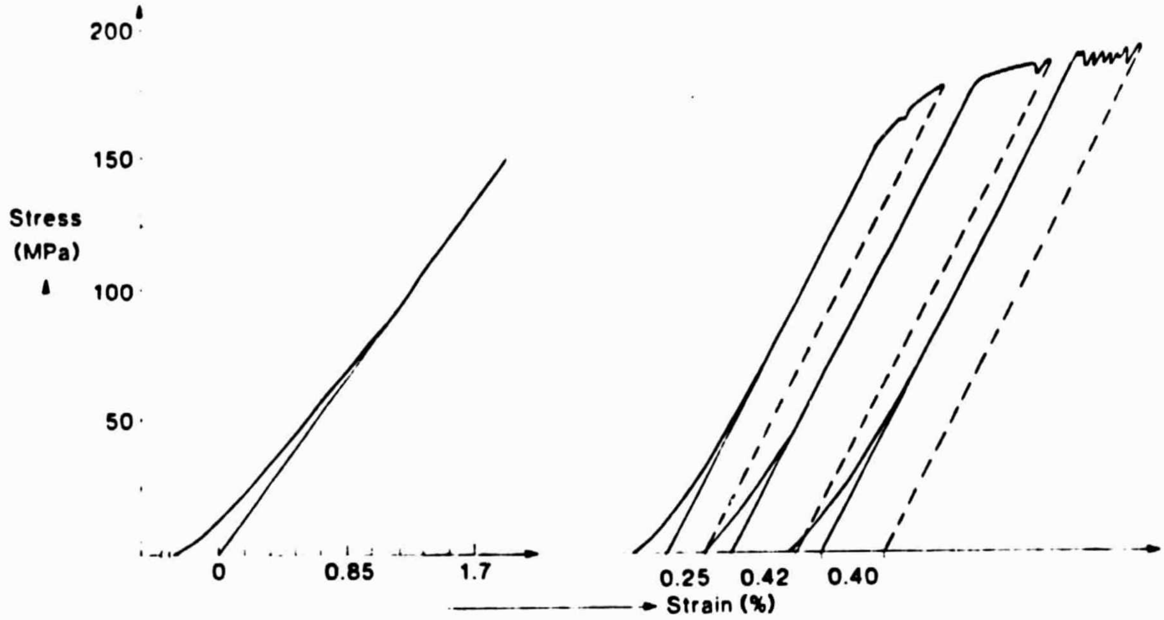


Fig. 3. Longitudinal wave velocity vs. applied tensile stress after different amount of prestrain.

