LASER GENERATION AND INTERFEROMETRIC DETECTION OF ULTRASOUND

IN ANISOTROPIC MATERIALS

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INTRODUCTION

Current investigation into the influences of material anisotropy on the signature of laser generated waveforms in single crystals using interferometric detection has shown that the orientation of the lattice not only influences the speed of wave propagation but also the overall shape of the detected waveform. In few grained crystalline materials which exhibit strong anisotropy, the misorientation of grains relative to one another may be observed in the signature of detected waveforms. As a result of the reproducibility and the inherent directivity of laser generated ultrasound, the lattice orientation of a specimen relative to its boundaries may be inferred by observing both wave velocities and wave signatures.

THEORY

Laser ultrasonic investigations of anisotropic, crystalline materials differ from conventional ultrasonic testing of materials in several important aspects. In conventional ultrasonic testing, ultrasonic displacements in a material are produced directly by displacing the boundary of the material using a contacting transducer. Ultrasonic displacements produced in this manner primarily are sensitive to the elastic properties of a material. For laser generation of ultrasound in the thermoelastic regime, the electronic, thermal and elastic properties of the material being tested can be important. The strength and penetration of the laser ultrasonic source into the material directly depend on these material properties. First, the radiation incident on the material boundary is absorbed by the material. For metals the mechanisms of radiation absorption and thermalization depend primarily on the electronic properties of the material.\(^1\) Absorption and thermalization variations with crystallographic direction necessarily vary the thermal source region within the material. However, for many metals, the absorption depth for optical radiation is on the order of nanometers and is not consequential in the interpretation of laser ultrasonic waveforms.\(^2\) As a result, variations in the absorption and thermalization characteristics with crystallographic direction are assumed to have minimal effect on the laser ultrasonic waveforms detected in single-crystal metals. Secondly, the thermal transport properties of the material must be taken into account. From the theory of thermoelasticity, the parabolic heat conduction equation in the thermal stress approximation may be written as follows:
\[ k_{ij} T_{i,j} - c_v \dot{T} = -Q \]  

(1)

where \( k_{ij} \) is the thermal conductivity tensor, \( T \) is temperature increment relative to ambient, \( c_v \) is the thermal heat capacity, and \( Q \) is the thermal energy source. Subscripts after a comma indicate differentiation with respect to the corresponding spatial coordinate, and the repeated subscript summation convention holds. The effect of the thermal conductivity anisotropy is important in laser ultrasonics as the temperature field resulting from laser heating serves as the source for elastic displacements. This is shown by the theory of thermoelasticity where the differential equation governing elastic displacements in an anisotropic material may be obtained from the Duhamel-Neumann relations and may be written as follows:

\[ c_{ijkl} u_{k,l} - \beta_{ij} T_{i,j} = \beta_{ij} T_{i,j} \]  

(2)

with

\[ \beta_{ij} = c_{ijkl} \alpha_{kl} \]  

(3)

where \( c_{ijkl} \) are the second order elastic constants, \( u_i \) is the \( i \)th component of the elastic displacement vector, \( \rho \) is the material density, and \( \alpha_{kl} \) are the coefficients of thermal expansion. Specifically, equation (2) shows that the spatial derivative of temperature multiplied by the appropriate constants acts as the source for elastic waves in the material.

In general, for thermoelastic laser-generated ultrasound in metals, all of the anisotropic properties discussed above contribute to the character of the observed displacements. As a result, the interpretation of recorded waveforms can become quite involved especially when the normal to the sample surface is not in a high symmetry direction. However, crystal lattices with cubic symmetry behave in an isotropic fashion for thermal conduction and for thermal expansion (which is homogeneous deformation process). This thermal behavior in cubic systems has been verified experimentally and has been used to separate thermal from elastic effects in thermoacoustic imaging systems. Consequently, significant simplification to the theoretical problem of thermoelastic, laser generation of ultrasound occurs when the material studied has a cubic lattice. In cubic systems, only the elastic anisotropy of the material contributes to the observed effects of material anisotropy.

**EXPERIMENT**

The purpose of the experimental study presented here was to determine the presence of ectopically nucleated grains in an otherwise single crystal specimen. The material under investigation was a nickel-based superalloy with a cubic lattice. Two parallelepiped samples of the alloy were used in the experiment to study the effects on laser ultrasonic wave propagation by elastic wave interaction with a grain boundary and the effects of lattice orientation on the observed ultrasonic displacements. The effect of the lattice orientation on the observed ultrasonic displacements produced by laser generation served both to indicate the smallest variation in lattice misorientation between grains which could be detected and to indicate the orientation of the sample under study. Laser ultrasonic determination of lattice orientation provides a potentially noncontacting method, similar to X-rays, for crystallographic orientation analysis. For all of the studies shown here, laser generation was performed in the ablative regime. The ablative laser source can behave like a mechanical impulse to the sample surface. In the general case for material anisotropy, such a source simplifies data interpretation compared to the analysis required for interpretation of data obtained using a thermoelastic source since the effects of elastic anisotropy would dominate the observed waveforms.