N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED
IN THE INTEREST OF MAKING AVAILABLE AS MUCH
INFORMATION AS POSSIBLE

NONDESTRUCTIVE ULTRASONIC CHARACTERIZATION
OF ENGINEERING MATERIALS

FINAL REPORT

GRANT NCC1-88

Kamel Salama
Mechanical Engineering Department
University of Houston

4800 Calhoun Houston, Texas
77004

NOVEMBER 1985

TABLE OF CONTENTS

NONDESTRUCTIVE ULTRASONIC CHARACTERIZATION
OF ENGINEERING MATERIALS

Final Report
Grant NCC1-88

ABSTRACT

This final report describes the accomplishments obtained under a research program supported by NASA Langley Research Center, to develop an ultrasonic method for the nondestructive characterization of mechanical properties of engineering materials. The method utilizes measurements of the nonlinearity parameter which describes the anharmonic behavior of the solid through measurements of amplitudes of the fundamental and of the generated second harmonic ultrasonic waves. The nonlinearity parameter is also directly related to the acoustoelastic constant of the solid which can be determined by measuring the linear dependence of ultrasonic velocity on stress. A major advantage of measurements of the nonlinearity parameter over that of the acoustoelastic constant is that it may be determined without the application of stress on the material, which makes the method more applicable for in-service nondestructive characterization.

The primary goal of the program was to establish relationships between the nonlinearity parameter of second-harmonic generation and the percentage of solid solution phase in engineering materials such as heat treatable aluminum alloys. These alloys are available commercially and their mechanical properties are well documented. The acoustoelastic constants were also to be measured on these alloys for comparison and confirmation.

The acoustic nonlinearity parameter has been determined in the heat treatable aluminum alloys 6061-T6, 2024-T4 and 7075-T551 using the

ultrasonic harmonic generation technique. The measurements were made using a 10 MHz longitudinal ultrasonic transducer for transmission and a capacitive transducer for the detection of second harmonic. The results indicate a linear relationship between the nonlinearity parameter and the volume fraction of second phase precipitates in these alloys. This finding is consistent with the ordered dependence of nonlinearity parameter on the molecular structure of cubic crystals for a given propagation mode. Independent measurements made on the acoustoelastic constants of the same alloys are found to exhibit a similar dependence on second phase.

INTRODUCTION

Since most mechanical properties are characteristic of the bulk of the solid, ultrasonic methods seem to offer the best promising techniques for these measurements. In order to serve as many applications as possible, the methods to be developed have to satisfy certain criteria. 1) The method should be sensitive to variations in mechanical properties and/or residual stresses, but insensitive to variations in microstructure and chemical compositions. 2) The method should be able to distinguish between variations in mechanical properties and variations in residual stresses. 3) The method should not require reference specimens made of the same material to be inspected. A major difficulty in methods currently used, has been their inability to determine some reference level for variations in mechanical properties or zero stress state in materials, especially in the presence of texture or texture gradients that exist in most structural materials. 4) The method should be frequency independent or with established frequency dependence in order to avoid frequency restrictions in reference specimens.

The majority of current efforts in nondestructive materials characterization are directed towards measurements of ultrasonic velocity[1-3] and/or attenuation[4,5]. Both measurements, however, suffer from severe difficulties which limit their applications[6]. Absolute velocity measurements are very insensitive to variations in mechanical properties and/or residual stresses. The maximum change in ultrasonic velocity due to changes in these quantities is within 1% for most engineering materials. Changes in ultrasonic velocity can normally be measured with high accuracy (within $\pm 0.001\%$), but absolute values of the

velocity is limited to an accuracy of $\pm 0.1\%$. This means that changes in mechanical properties and/or residual stresses on the same specimen can be detected rather readily, while absolute values of these quantities measured on different specimens can be detected with larger errors. In addition, values of ultrasonic velocity in engineering structural materials at zero stress state or reference state of mechanical properties are difficult to determine. This constitutes a major difficulty in the use of ultrasonic velocity in the determination of these properties.

On the other hand, ultrasonic attenuation measurements vary considerably when mechanical properties of the solid are varied, but remain unchanged when residual stresses are changed. This seems to indicate that ultrasonic attenuation can be an attractive candidate for measurements of mechanical properties. The measurements, however, suffer from two major difficulties. First, attenuation measurements depend strongly on the type of bond used between the transducer and specimen. Significant errors in attenuation coefficients are obtained when different runs are made, even on the same specimen when using the same bonding material. Secondly, attenuation coefficients in engineering materials depend strongly on frequency, and no relationship have yet been established to take into account the frequency dependence. In addition, considerable error in attenuation measurements may result from scattering and divergence of ultrasonic waves.

