ULTRASOUND AS A PROBE OF DISLOCATION DENSITY IN ALUMINUM

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Summary Ultrasound is widely used a Non Destructive Evaluation tool. This is based on the interaction of acoustic waves with defects, flaws and objects inside elastic bodies. Could ultrasound be used as a similar tool to evaluate the plastic performance of materials? An affirmative answer involves the theory of dislocation-wave interaction, and Resonant Ultrasound Spectroscopy (RUS) measurements with aluminum. The theory is a generalization of the Granato-Lücke formulation that takes into account the vector character of both elastic waves in solids and dislocation line defects. Experiments involve measurements with aluminum samples that have been subject to different — mechanical annealing and cold rolling — treatments. The RUS experiments measure the speed of shear waves in the different samples with an accuracy of better than 0.1%, leading to a discrimination of the dislocation density between the samples.

INTRODUCTION

Dislocation dynamics is a problem at the root of a number of outstanding issues in the mechanics of materials. For example, in the brittle to ductile transition, or in fatigue, where there is wide agreement that dislocations play a significant, possibly determinant, role. From an engineering design point of view the issue of brittle to ductile transition is well controlled in the sense that structures can be, and are, successfully constructed. From a basic science point of view, however, those phenomena are far from being understood, in the sense that current theoretical modeling has, to the best of our knowledge, no predictive power: If a new form of steel, say, is fabricated, current theory cannot make quantitative predictions concerning its mechanical properties as a function of temperature or cyclic loading. It is our opinion that one important cause for this lack of basic knowledge lies in the paucity of experimental measurements (as opposed to visualizations) concerning dislocations. This is so because dislocations need to be seen through electron microscopy of samples that must be specially prepared. It stands thus to reason that it would be desirable to have quantitative measurements carried out with noninvasive probes.
Ultrasound is, of course, widely used a Non Destructive Evaluation tool. This is based on the interaction of low intensity acoustic waves with defects, flaws and objects inside elastic bodies. But acoustic or, better, elastic, waves also interact with dislocations. Could this interaction be unraveled and put to use to provide needed data about the plastic behavior of materials, at least partially? Here we present results in this direction.

THEORY

Interaction of an elastic wave with a single dislocation

A plane elastic wave with wave vector $\vec{k}_i$ is incident upon a dislocation segment of length L pinned at the ends. As a response, the segment will oscillate and as a consequence of said oscillation, "secondary", or "scattered", radiation will emerge. The scattering problem is to characterize the secondary radiation far away (relative both to length L and wavelength λ) from the dislocation, in terms of the polarization of the incident wave, geometry of the dislocation relative to the incident wave, and direction of observation. This characterization is provided by the scattering amplitude, defined as the angular response of the scatterer. It is noteworthy that the scattering will induce mode conversion (transverse to longitudinal and longitudinal to transverse), even though everything is linear outside the dislocation core. That is, a purely longitudinal incident wave will be partly scattered as longitudinal, and partly as transverse; and the same will be true for a purely transverse incident wave. Indeed, there are nine scattering amplitudes, one for each pair of incident and scattered polarizations. Quantitative expressions for the scattering amplitudes are simplest when the wavelength of the incident radiation is large compared to the dislocation length: $L \gg \lambda$, since in this case only the fundamental mode of the string is

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significantly excited.

Interaction of an elastic wave with many dislocations

In practice, it is very difficult to study experimentally the dynamics of an isolated dislocation (Figure 2), and a multiple scattering formalism must be used to study the collective response of many dislocations to an elastic wave. The net effect of the dislocations is to change ΔV_T in the speed of propagation V_T of transverse elastic wave by an amount that is proportional to nL^3, where n is the number of dislocations per unti volume, and L is the typical dislocation length [1]:

$$\frac{\Delta V_T}{V_T} = \frac{4}{5\pi^4} nL^3 \, .$$

Thus, measuring ΔV_T will provide a measure of dislocation density.

EXPERIMENT

Resonant Ultrasound Spectroscopy (RUS) allows precise measurements of the elastic constants of a sample independent of its symmetries. RUS is known to give more precise measurements for C_{44} than for C_{11}, and therefore a comparison with the theoretical predictions for the velocity of transverse waves is possible. We have used commercially 1100 pure aluminum. From the same bar, five samples were taken to prepare the studied conditions classified as original, annealed and laminated material: two samples were annealed at 400 ^{o}C, one for 5 hours and another for 10 hours. Other two were cold-rolled, one at 33% and another at 43%. Longer annealing means lower dislocation density, and stronger cold-rolling means higher dislocation density. The five samples were shaped as rectangular parallelepipeds. Opposite sides are parallel within 0.06^o and adjacent sides are orthogonal within 0.3^o, thus our samples can be safely modeled as perfect rectangular parallelepipeds.

A RUS apparatus was built in-house [2, 3], and used to measure the two elastic constants of the five samples. The sample-apparatus contact force is small, of the order of 0.1 N, which corresponds to about the half of the sample weight Mg $\approx$ 0.22 N. For each sample a set of thirty resonants frequencies is determined. Each resonant frequency is measured for several ultrasonic driving amplitudes (typically five) in order to verify that the resonances are well within the linear acoustic regime. Additionally, each sample is placed ten times in the apparatus in order to reduce errors due to slight dependence of the resonant frequencies on the contact load and positioning with respect to the ultrasonic receiver.

The resulting changes ΔV_T are clearly identified for the five samples, and they are consistent with the expected changes in dislocation densities. A comparison has been carried out with densities inferred from line broadening in X-ray diffraction measurements [4], with RUS providing a more accurate discrimination.

CONCLUSIONS

A full vector theory of wave-dislocation interaction is needed to interpret Resonant Ultrasound Spectroscopy (RUS) measurements. Carrying out such measurements in aluminum subject to different mechanical treatments shows that RUS is a technique well suited to measure dislocation densities non intrusively.

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