MEASUREMENT OF FLOW STRESS RELATED* PHENOMENA BY NONLINEAR ACOUSTICS

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Before going into acoustic harmonic generation, I should bring to your attention the definition of internal stresses which was made about 40 years ago[1]. Basically, we have to distinguish between two kinds of internal stresses. Internal stresses of the first kind are those which spread out over macroscopic distances of the order of millimeters. Applying x-rays, one obtains a line shift in the Bragg reflection due to a lattice parameter change. A simple example of internal stresses of the first kind is shown in Fig. 1, top: in bending a piece of material elastically, a line shift in the Bragg reflection will be found on the upper and lower surface. Internal stresses of the second kind are restricted to much, much smaller dimensions, say of the order of 1 μm or below. Bragg reflection does not show a line shift, but merely a line broadening. A typical example is shown in Fig. 1, bottom. Assume dislocations ($\perp$) are distributed in a material. The variation of the elastic stress field surrounding the dislocations is assumed to be sinusoidal and of the periodicity of the dislocation arrangement. If another dislocation is pushed against this chain of dislocations, it will see the stress field of the dislocation arrangement. In work hardening theories, this model is used to calculate the work hardening coefficient[2]. The present paper will be concerned mainly with the internal stresses of the second kind.

Let us now consider harmonic generation of finite amplitude acoustic waves. Harmonic generation is a subject that has been discussed in the literature for about 12 years. Assuming that a purely sinusoidal fundamental wave with amplitude U_1 is injected into a solid, the lattice anharmonicity will give rise to a harmonic generation (the potential in which the atoms move is not parabolic!) Hooke's law is usually used to calculate wave propagation. If the second order approximations in displacement and in deformation energy are included[3], a second harmonic driven by the fundamental (of amplitude U_1) is generated. The amplitude of this second harmonic is proportional to U_1^2, to ω^2 (the frequency of your first harmonic), the propagation distance x, and a combination of second and third order elastic constants, c_{ij} and c_{ijk}, respectively, as indicated in Eqn. (1).

$$U_{2e} = U_1^2\ \omega^2 x \left[f(c_{ij}, c_{ijk})\right] e^{2i(\omega t - kx)} \qquad (1)$$

About ten years ago, Elbaum et al[4] started to study ductile materials, using harmonic generation. Ductile materials contain dislocations which are mobile. Elbaum et al observed that dislocations contribute to the second harmonic generation due to a nonlinearity in the stress strain relation. Its amplitude also is proportional to the U_1^2, ω^2, and x. It is also a function

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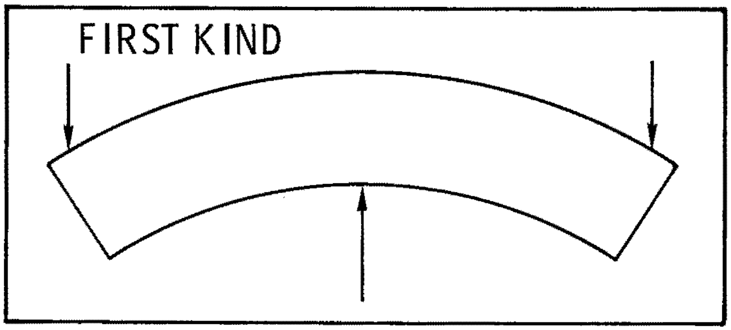

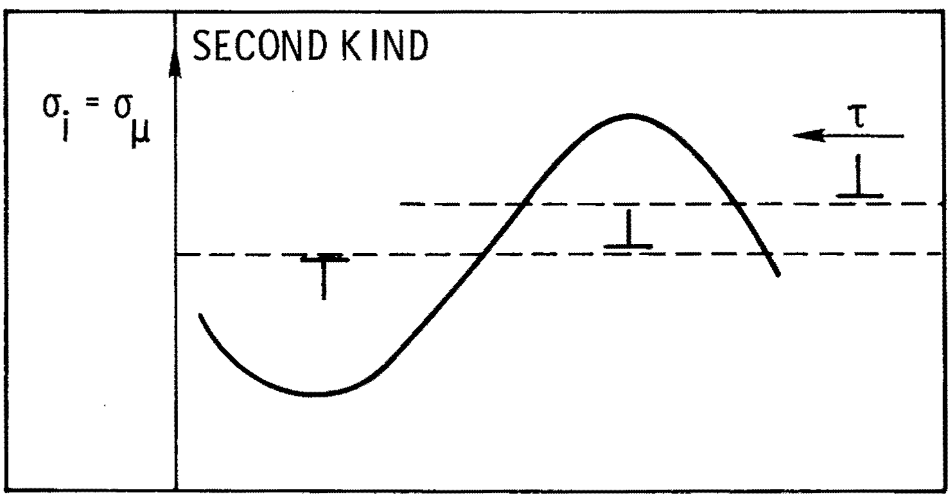

Fig. 1. Top: Three-point bending in the elastic range as an example of an internal stress of the first kind.