In summary, it is apparent that the use of absolute values of ultrasonic velocity and/or attenuation in determining mechanical properties or residual stresses suffer from severe limitations and difficulties. Only in the case of ideal solids such as single crystals,

may velocity and attenuation be related to mechanical properties[7]. Further, these measurements will be successful in the laboratory environment and not in a field environment. Attention is therefore directed towards measurements other than those of ultrasonic velocity and attenuation coefficient to be used for the nondestructive characterization of mechanical properties and residual stresses. Two parameters, namely the stress dependence of ultrasonic velocity and the nonlinearity parameter of second harmonic generation, are believed to offer the best promise for these measurements. The following gives a brief review of these two parameters.

STRESS DEPENDENCE OF ULTRASONIC VELOCITY

Calculations have shown that changes in ultrasonic velocities are linear functions of applied stress where the slope of this linear relationship provides a measure for third-order elastic constants[8]. Unknown stresses can be determined when both the velocity in the absence of stress as well as values of third-order elastic constants are known independently. The measured velocity in engineering materials, however, strongly depends on microstructural features which makes it necessary to develop a calibration between velocity and stress for each material in order for the method 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[9]. Efforts are underway at present to find solutions for these problems in order to use velocity measurements to determine residual stresses[10,11].

On the other hand, recent investigations on plain carbon steels have shown that acoustoelastic constants depend on the carbon content in these steels[12,13]. The results show a linear relationship between the acousto-elastic constant and the nominal precentage of ferrite phase in these steels. The results also indicate that the addition of heavy alloying elements to the steel does not change the value of the acoustoelastic constant as long as the amount of ferrite phase remains the same. This behavior indicates a strong relationship between the variations of ultrasonic velocity with stress and the amount of solid-solution phase in the alloy. If this behavior prevails in other types of steels, it would then be possible to use the acoustoelastic constant to measure the percentage of ferrite phase in steels, which control some of the mechanical properties such as strength, hardness and ductility.

This behavior has also been observed in five aluminum alloys containing a wide variety of strengthening alloying elements[14]. The acoustoelastic constants are measured on specimens made of the four aluminum alloys 1100-0, 5052, 6061-T6, 3003-T251 and 2024-T351, and the data shows a linear dependence between acoustoelastic constant and the percentage of solid-solution phase in the alloy. This dependence is similar to that observed in steel and confirms the conclusion drawn using the steel data.

It has to be realized, of course, that the acoustoelastic constant may depend on other variables such as microstructure and work hardening, and the results obtained are limited to specimens of the alloys investigated. Nevertheless, the results indicate a strong dependence of acoustoelastic constant on the amount of ferrite phase in the case of steels and the amount of the solid solution phase in the case of

aluminum. The study is certainly a step forward towards the possibility of using this quantity in materials characterization. In both alloying series, the presence of the solid-solution phase strongly influences mechanical properties.

NONLINEARITY PARAMETER

An alternative method to the uniaxial stress measurements to determine the anharmonic behavior of a solid is the measurement of harmonic distortion of an initially sinusoidal ultrasonic wave[15,16,17]. A major advantage of this method is that the nonlinearity parameter β which describes the anharmonic behavior of the solid may be determined without the application of stress which makes the method extremely practical as a nondestructive evaluation technique. The method also can be readily adopted for measurements at temperatures other than that of room temperature. In this method, one excites a finite amplitude of longitudinal ultrasonic wave which propagates through the specimen. By measuring the fundamental amplitude and the generated second harmonic amplitude, one can determine nonlinearity parameter which constains a linear combination of the second- and the third-order elastic constants. This can experimentally be obtained from the measurements of the absolute values of the amplitudes of the fundamental and the generated second harmonic of an initially sinusoidal longitudinal wave.

For a cubic crystal structure, the nonlinearity parameter β is the negative of the ratio of the nonlinear term to the linear term in the nonlinear wave equation for finite amplitude longitudinal waves propagation along a principal direction of the medium. For pure mode

longitudinal sound waves propagating along a principal axis, the wave equation can be written in the form,

$$\rho_0 \frac{\partial^2 u}{\partial t^2} = K_2 \frac{\partial^2 u}{\partial a^2} + (3K_2 + K_3) \frac{\partial u}{\partial a} \cdot \frac{\partial^2 u}{\partial a^2} \qquad (1)$$

where K_2 and K_3 are the linear combinations of the second- and the third-order elastic constants.