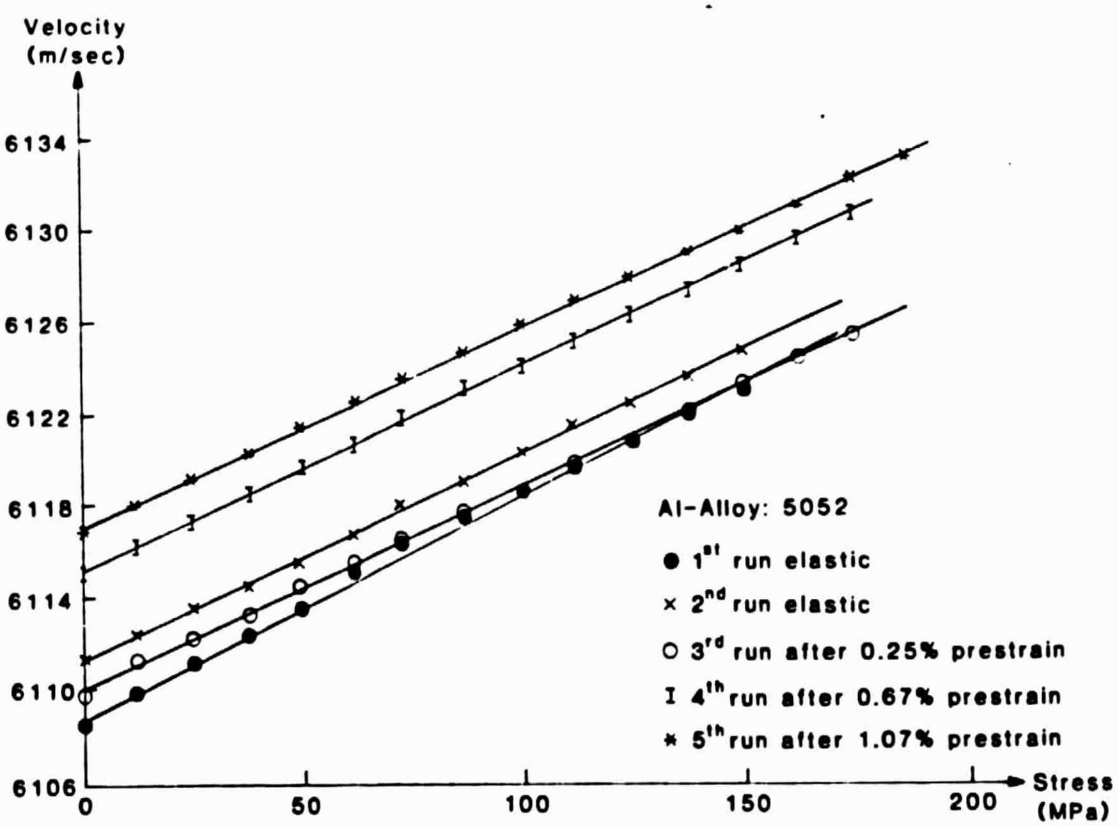


Table 2. Acoustoelastic constants and longitudinal wave velocities after different amounts of prestrain.

Al-Alloy 5052				
Prestrain %	Velocity (m/sec)		Acoustoelastic Constant (x10⁴MPa)	
	Absolute	Relative Change %	Absolute	Relative Change %
0	6108.5	—	6.38	—
0	6108.9	+ 0.007	6.86	+ 7.5
0.25	6109.7	+ 0.02	7.06	+ 10.7
0.67	6115.1	+ 0.11	6.91	+ 8.3
1.07	6116.8	+ 0.14	7.08	+ 11.0

Al-Alloy 2024-T351				
Prestrain %	Velocity (m/sec)		Acoustoelastic Constant (x10⁴MPa)	
	Absolute	Relative Change %	Absolute	Relative Change %
0	6153.3	—	7.52	—
0	6153.4	+ 0.002	7.54	+ 0.3
0.28	6148.6	− 0.08	7.48	− 0.5
0.54	6147.5	− 0.09	7.44	− 1.1

In the case of the strain hardened alloy (5052) the acousto-elastic constant reaches a constant value only after a prestrain of 0.25%. However the acousto-elastic constant of the precipitation hardened alloy 2024, remains unchanged within the inaccuracy of about 1%. The sound velocity in 5052 is constant until 0.25% prestrain. At higher amounts of prestrain a slight increasing of the velocity is indicated. In 2024, however, the ultrasonic velocity seems to decrease with prestrain. But these changes of the velocities are within the measuring inaccuracy of about 0.1%.

In these measurements at least three samples of each alloy are investigated as described. The values of the acousto-elastic constants of each alloy are found to be equal within ± 1%. Table 3 includes the values of this constant for the five alloys investigated along with the measured values of the yield strength and the Brinell hardness.

Al-Alloy	Solid-Solution Phase (%)	Acoustoelastic Constant (x10⁴ MPa	Yield Strength (MPa)	Brinell Number (500Kg load, 10mm ball)
5052	99	7.08	155	63
3003	96	7.74	100	40
1100-0	92	9.00	20	23
6061-T6	98	7.90	240	94
2024-T351	96	7.47	270	120

Table 3. Acousto-elastic constant, yield strength and Brinell Number of the examined alloys.

DISCUSSION

The Al-alloys investigated belong to two groups of alloys with different mechanisms to control the mechanical strength. Basically, the strengthening is caused by all processes which increase the inhomogenity of the material. In one type of alloys (1100, 3003, 5052) work hardening is achieved by the increase of the density of lattice defects, especially the dislocation density in the solid solution phase. The interactions of the dislocations with each other and with other defects make it more difficult to dislocations to move. In the other type of alloys (2024, 6061) the precipitations of second phase form obstacles for dislocation movements and result in the subsequent increase of strength. The parameters which determine the efficiency of the obstacles are the stiffness, shape, size and distribution as well as the volume ratio of the second phase precipitations in the alloy. Variations in these parameters change the mechanical properties of the Al-alloys.