Bottom: Dislocation arrangement as an example of internal stresses of the second kind.

of the loop length, L, of the dislocation and the dislocation density, Λ as shown in Eqn. (2).

$$U_{2d} = U_1^2 \omega^2 x\left[f (L, \Lambda)\right] e^{2i(\omega t-kx)} \quad (2)$$

Both amplitudes, given by Eqns. (1) and (2), add up to the total amplitude observed experimentally.

Recently, the Science Center became interested in harmonic generation as a possible tool to study internal stresses of the second kind. At present, the signal input frequency is at 30 MHz and the dynamic range of the equipment is better than 60 dB. A typical example of harmonic generation in fused silica (a brittle material, in which dislocation motion can be neglected) is shown in Fig. 2. In this figure, harmonics up to the fourth may be observed. Fused silica was used since its damping is very low (0.16 dB/cm) due to negligible dislocation motion at room temperature. Since second and third order elastic constants of this material are known[5], fused silica was considered to be an ideal material for testing the equipment, according to Eqn. (1). Satisfactory results were obtained as discussed in more detail elsewhere,[6] indicating that the present equipment operates as expected.

Since Elbaum et al[7] had found that the third harmonic may even be more sensitive to dislocation contributions, the Science Center also became interested in the question of how much the fourth order elastic constants, c_{ijkl}, would contribute to the third harmonic. Use of a model previously used to explain harmonic generation in lossless fluids[8], and adaption of this model to solids yields the normalized harmonic amplitudes as a function of a normalized propagation distance x/L_0, where x is the actual propagation distance and L_0 is the so called discontinuity length[6]. The full curves in Fig. 3 show the theoretically expected harmonic amplitudes up to the fourth if only second and third order elastic constants contribute to the harmonics and if the solid is reasonably low in attenuation. The data points in Fig. 3 present a summary of measured harmonics on four different experiments on two fused silica samples, by adjusting the single parameter L_0 for best fit to all harmonics simultaneously. The agreement is excellent, as indicated in the figure. Thus, as is shown, aside from possible dislocation contributions to harmonic generation, only the third order elastic constants contribute to the harmonic generation. This simplifies the analysis of the data to be obtained on ductile materials a great deal, as will be discussed below.

Let us now turn our attention to aluminum, a ductile material. In Fig. 4, the normalized second harmonic as well as the normalized third harmonic are plotted against the state of deformation, expressed at the compressional stress applied to the aluminum before the data were taken. Zero stress indicates that the first set of data were obtained on a single crystal of aluminum as grown with a dislocation density of roughly $10^6/cm^2$. Thereafter, the crystal was subjected to 5 and 10 times the original flow stress. Using the third order elastic constants of aluminum[9], and calculating the second harmonic (dotted line in Fig. 4), the experimentally observed second harmonic turns out to be much too high for the zero stress condition. As the crystal is subjected to compressional loads, the observed second harmonic approaches the dotted line asymptotically. This trend is to be expected since the dislocation