Considering an initially sinusoidal distribution at $a = 0$, the solution of eq. (1) is of the form,

$$u = A_1 \sin(ka - wt) + (A_1^2 k^2 a/8) \, \beta \cos 2(ka - wt) + \ldots \qquad (2)$$

where a is the propagation distance, $k = 2\pi/\lambda$ is the propagation constant, and A_1 is the amplitude of the fundamental wave. The amplitude of the generated second harmonic is then given by,

$$A_2 = (A_1^2 k^2 a/8)\beta \qquad (3)$$

where

$$\beta = -(3K_2 + K_3)/K_2 \qquad (4)$$

and also can be written in terms of the measured quantities as

$$\beta = 8(A_2/A_1^2)(1/k^2 a) \qquad (5)$$

The nonlinearity parameter β can then be experimentally determined by measuring the absolute values of the amplitudes of the fundamental and the generated second harmonic wave signals A_1 and A_2, respectively. The development of a capacitive detector and its calibration[18] permit the absolute determination of the amplitude of finite sinusoidal ultrasonic waves.

PROGRAM OBJECTIVES

Studies performed on steel and aluminum alloys have shown that variations of ultrasonic velocity with stress are linear and the slopes of these linear relationships are sensitive to variations in mechanical properties and internal stresses. The stress dependence studies showed that the acoustoelastic constants in steel and aluminum alloys vary linearly with the percentages of solid solution phases in these alloys. This behavior should then lead to the development of practical methods to characterize mechanical properties of engineering materials nondestructively. In steels, mechanical properties can be expressed with reasonable accuracy by a simple relationship between the specific property and the amounts of ferrite and perlite phases present in the steel alloy[19].

It is therefore the primary goal of the research program to study the utilization of the nonlinearity parameter of harmonic generation and the stress dependence of ultrasonic velocity to characterize mechanical properties of engineering materials. The study would also result in the fundamental understanding of the calculations of harmonic properties in alloys containing several phases. No information is currently available for third-order elastic constants in alloys[20].

The study was to establish relationships between the nonlinearity parameter of second-harmonic generation and the percentage of solid solution phase in a two-phase alloy system such as those of aluminum. Similar relationships were also to be established between acoustoelastic constants and percentage of second phase precipitates in the same alloy system. These alloys are available commercially and their mechanical properties are well documented. The acoustoelastic constants was to be measured on these alloys for comparison and confirmation. Further, the study was also aimed at measurements of the variations of the nonlinearity parameter and the acoustoelastic constant as a function of work hardening. These measurements determine the possibility of separating the effects of phase and work hardening variations on the anharmonic properties of alloys.

EXPERIMENTAL

The alloys used in this investigation are 6061-T6, 2024-T4 and 7075-T551. The nominal compositions of these alloys are shown in table 1. The specimens used in the harmonic generation measurements are manufactured in the form of cylinders, of 1-1.5 inch diameter and 1.5 inch in length. The opposite faces of the specimen are polished to be flat and parallel to less than .0001 inch.

In the harmonic generation measurements, a nominally 10 MHz electrical tone-burst is used to drive a 1/2 inch diameter Lithium Niobate transducer of 10 MHz fundamental frequency to launch an acoustic tone-burst into the aluminumium specimen. The acoustic harmonic wave is then detected at the opposite end of the specimen using a capacitive transducer. The nonlinearity parameter is then determined by measuring

the absolute amplitude of the fundamental acoustic wave and that of the second harmonic. Detailed information regarding the experimental technique and the measurement procedure can be found elsewhere.[21]

In order to measure the AEC, the cylinderical samples used in the nonlinearity parameter measurements are cut into a .7 x .7 x 1.5 cubic inch blocks. In these measurements, the stress is applied perpendicular to the sound propagation direction. Changes in the ultrasonic velocity are measured using the pulse-echo-overlap system which is described in detail in reference 22 along with the loading system used.

The experimental arrangement for the harmonic generation measurements and the AEC measurements are shown in figures 1 and 2, respectively. Using these systems, the systematic uncertainty in determining β and AEC are found to be 14%, and 2%, respectively. The volume fraction of the second phase is determined by measuring the size of the second phase precipitates relative to the solid solution phase on the etched and polished surfaces of specimens used in the investigation. The Rockwell-F hardness of the specimens' surfaces are measured using a conventional hardness tester.

RESULTS AND DISCUSSIONS

The values of the ultrasonic longitudinal velocity V, the nonlinearity parameter β and the acoustoelastic constant (AEC) for the spcimens used in this investigation are listed in table 2. Also included in this table, are the values of hardness and volume fraction of second phase in the same specimens used in the ultrasonic measurements. From this table, one can see that the changes in the absolute value of the longitudinal velocity is small, (~ 1%), while

those of β and AEC are 40.2% and 37%, respectively. The plots of the nonlinearity parameter β and AEC versus volume fraction of the second phase precipitates are displayed in figure 3. From this figure, we note that the presence of second phase precipitates has a large effect on both the values of the nonlinearity parameter β and the AEC. Moreover, one can see that both β and AEC decreases linearly with the decrease of the volume fraction of second-phase precipitates in the aluminum alloys investigated. It is also interesting to note that the changes of both β and AEC with volume fraction of second phase are almost equal, indicating similar sensitivity of the two parameters on phase composition. This resul is expected since β and AEC are functions of the third order elastic constants of the solid which have been observed to be sensitive to the microstructural properties of the material.