Figures 4 and 5 display plots of the measured yield strength (Fig. 4) and hardness (Fig. 5) as a function of the percentage of solid-solution phase, present in the alloys. From these figures one can see that both quantities decrease with the increase of percentage of solid-solution phase in the precipitation hardened alloys 2024 and 6061. This behavior is due to the decrease of second-phase obstacles in the alloy with higher percentage of solid solution phase. In the strain hardened alloys 1100, 3003 and 5052, however, yield strength and hardness are increased as the amount of solid solution phase is increased. The reason for this behavior is not obvious. A possible explanation is based on the solid-solution hardening effect. It may be assumed that the density of alloying atoms in the Al-lattice of 5052 is bigger than in the alloys 3003 and 1100 respectively, so that this basic hardening effect is more efficient in 5052 alloy. No experiments, however, have been performed to test this hypothesis.

The plot of the acousto-elastic constants of the five alloys investigated versus the percentage of solid-solution phase is displayed in Fig. 6. From the figure one can see that the acousto-elastic constants of the Al-alloys change linearly as a function of percentage of solid-solution phase. Similar linear behavior has been found for the third order elastic constants of the Cu-Ni system (Salama and Alers, 1977). It is seen that the behavior of the acousto-elastic constants in the strain hardened alloys 1100, 3003 and 5052 is opposite to those of the precipitation hardened alloys 6061 and 2024. The increasing behavior of the acousto-elastic constant as a function of percentage of solid-solution phase was also found by Heyman et al. (1983) in steel alloys containing different amounts of carbon. The acousto-elastic constants are found to increase by about 20% when the ferrite phase is increased from 86 to 97%. The increase of the acousto-elastic constants in the two precipitation hardened Al-alloys is approximately 5% when the solid solution phase is increased from 96 to 98%. Comparing these results, it seems that the rate of increase of the acousto-elastic constant with percentage of solid-solution phase in the steel and in the precipitation hardened Al-alloys is similar.

Fig. 4. Yield strength vs. solid-solution phase percentage of the examined Al-alloys.

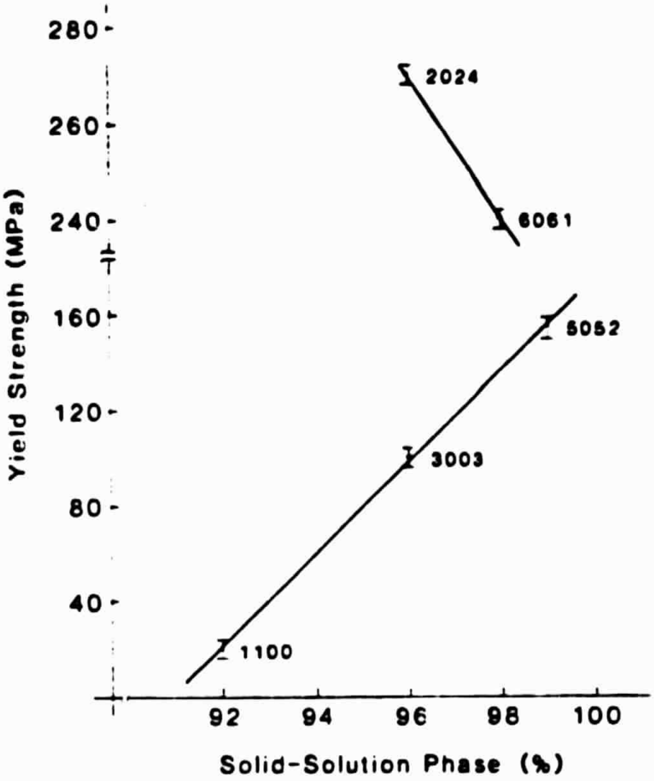
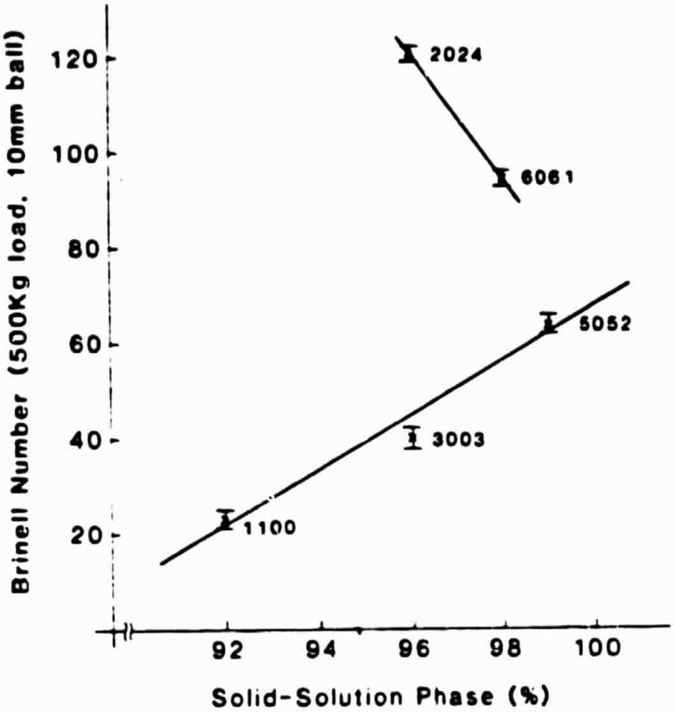