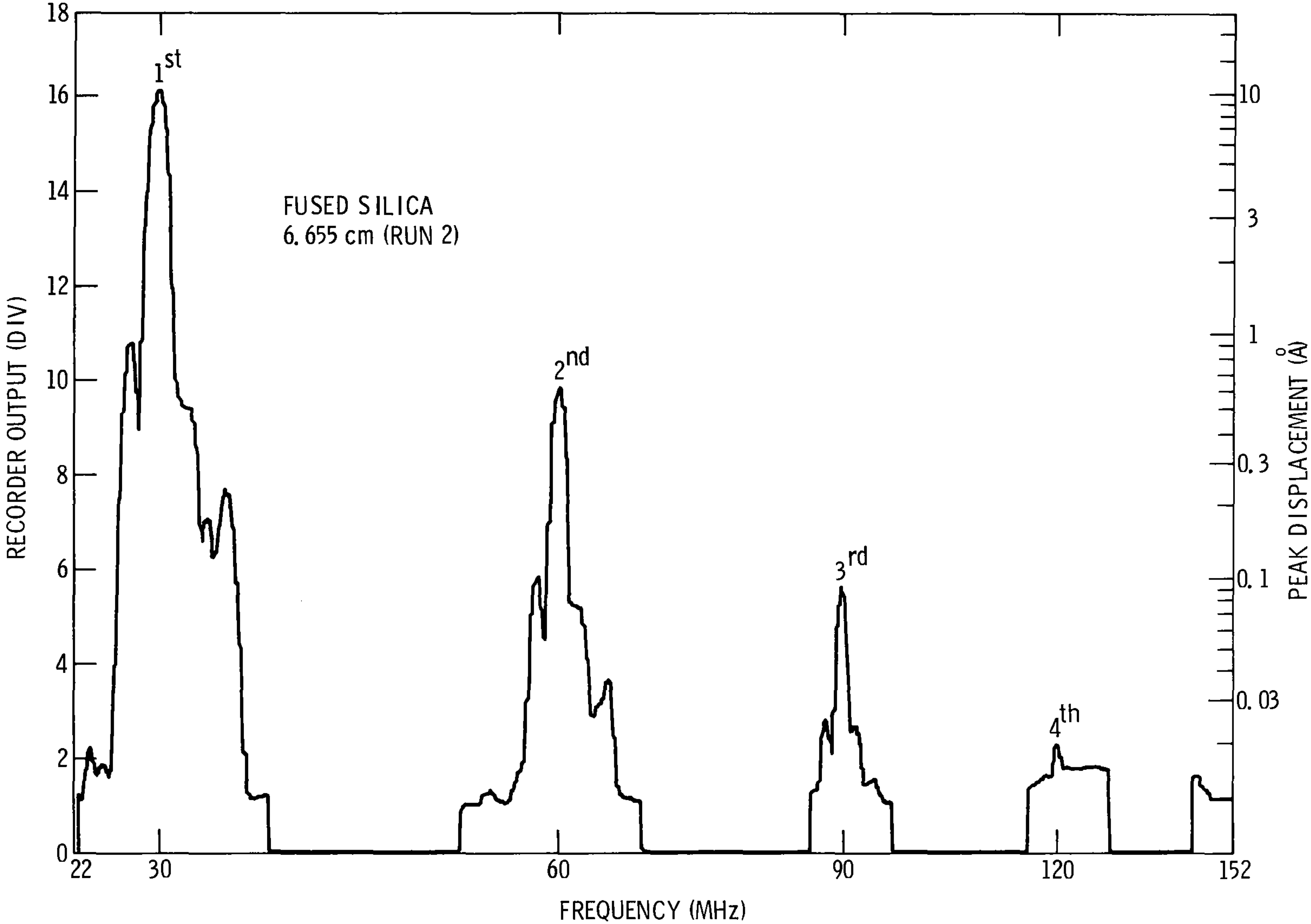

Fig. 2. Typical Frequency Spectrum of a Pulse in Fused Silica.