The nonlinearity parameter β is plotted as a function of AEC in figure 4. From this figure, it is seen that β is a linear function of AEC, indicating the possibility of using this parameter in characterizing material properties. The plots of β and AEC as a function of hardness are displayd in figure 5. From this figure one can see that both β and AEC increases as the hardness is increased. Figure 5 also indicates a possible relationship between these two parameters which can be determined nondestructively and mechanical properties of these alloys.[23]

CONCLUSION

In this investigation we show that both the nonlinearity parameter β and the AEC decreases linearly with the decrease of the volume fraction of second phase precipitates in the aluminum alloys

investigated. Also we find that both the nonlinearity parameter β and AEC increases as the hardness is increased. In addition, the nonlinearity parameters and the acoustoelastic constants are linearly related indicating the possibility of using the nonlinearity parameter in the nondestructive characterization of material properties.

REFERENCES

1. G.S. Kino, D.M. Barnett, N. Grayeli, G. Herman, J.B. Hunter, D.B. Ilic, G.C. Johnson, R.B. King, M.P. Scott, J.C. Shyne and C.R. Steele; J. of NDE, 1, 67 (1980).

2. N.N. Hsu, T.M. Proctor, Jr. and G.V. Blessing, J. of Testing and Evaluation, 10, 230 (1982).

3. S.R. Buxbaum and R.E. Green, Jr., Proc. First Workshop on NDE of Titanium, O.P. Arora, H.H. Chaskelis and N.K. Batra, eds., p. 15 (1982).

4. J.C. Shyne, N. Graylei and G.S. Kino, Nondestructive Evaluation: Microstructural Characterization and Reliability Strategies, O. Buck and S.M. Wolfe, p. 133 (1980).

5. E. Schneider and K. Goebbels, New Procedures in Nondestructive Testing, P. Holler, ed., p. 551 (1983).

6. M.R. James and O. Buck, Critical Reviews in Solid State and Materials Science, p. 61 (1980).

7. G.A. Alers and K. Salama, Dislocation Dynamics; A.R. Rosenfield, G.T. Hahn, A.L. Bement, Jr. R.I. Jaffee, eds., p. 211 (1968).

8. R.E. Green, Treatise on Materials Science and Technology, vol. 3, (1973).

9. P.J. Noronha, J.R. Chapman and J.T. Wert, J. of Testing and Evaluation 1, 209 (1973).

10. R.B. King and C.M. Fortunko, IEEE Ultrasonic Symposium, p. 885 (1982).

11. R.B. Thompson, J.S. Smith and S.S. Lee, Symposium on NDE for Use in Materials Processing, O. Buck and S. Wolfe, eds., (1983).

12. J.S. Heyman, S.G. Allison, K. Salama and S.L. Chu, Symposium on NDE for Use in Materials Processing, O. Buck and S. Wolfe, eds., (1983).

13. S.G. Allison, J.S. Heyman and K. Salama, IEEE Ultrasonic Symposium (1983).

14. E. Schneider, S.L. Chu and K. Salama, Review of Progress in Quantitative NDE, San Diego (1984).

15. W.T. Yost and M.A. Breazeale, Phys. Rev. 9B, 510 (1974).

16. J.H. Cantrell, Jr., Phys. Rev. B21, 4191 (1980).

17. W.T. Yost, J.H. Cantrell, Jr., and M.A. Breazeale, J. Appl. Phys., 52, 126 (1981).

18. R.D. Peters, M.A. Breazeale and V.K. Paré, Revi. Sci. Inet. 39, 1505 (1968).

19. R.M. Brick, A.W. Pense and R.B. Gordon, Structure and Properties of Engineering Materials, Fourth Edition, McGraw-Hill, p. 162 (1977).

20. K. Salama and G. A. Alers, Physica Satatus Solidi(a), 41, 24 (1977).

21. J.H. Cantrell, Jr. and M.A. Breazeale, Phys. Rev. B17, 4864 (1978).

22. J.S. Heyman, Pulsed Phase Locked Loop Strain Monitor, U.S. Patent LAR 12772-1 (1980).

23. P. Li, W. T. Yost, J.H. Cantrell and K. Salama, IEEE Ultrasonic Symposium (1985).

Table 1

Chemical composition (% by Weight) in aluminum alloys

	Cu	Cr	Mg	Mn	Si	Zn
6061	-	0.2	1.0	-	0.6	-
2024	4.5	-	1.5	0.6	-	-
7075	1.5	0.3	2.5	-	-	5.5