Fig. 5. Brinell number vs. solid-solution phase percentage of the examined Al-alloys.



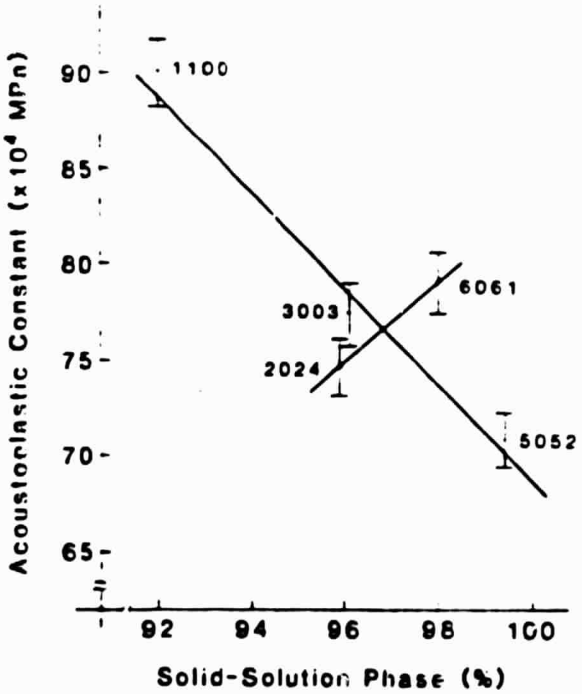
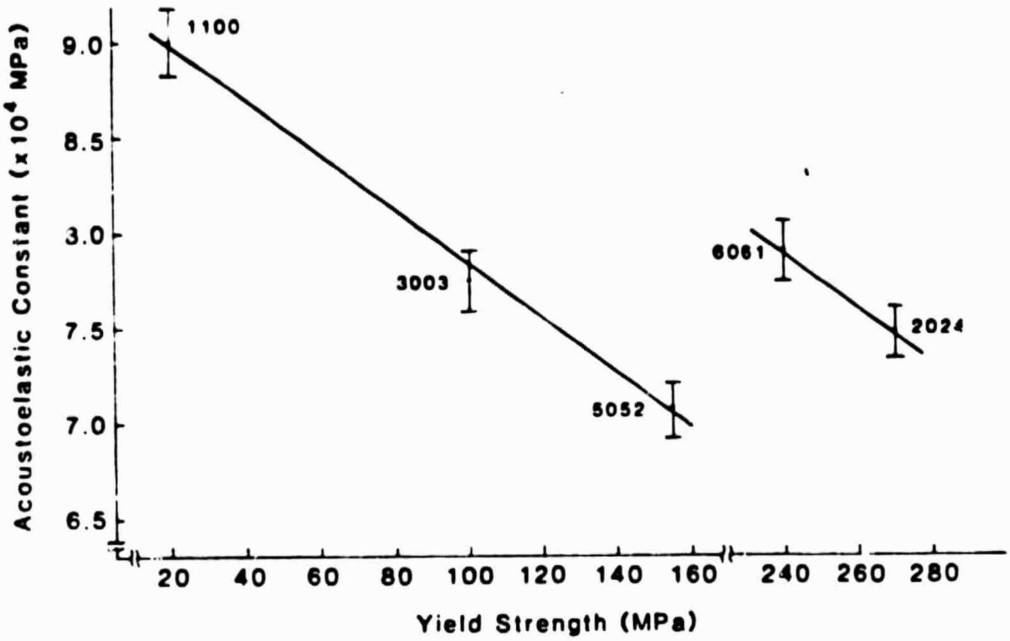