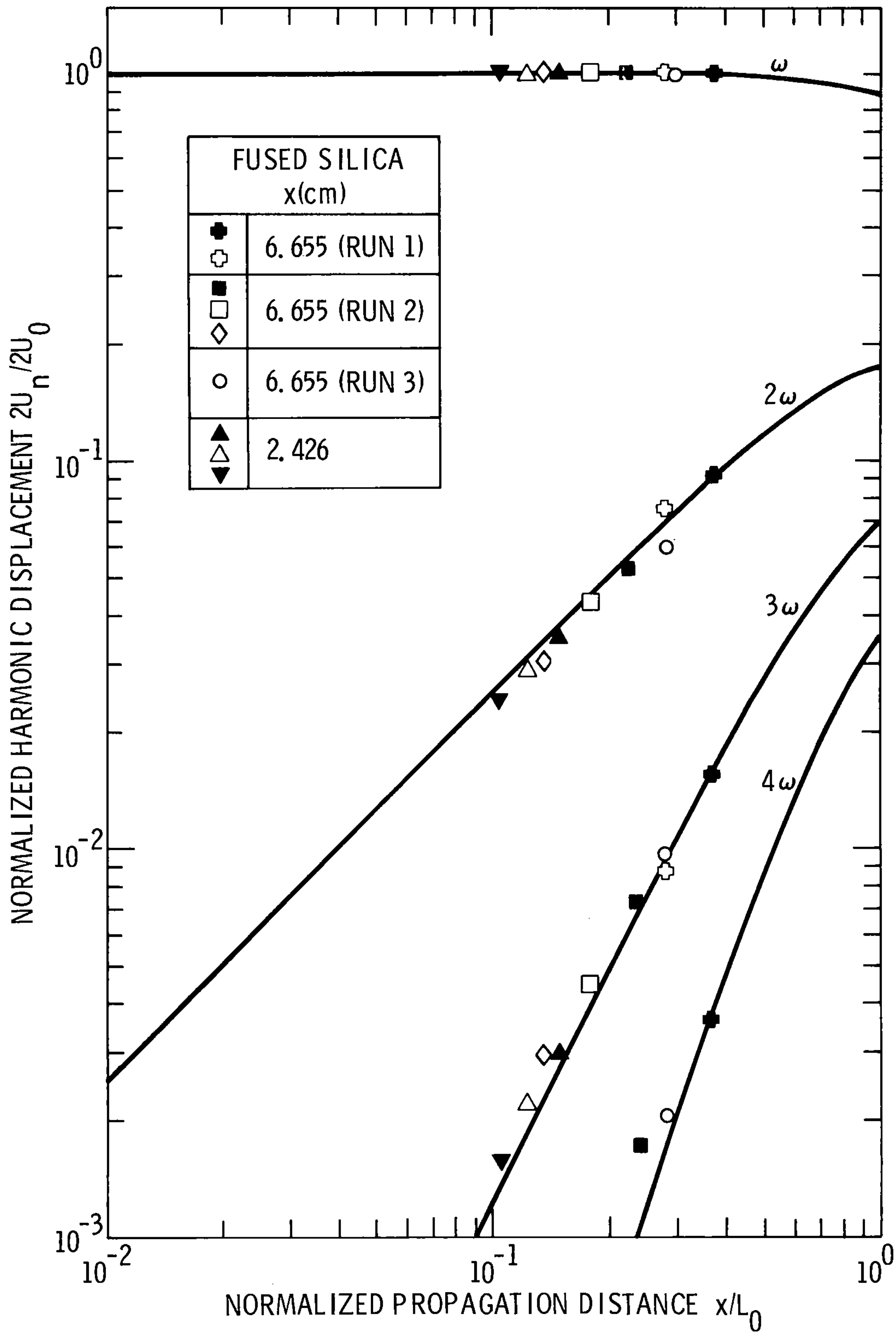

Fig. 3. Normalized harmonic displacement vs propagation distance for fused silica. Solid curves are theoretical predictions.