Table 2

Values of quantities measured in aluminum alloys

	B	AEC	v	%	R_f
6061-T6	5.1	4.02	6.27	.3	60.8
2024-T4	7.7	5.87	6.20	2.3	70.8
7075-T551	8.6	6.38	6.21	2.9	77.3

B   = nonlinearity parameter
AEC = acoustoelastic constant (10^4 MPa)
%   = % of the volume fraction of second phases
v   = velocity (10^3 m/s)
R_f = Rockwell f hardness
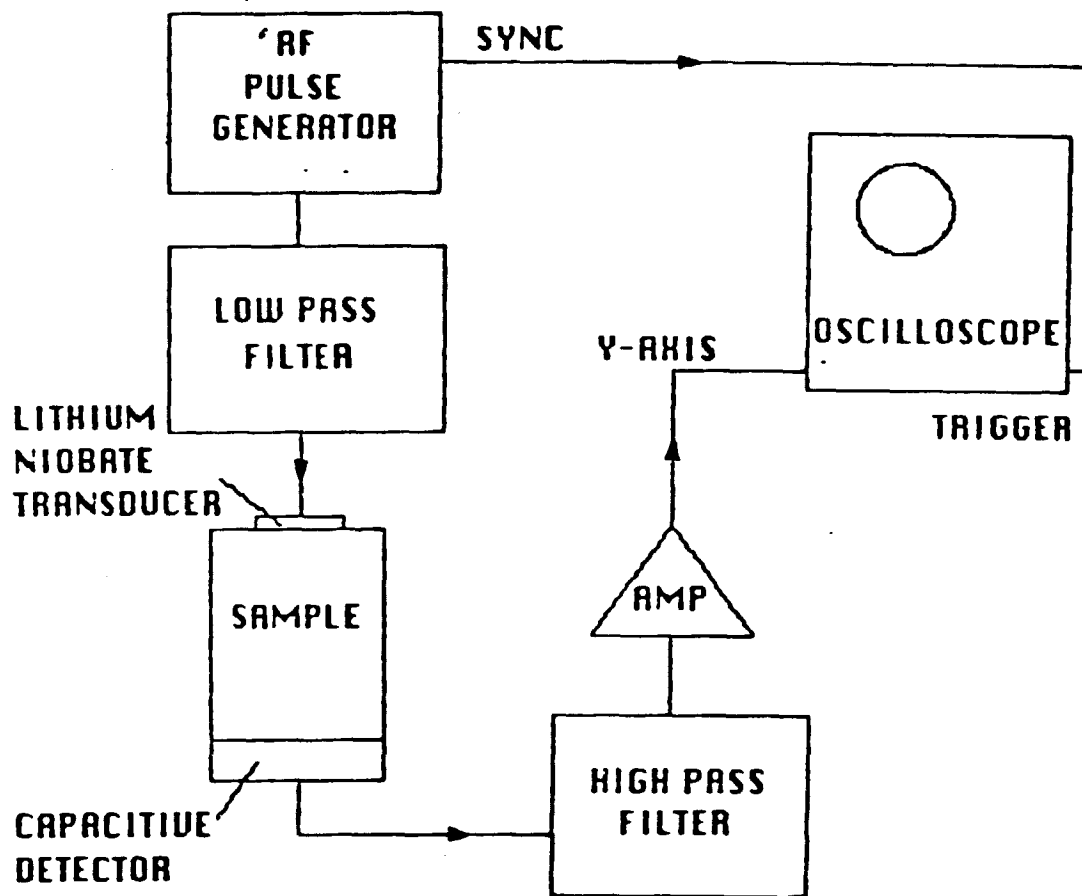
FIGURE 1