Fig. 6 Acousto-elastic constant vs. solid-solution phase percentage of the examined Al-alloys.

Fig. 7. Acousto-elastic constant vs. yield strength of the examined Al-alloys



Figures 7 and 8 finally, indicate a strong linear dependence between the acousto-elastic constants and the yield strengths and hardness values.

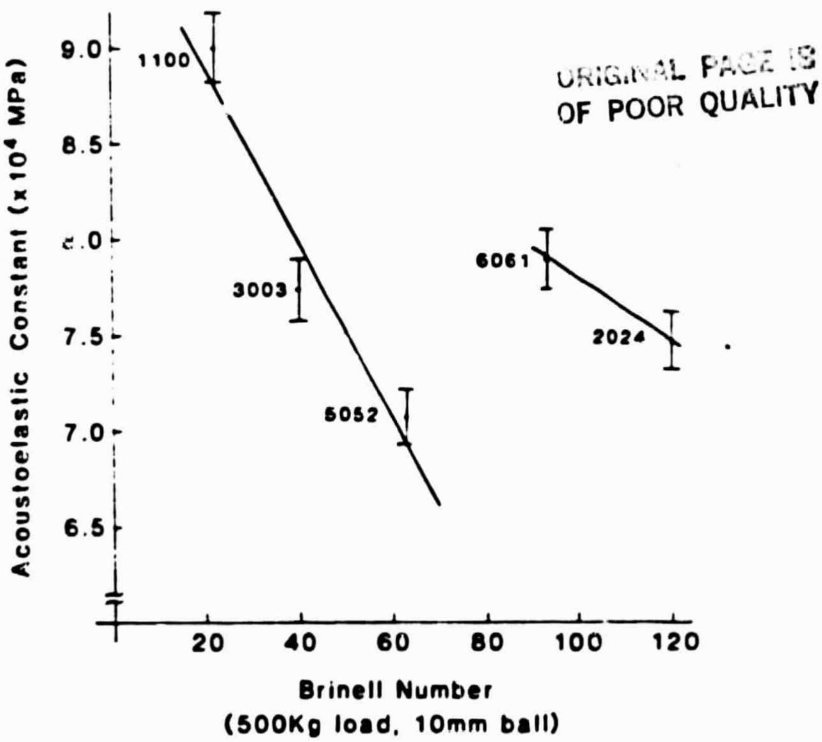


Fig. 8. Acousto-elastic constant vs. Brinell number of the examined Al Alloys.

In conclusion, it can be pointed out, that there is a strong relationship between the acousto-elastic constants and the percentage of solid-solution phase in Al-alloys. Furthermore, the results indicate that this dependence is also sensitive to the different mechanisms which control the mechanical properties in these alloys.

This microstructure dependence must be taken into consideration in the stress determination using ultrasonic techniques. Additional investigations with shear waves are recommended in order to determine the microstructure dependence of the third order elastic constants ℓ, m and n. Recent results on steels (Schneider et al., 1984) show that these constants can have different dependencies.

The linear relationship between the acousto-elastic constant and the yield strength and hardness indicate the possibility of determining some mechanical properties using nondestructive methods. The relationship depends on whether the alloys are strain hardened or precipitation hardened. In the strain hardened alloys, the acousto-elastic constants increase as the amount of solid-solution phase is decreased, while the behavior is opposite in the precipitation hardened alloys. This difference in behavior can be correlated with the difference in the mechanisms by which mechanical properties are controlled in each type of alloys.

ACKNOWLEDGEMENT

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