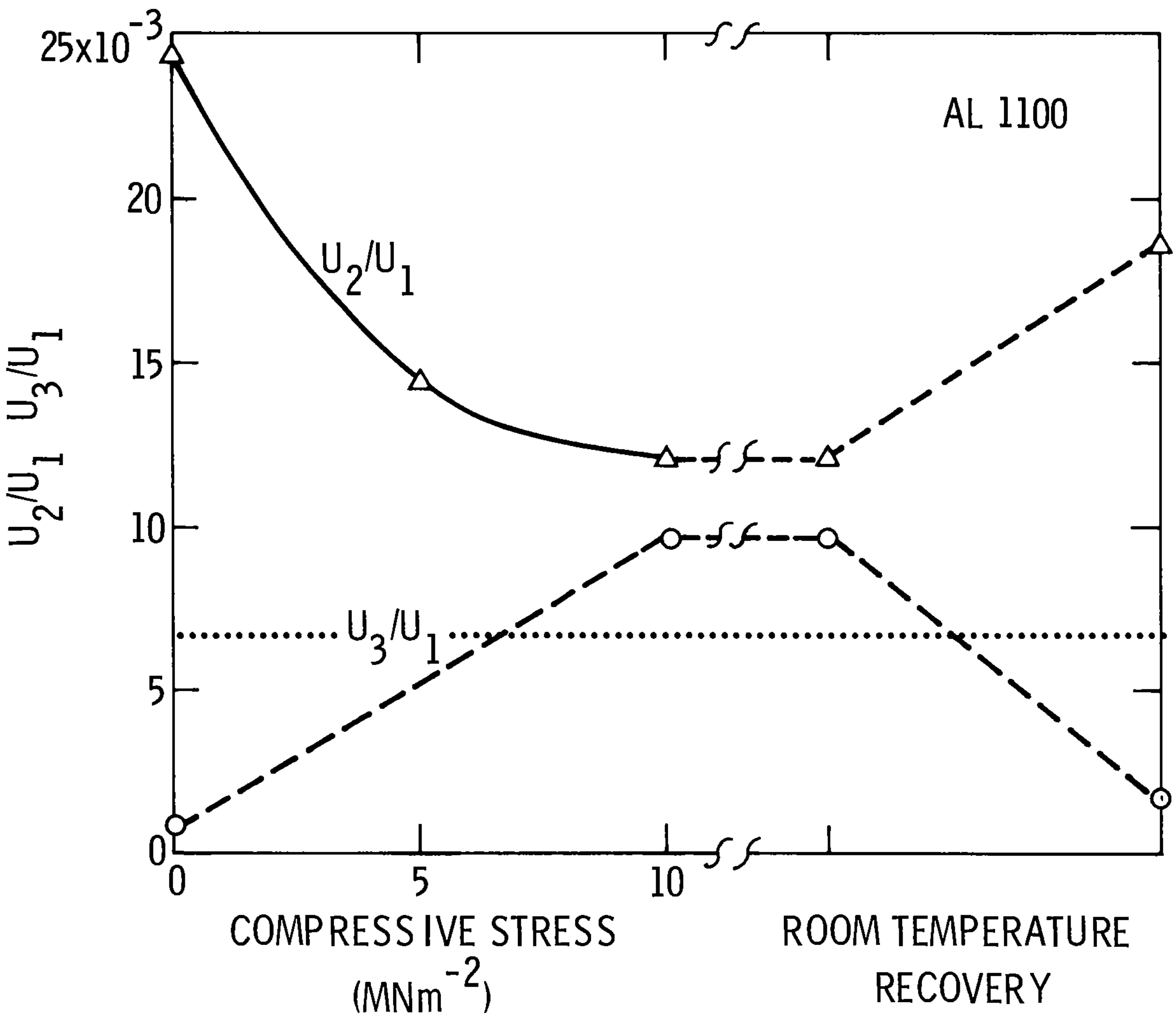

Fig. 4. Normalized Second and Third Harmonic Displacement versus Compressive Stress and room temperature recovery for 30 MHz Longitudinal Waves in Aluminum.

contribution to harmonic generation. At the same time, the third harmonic increases markedly.

Aluminum is a material with a relatively high stacking fault energy, ε. A large ε causes dislocations to cross slip easily causing a reduction in work hardening. A long time room temperature anneal shows the effect clearly, as show on the right hand side of Fig. 4. The second harmonic increased and the third harmonic decreased as a function of annealing time.

The effects of fatigue after coldwork are shown in Fig. 5. The second harmonic increased during a compression-compression fatigue of pure aluminum. At the same time, the surface hardness of the material decreased as expected in fatigue softening. Again this observation is as expected. As mentioned before, the work hardened state results in a large dislocation density with short dislocation loop lengths. As the material is fatigued, dislocations annihilate each other in part but most of them are swept aside and form cell walls[10]. The areas between the cell walls are almost dislocation-free with a few very long loops. These loops could be about 10^{-4} cm long which is about the same loop length as expected in the virgin crystal. During fatigue, these dislocations oscillate back and forth. On the surface extrusions and intrusions are formed[11] resulting in microcracks at the later stages of fatigue. At the present, it is believed that these dislocations with a long loop length cause the second harmonic to grow. Similar observations have been reported recently in the Russian literature[12].

Strong effects on second harmonic generation were also observed during aging of the high strength alloy Al 2219. In the solution softened condition (T3), the second harmonic as well as the surface hardness are quite low, as shown in Fig. 6. During stepwise aging at 190°C (40 hours each step) the second harmonic increased as did the surface hardness. The first aging step establishes what is called the T6 condition, during which precipitates are formed. An electron micrograph was taken of the material in the T6 condition[13], which shows these precipitates (see Fig. 7). Interface dislocations can be clearly identified. Whether or not these interface dislocations are the ones causing the increased second harmonic is not clear at the present time.

Al 2219 was also subjected to an external stress not exceeding 0.3 σ_y. During application of the stress, measurements of the second harmonic have been made, as shown in Fig. 8. No effect on the second harmonic was noticed. According to our definition at the beginning, this external stress induces an internal stress of the first kind. As expected, such a stress does not affect the second harmonic.

In conclusion, it can be stated that changes in the dislocation structure, that means internal stresses of the second kind, can be detected easily, by harmonic generation. However, a better qualitative and quantitative understanding should be obtained by combined ultrasonics and electron transmission experiments.