System used for measurements of Nonlinearity Parameter
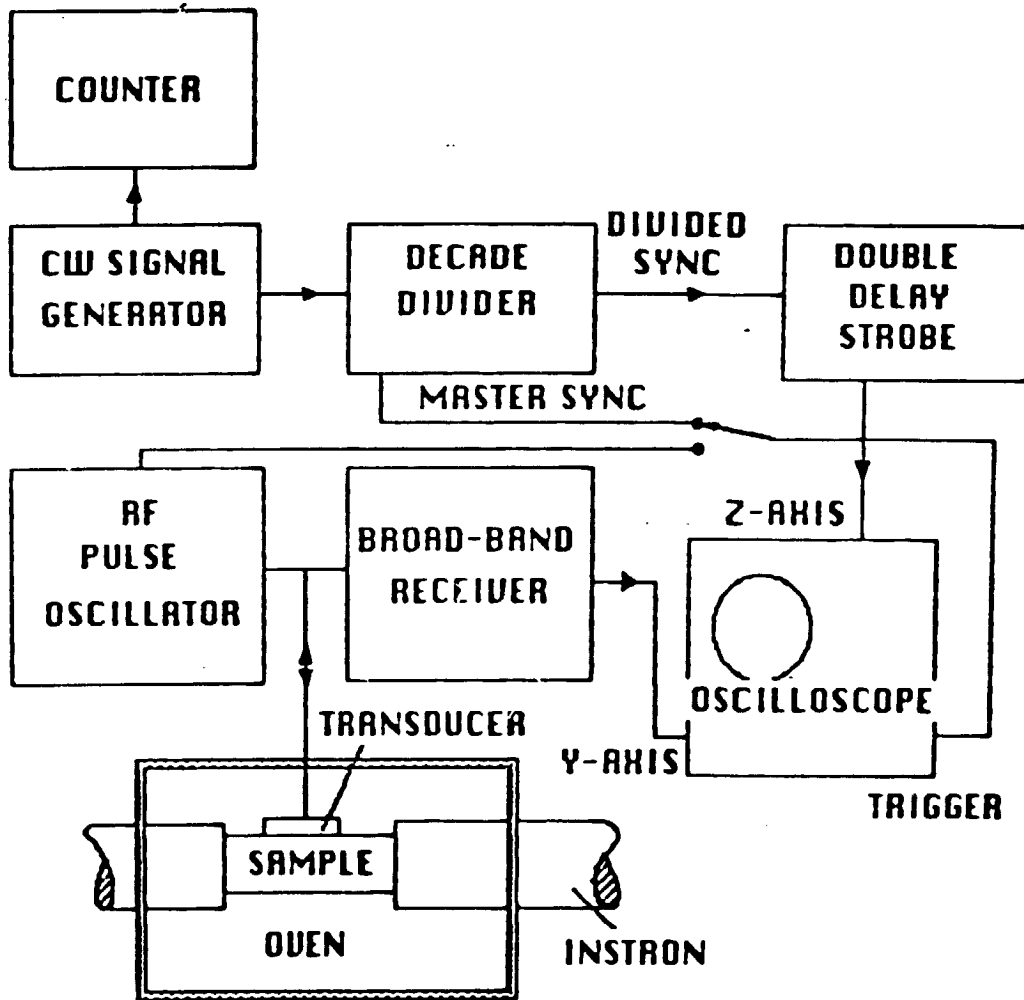
FIGURE 2

System used for measurements of Acoustoelastic Constant
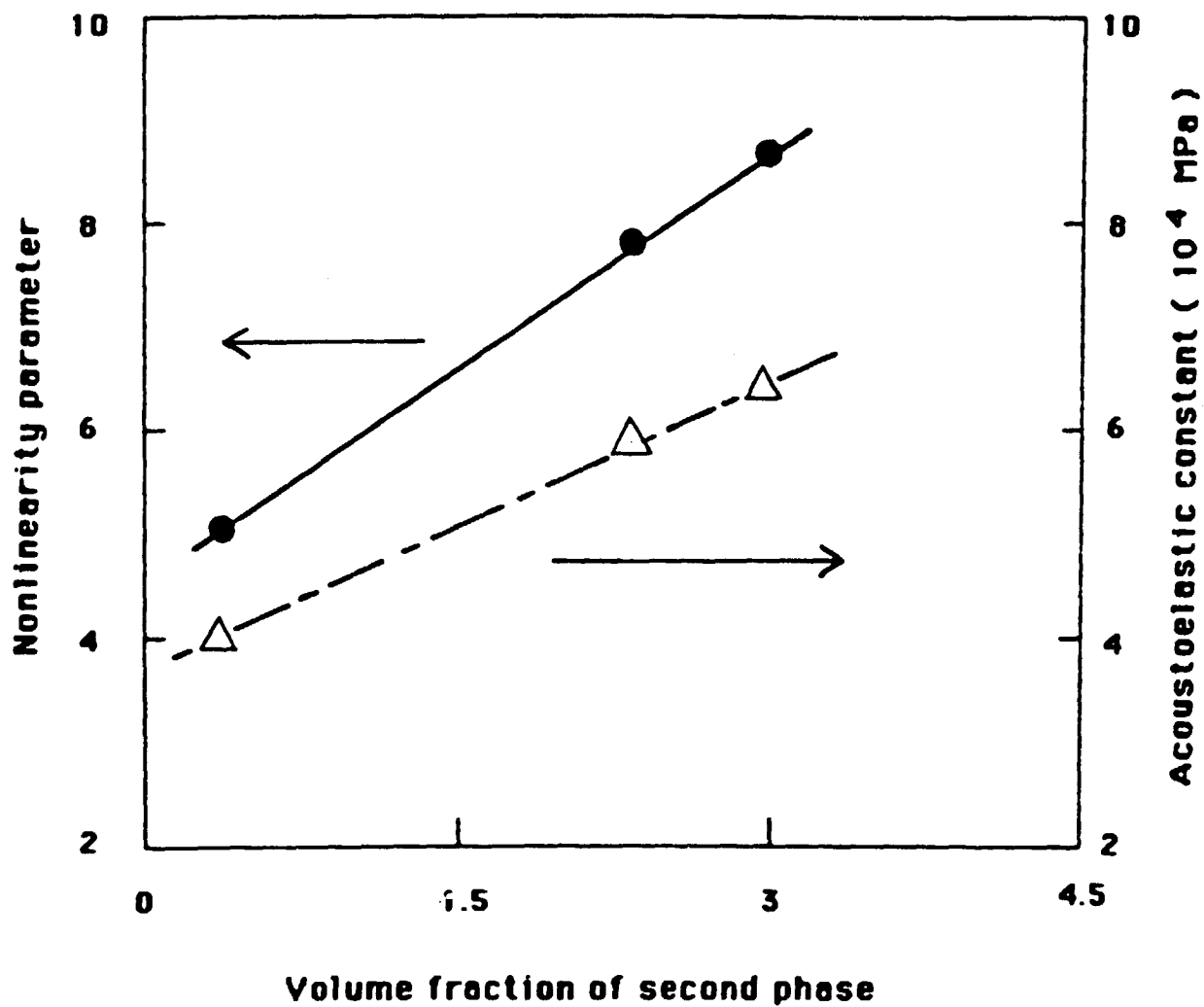
Figure 3 - Plots of nonlinearity parameter and acoustoelastic
constant as a function of volume fraction of second
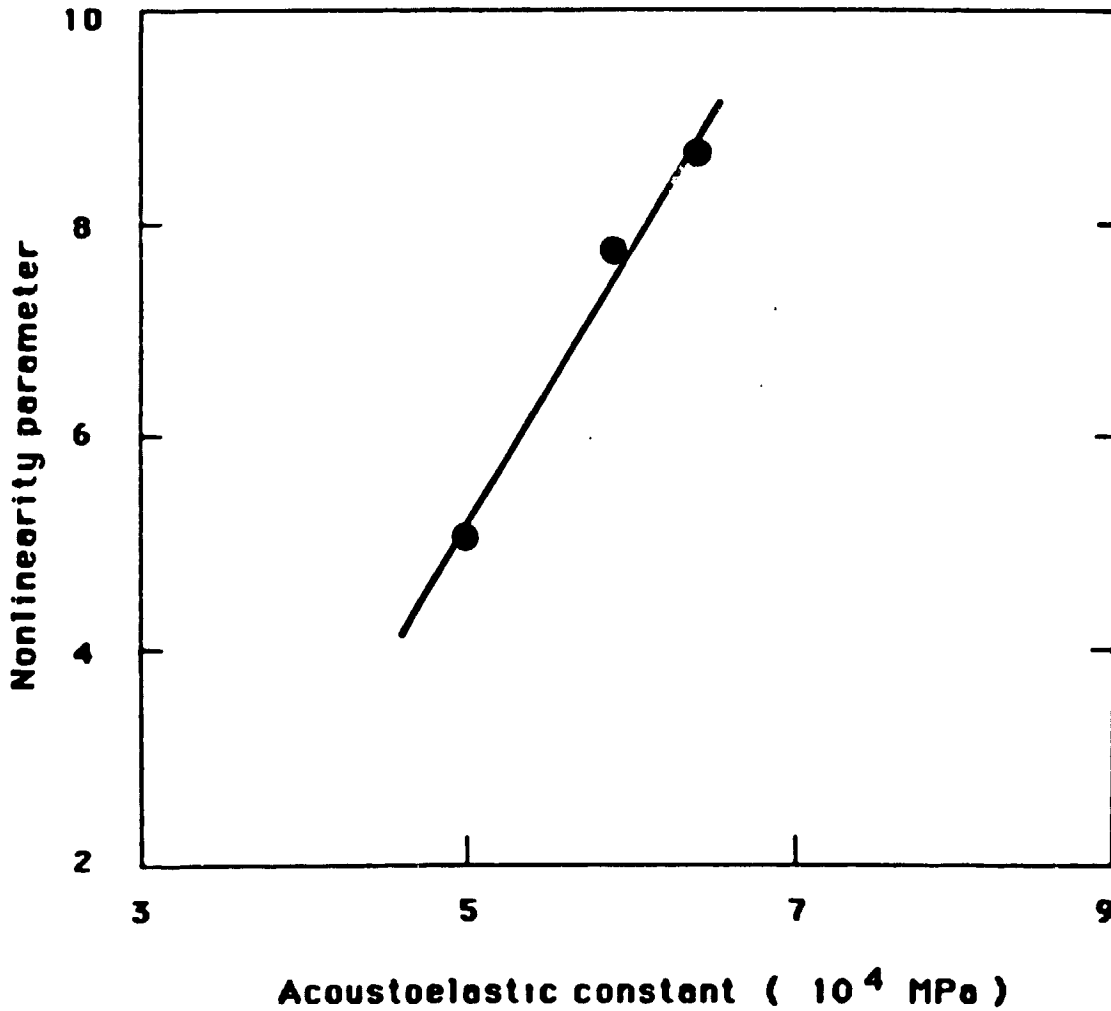phase precipitates