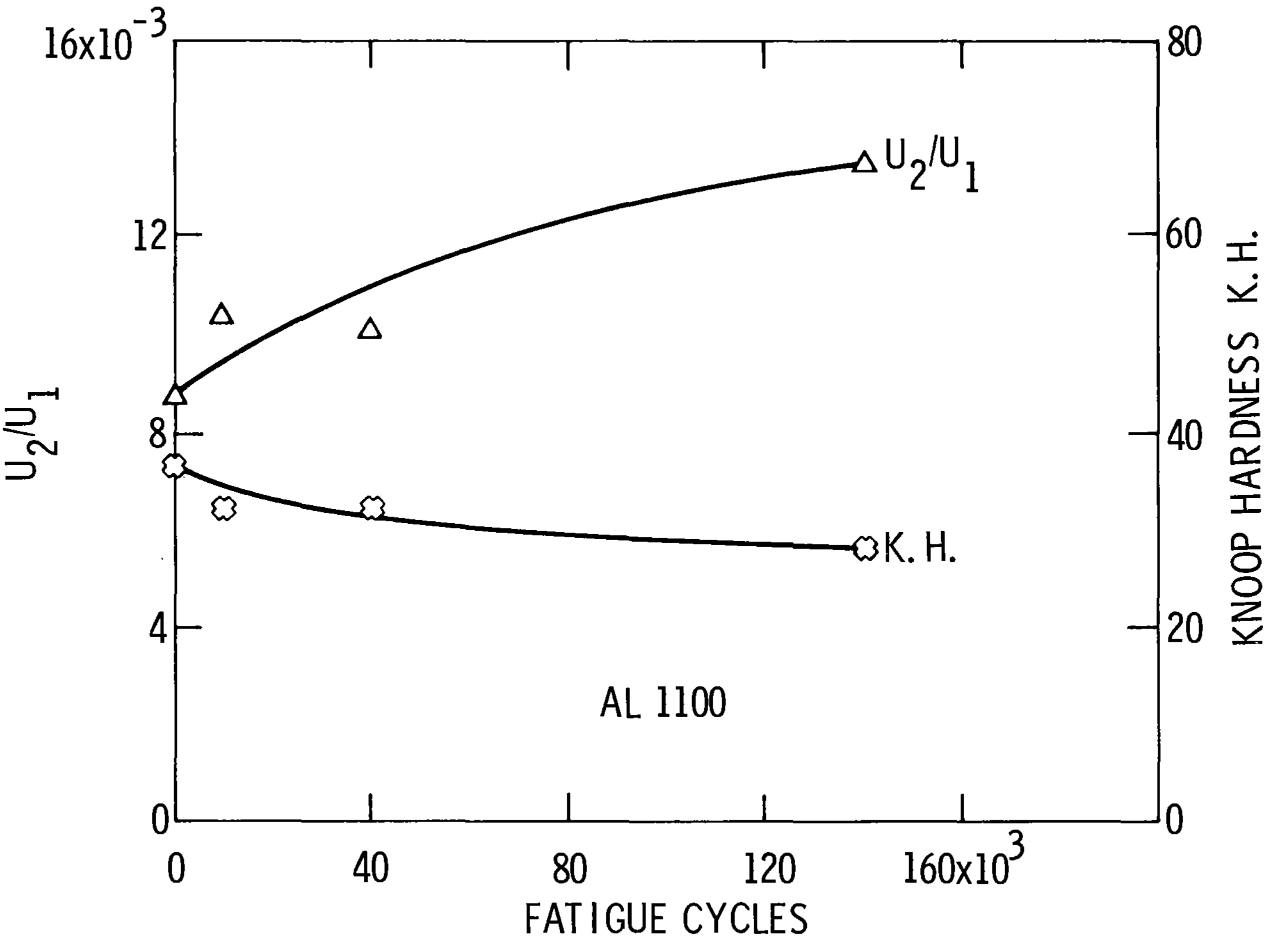

Fig. 5. Normalized Second Harmonic Displacement and Knoop Hardness as a function of fatigue in Aluminum 1100.

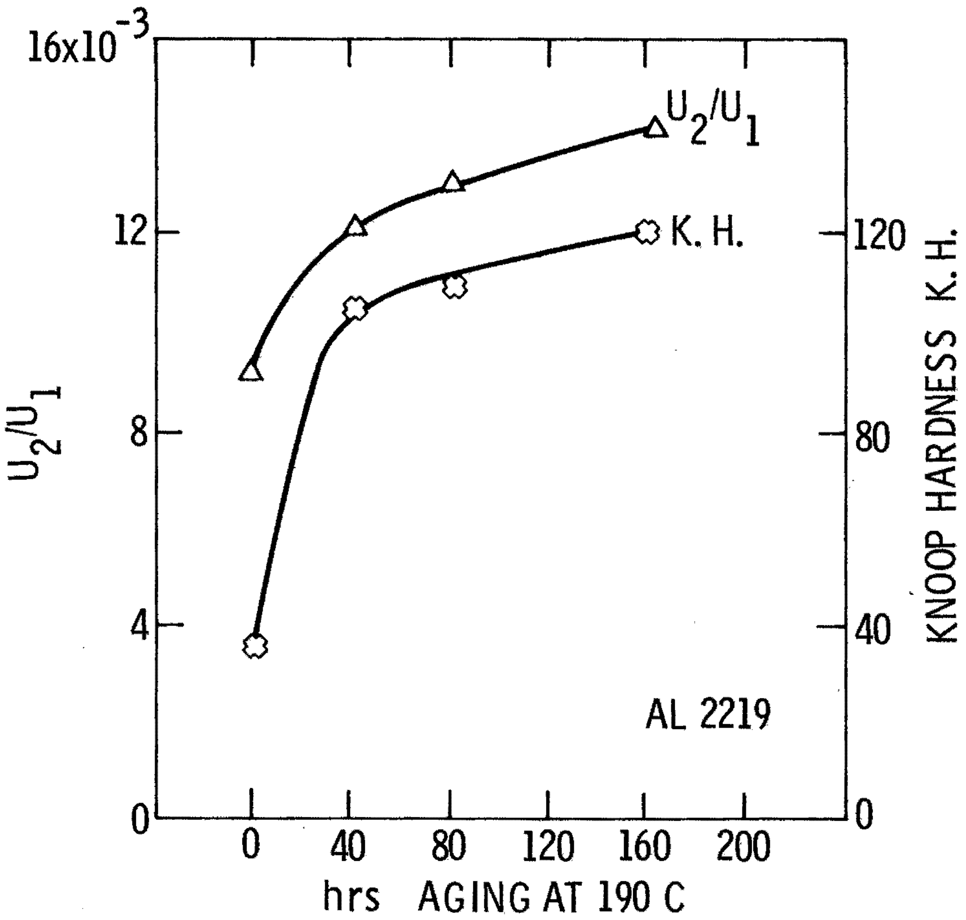

Fig. 6. Normalized Second Harmonic Displacement and Knoop Hardness as a function of Aging Time at 190°C in Al 2219.