Figure 4 - Nonlinearity parameter as a function of
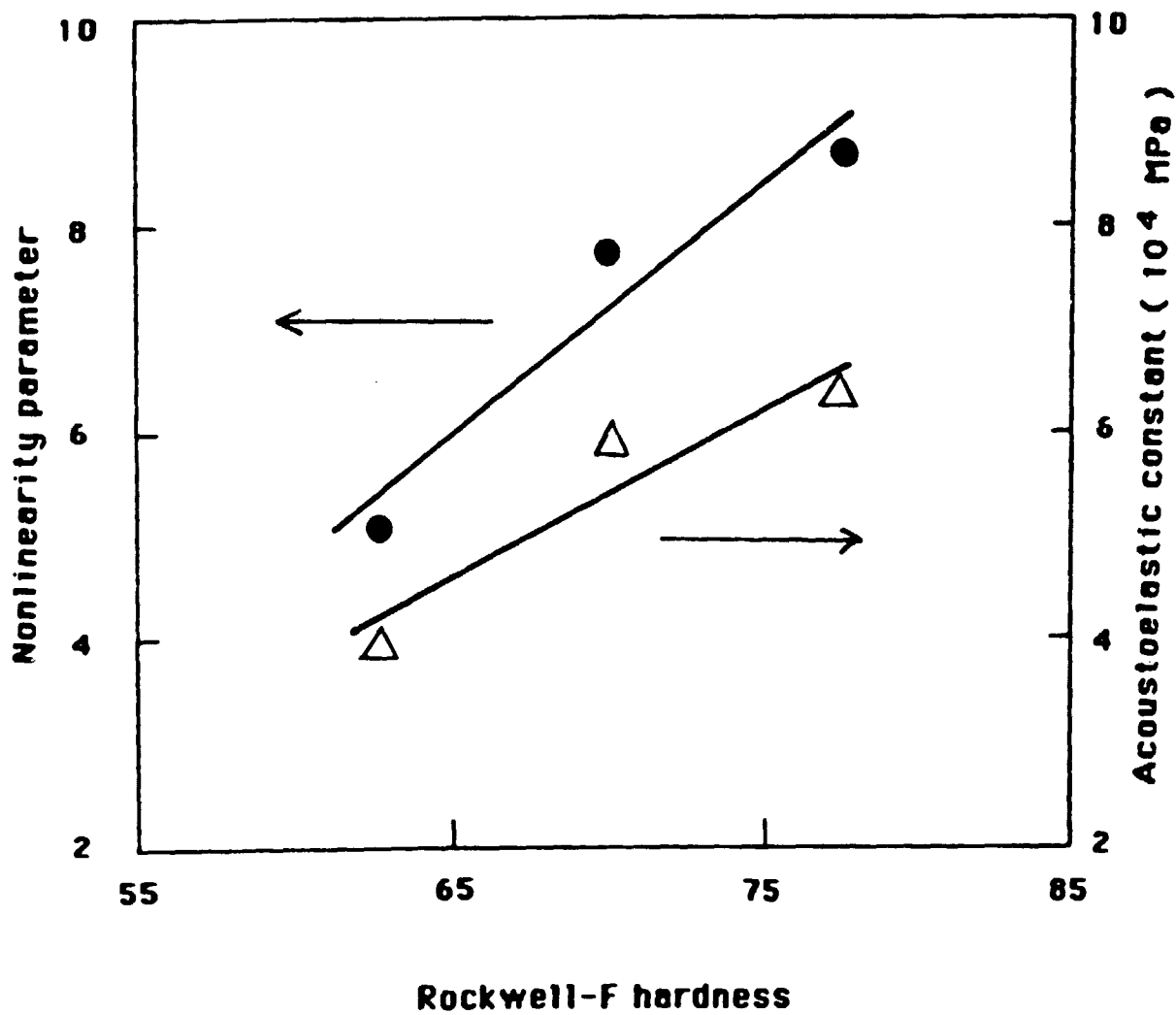Acoustoelastic constant in aluminium alloys

Figure 5 — Plots of nonlinearity parameter and acoustoelastic constant as a function of Rockwell-F hardness.