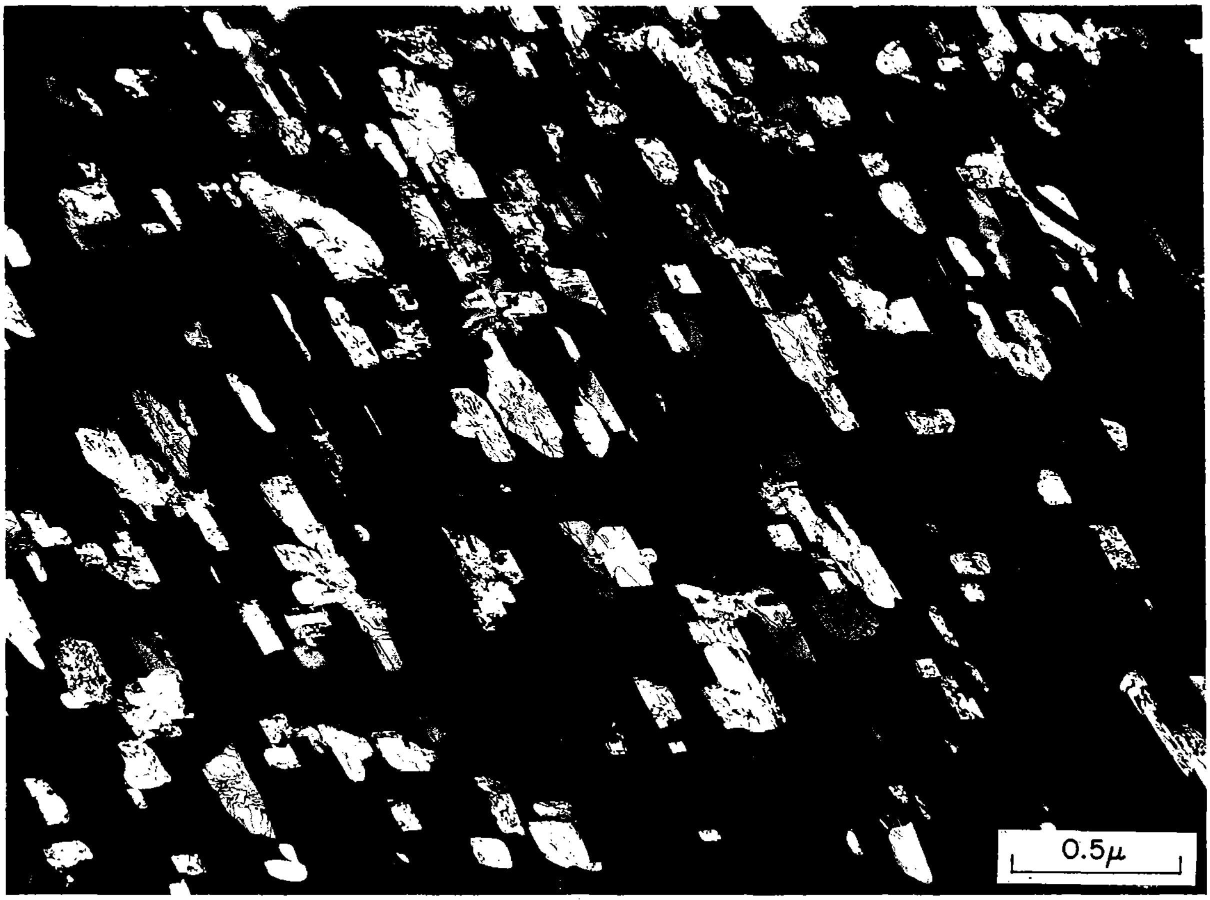

Fig. 7. Precipitates after 40 hours aging at 190°C in Al 2219.
Note the interface dislocations.

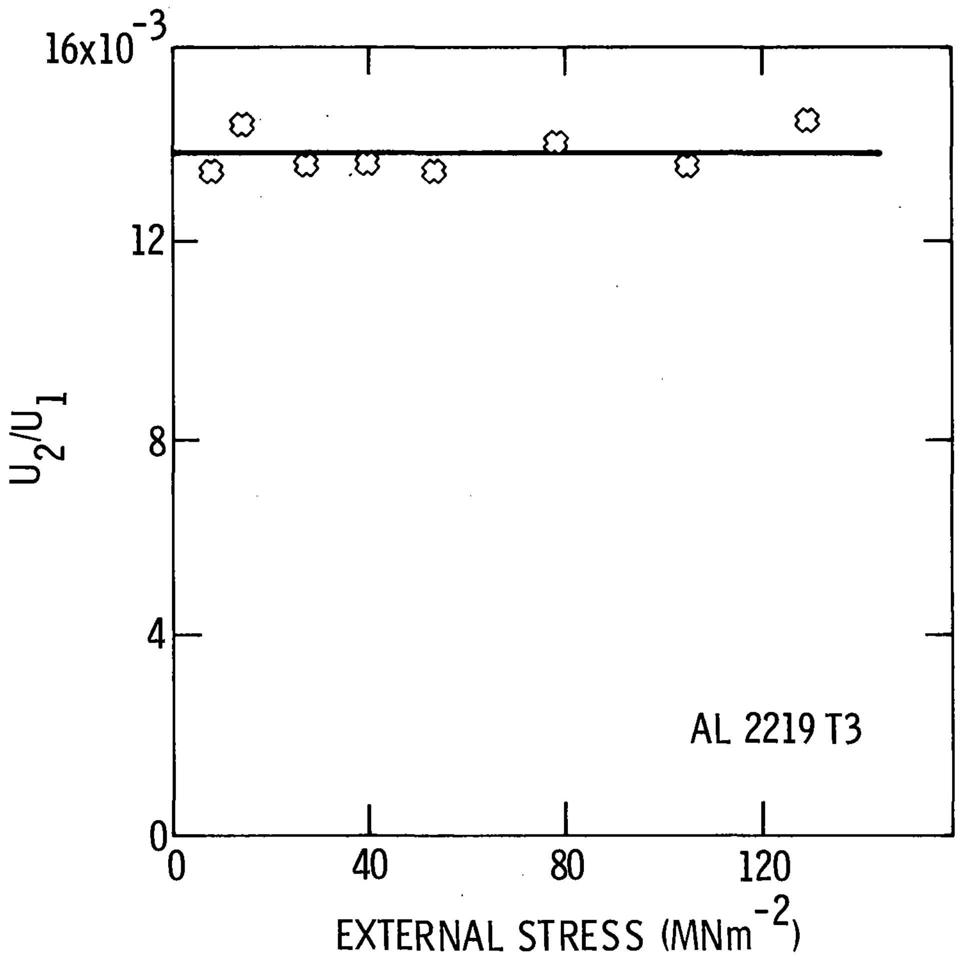

Fig. 8. Normalized Second Harmonic Displacement as a function of External Stress in Al 2219.

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DISCUSSION

DR. WALKER (AFOSR): Thank you very much, Dr. Buck. Are there any questions?

DR. GREEN (John Hopkins University): The amplitude of the second harmonic is a linear function of distance. In the only experiments ever made, I think Krasil'nikov made some, it went through a maximum. Thus you could get two amplitude values of the second harmonic. It is a question of specimen thickness. Have you thought about that problem or a way to get around it?

DR. BUCK: That's correct. This maximum comes about at the discontinuity length $x=L_0$ in Fig. 3. In our experiments, we stayed below that discontinuity length.

DR. GREEN: What is the length L_0 in aluminum?

DR. BRUCE THOMPSON (Rockwell International Science Center): It is a function of the amplitude of the input waves. It varies inversely with the driving displacement. You can figure out what it is in fused silica. It is not that much different in aluminum.

DR. BUCK: That would mean, using the fused silica data in Fig. 3, L_0 could be roughly in the order of 10 cm to 30 cm, depending on amplitude.

DR. WALKER: Are there any other questions?

PROF. HARRY TIERSTEN (Rensselaer Polytechnical Institute): When you make the measurements, do you make the measurements away from where the transducer is and then a certain number of wavelengths away? How many wavelengths from where the input is and how many wavelengths away? I only care about wavelength numbers.

DR. BUCK: The fundamental frequency was 30 MHz. Thus the wavelength would be about 0.02 mm and the specimens are about 3 cm long. Since the input transducer is on one side of the specimen and the microphone on the other side, there are roughly 1500 wavelengths between input and microphone.

PROF. TIERSTEN: Is 1500 wavelengths the distance between the two points? Is one of them at the input transducer?

DR. BUCK: No, the data you saw were all taken at the microphone end of the specimen.

PROF. TIERSTEN: How do you know U_1 without measuring it at the input?

DR. BUCK: We measure U_1 and U_2 both at the microphone. As a matter of fact, we measure all harmonics at the microphone.

PROF. TIERSTEN: Then U_1 is assumed to be pretty much the same as it was at the input?

DR. BUCK: Yes, at least for low damping materials.